Marie Rusinová[1], Miloš Lavický[2], Miloš Kalousek[2], Martin Sedlmajer[3]

Analysis of the Effect of Gypsum-Based Fire Protection Cover on Charring of Wooden Bearing Elements

Analiza utjecaja protupožarne obloge na bazi gipsa na pougljenje drvenih nosivih elemenata

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ABSTRACT • *Fire resistance of load-bearing wooden structures is evaluated by the charring of surface layers of wooden bearing elements. The degree of resistance is determined by the onset and course of charring; these basic parameters are affected by the cover structure as well as by cavity fillers between the individual bearing elements. This article focuses on analysing the structure of fire protection covers based on gypsum boards, namely gypsum plasterboards and gypsum fibreboards. The foundation for the current analysis, based on the ignition temperature of the load-bearing timber element under the fire cover, includes the results of experimental fire tests carried out on test specimens in a fire furnace with a standard time-temperature curve set to simulate a fire. In addition, a numerical analysis of the temperature behaviour in the structure was carried out in order to compare the experimental results with the values obtained by mathematical analysis. Finally, the influence of the cover layers on the resulting fire resistance of the analysed structures is evaluated.*

KEYWORDS: *fire resistance, ignition temperature, gypsum plasterboard, gypsum fibreboard, fire test*

SAŽETAK • *Vatrootpornost nosivih drvnih konstrukcija ocjenjuje se prema pougljenjenim površinskim slojevima. Stupanj otpornosti određen je na početku i tijekom pougljenjivanja, a na nj utječe pokrovna konstrukcija, kao i ispune šupljina između pojedinih nosivih elemenata. Ovaj je rad fokusiran na analizu strukture protupožarnih obloga na bazi gipsanih ploča, odnosno gips-kartonskih i gips-vlaknatih ploča. Analiza temperature zapaljenja nosivoga drvnog elementa ispod protupožarne obloge obuhvaća rezultate eksperimentalnog simuliranja požara sa standardnom krivuljom vrijeme – temperatura na uzorcima na kojima je provedeno ispitivanje gorivosti. Osim toga, provedena je numerička analiza kretanja temperature u konstrukciji kako bi se eksperimentalni rezultati usporedili s vrijednostima dobivenim matematičkom analizom. Na kraju je ocijenjen utjecaj obloga na vatrootpornost analiziranih konstrukcija.*

KLJUČNE RIJEČI: *vatrootpornost, temperatura zapaljenja, gips-kartonska ploča, gips-vlaknata ploča, ispitivanje gorivosti*

[1] Author is assistant professor at Brno University of Technology, Faculty of Civil Engineering, Institute of Building Structures, Brno, Czech Republic. https://orcid.org/0000-0002-0641-5448
[2] Authors are associate professors at Brno University of Technology, Faculty of Civil Engineering, Institute of Building Structures, Brno, Czech Republic. https://orcid.org/0000-0002-2002-0960; https://orcid.org/0000-0002-4712-9915
[3] Author is assistant professor at Brno University of Technology, Faculty of Civil Engineering, Institute of Technology of Building Materials and Components, Brno, Czech Republic. https://orcid.org/0000-0003-2615-7922

1 INTRODUCTION
1. UVOD

The use of wooden elements in construction is subject to strict regulations regarding their fire resistance, as fire safety is a major concern in any building. Increasing the fire resistance of timber structures is a frequent subject of research. The aim of this paper is to highlight the importance of gypsum-based boards as a fire protection cover on the overall fire resistance of a timber structure and on the possible delay of the charring process of load-bearing timber elements. This paper brings a new perspective to this area of investigation in comparing the benefit to the fire resistance of the structure using a fire protection cover of either gypsum plasterboards or gypsum fibreboards. The findings obtained from the fire tests were further illustrated by numerical analysis.

The onset of charring is an important factor in determining the fire resistance (Bisby and Frangi, 2015; Östman, Brandon and Frantzich, 2017; White, 2016) of a timber element. When exposed to fire, wood undergoes a process of charring, which is the partial burning or carbonization of the wood due to high heat in the absence of oxygen (Kuklík and Kuklíková, 2010). The charring process creates a protective layer of char that acts as an insulator, slowing down the rate of heat transfer from the flames to the wood. As the char layer forms, the wood becomes progressively more resistant to fire. Therefore, the onset of charring and the rate at which it progresses are key factors in determining how long a wooden element can resist the effects of fire. The aim of our research was to determine the time difference in the onset of charring of a load-bearing timber element when gypsum plasterboard or gypsum fibreboard was used as a fire protection cover.

Gypsum plasterboards and mineral fibreboards are the most commonly used materials for passive fire protection covers. Academic literature (Fitzgerald, 2004; Thomas, Buchanan and Fleischmann, 1997; Just, Schmid and König, 2010; Piloto, Rodriguez-del-Rio and Vergara, 2022) provides information and relationships for determining the charring rate, charring onset, and cover failure time of these fire protection covers. However, these characteristics may be more difficult to determine for less commonly used compositions.

This article focuses on fire protection covers consisting of two layers of gypsum plasterboards mounted on a steel profile grid or oriented strand boards, as well as two layers of gypsum fibreboards mounted on particle board or oriented strand board.

Figure 1 Experimental fire furnace with test specimen TS1 (photo: authors)
Slika 1. Eksperimentalno ložište s ispitnim uzorkom TS1 (autorska fotografija)

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Test specimens
2.1. Ispitni uzorci

The present analysis investigates how fireproofing affects the onset of charring of timber load-bearing elements. The results obtained by this analysis are based on experimental fire tests of material specimens carried out in accordance with European testing and classification standards for ensuring the fire safety of structures. Modifications were made to these tests to adapt them for use in an experimental fire furnace with an exposure area of 2 m², as shown in Figure 1.

The figures below (Figure 2, Figure 3, Figure 4, Figure 5) provide explicit information about the test specimens, including their individual compositions. In all cases, the fire protection cover had a surface layer directly exposed to high temperatures simulating fire.

The test specimens had dimensions of 1 m × 2 m to fit the test furnace and consisted of wooden prisms with the top covered with gypsum-based boards and wood-based boards. The space between the wooden beams was filled with EPS 100 foam polystyrene for test specimens TS1 and TS2 and mineral wool with a density of 148 kg·m^{-3} for test specimens TS3 and TS4. The test fire protection covers were attached from the underside of the exposed fire and had the following composition (described from above):

(1) Test specimen TS1 (see Figure 2) - oriented strand board with a thickness of 15 mm, steel grid with a thickness of 60 mm (an air gap with a thickness of 10 mm and mineral wool with a density of 148 kg/m^3 mm and a thickness of 50 mm are inside) and two gypsum plasterboards, each with a thickness of 12.5 mm.

(2) Test specimen TS2 (see Figure 3) - oriented strand board with a thickness of 15 mm and two gypsum plasterboards, each with a thickness of 12.5 mm.

(3) Test specimen TS3 (see Figure 4) - oriented strand board with a thickness of 15 mm and two gypsum fibreboards, each with a thickness of 10 mm.

(4) Test specimen TS4 (see Figure 5) – particleboard of Euroclass B with a thickness of 16 mm and two gypsum fibreboards, each with a thickness of 10 mm.

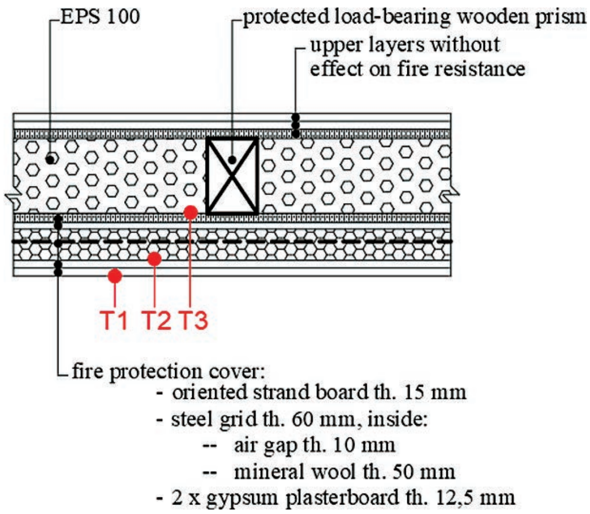

Figure 2 Configuration of test specimen segment TS1
Slika 2. Konfiguracija segmenata ispitnog uzorka TS1

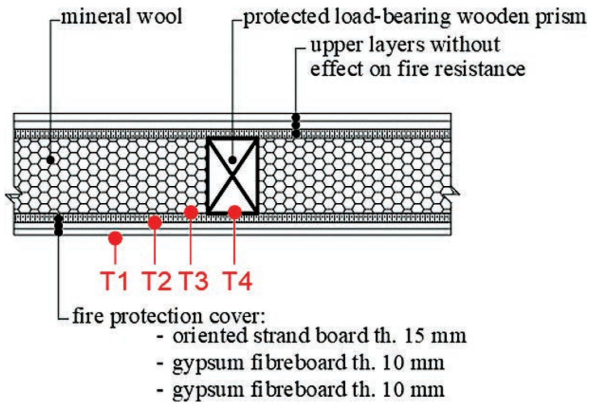

Figure 4 Configuration of test specimen segment TS3
Slika 4. Konfiguracija segmenata ispitnog uzorka TS3

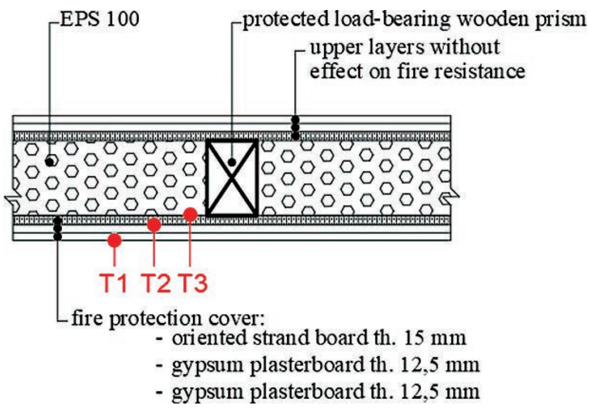

Figure 3 Configuration of test specimen segment TS2
Slika 3. Konfiguracija segmenata ispitnog uzorka TS2

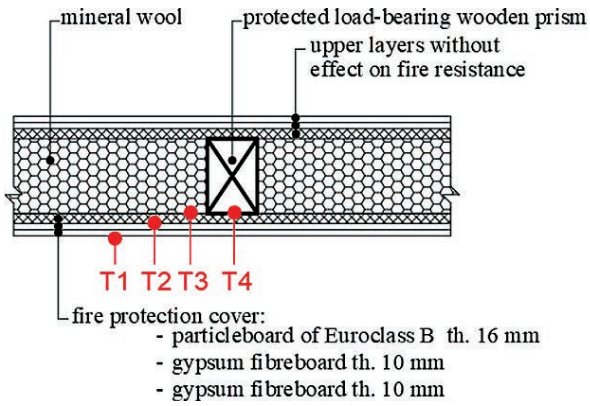

Figure 5 Configuration of test specimen segment TS4
Slika 5. Konfiguracija segmenata ispitnog uzorka TS4

The test specimens were equipped with K-type thermocouples. The T1 thermocouples were placed on a heated surface. The T2 thermocouples were placed on gypsum-based board and the T3 thermocouples on wood-based board (oriented strand board or particleboard). The test specimens TS3 and TS4 still had T4 thermocouples in the joint under the wooden prisms.

2.2 Test procedure
2.2. Tijek ispitivanja

The testing of specimens was carried out in a natural gas fire furnace, using a standard set time-temperature curve (EN 1363-1, 2012), with consideration given to the methodological procedures outlined in the standards for suspended ceilings (EN 1364-2, 1999; EN 1365-2, 2014). The test specimens were placed horizontally in the fire furnace and exposed to the fire from below.

The exposed surface area of each specimen was 1.92 m^2, and the maximum operating temperature limit of the fire furnace according to the time-temperature curve was 1100 °C. Thermocouples T1 to T4 were used to monitor temperatures at 1-minute intervals.

The heating curve in the furnace was continuously monitored and controlled to ensure that the specimen was exposed to temperatures in accordance with the standard time-temperature curve specified by the standard expression (ISO 834-1, 1999):

$$Q_g = 20 + 345 \log (8 \cdot t + 1) \qquad (1)$$

Where Q_g is the temperature of gases in the fire compartment under consideration (°C), and t is time (min). In the graphs presented below, this temperature is referred to as T_d.

The deviations from the prescribed temperature values based on the standard time-temperature curve were initially high during the beginning of the test, but after 6 to 7 minutes, they became negligible. It can be assumed that this faster start-up of temperatures did not significantly affect the experiment. Both the temperature and the pressure in the modified testing furnace were checked and found to correspond to the prescribed standard values.

2.3 Charring onset temperature
2.3. Temperatura početka pougljenjivanja

Wood is composed of cellulose, hemicellulose, and lignin that decompose when heated and release flammable gases. If the temperature is high enough, these gases can ignite and sustain a fire.

The ignition temperature of wood is the minimum temperature required to start a combustion reaction in wood although the heat source is removed. The ignition temperature of wood can vary depending on several factors. Generally, the ignition temperature of dry wood is around 300 - 350 °C (Shi and Chew, 2013). For the above fire tests, the isotherm of 300 °C was chosen as the ignition temperature, which means that the test meets the requirements of the standard.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Experimentally obtained results
3.1. Eksperimentalno dobiveni rezultati

3.1.1 Results for test specimen TS1
3.1.1. Rezultati za ispitni uzorak TS1

Based on the temperature data recorded by thermocouple T2, positioned above 12.5 mm thick gypsum plasterboards (Figure 6), it can be concluded that the protective effect of the two layers of gypsum plasterboards diminishes gradually between 39 and 50 minutes. The temperature of 300 °C in thermocouple T3 was reached in the 66th minute.

3.1.2 Results for test specimen TS2
3.1.2. Rezultati za ispitni uzorak TS2

According to the temperature readings from thermocouple T2 placed above the 12.5 mm thick gypsum plasterboard (Figure 7), it can be concluded that within the time interval of 37 to 45 minutes, the protective effect of both layers of gypsum plasterboards gradually decreases. This leads to a sudden increase in temperature in this thermocouple. The temperature of 300 °C in thermocouple T3 was reached at the 54th minute.

3.1.3 Results for test specimen TS3
3.1.3. Rezultati za ispitni uzorak TS3

Based on the temperature monitored in the thermocouple T2 placed above the gypsum fibreboards of 10 mm thickness (Figure 8), it can be concluded that in the interval of 36 to 53 minutes the protection effect of both layers of gypsum fibreboards is gradually lost. Consequently, sudden increase in the speed of temperature growth occurs in this thermocouple.

The isotherm of 300 °C reached the thermocouple T3 at the upper side of the oriented strand board in the 57th minute. The 300 °C temperature in the thermocouple T4 placed in the joint between the wooden prisms and the oriented strand board occurred in the 59th minute, i.e. with a delay of 2 minutes. This delay is caused by the curvature of the isotherm due to the effect of the different properties of the wooden prisms and the cavity filler (Figure 11).

3.1.4 Results for test specimen TS4
3.1.4. Rezultati za ispitni uzorak TS4

After monitoring the temperature using thermocouple T2 placed above 10 mm thickness gypsum fibreboards (Figure 9), it can be concluded that between 33 minutes and 52 minutes, the protective effect of both layers of gypsum fibreboard gradually diminishes. As a result, there is a sudden increase in temperature in this thermocouple.

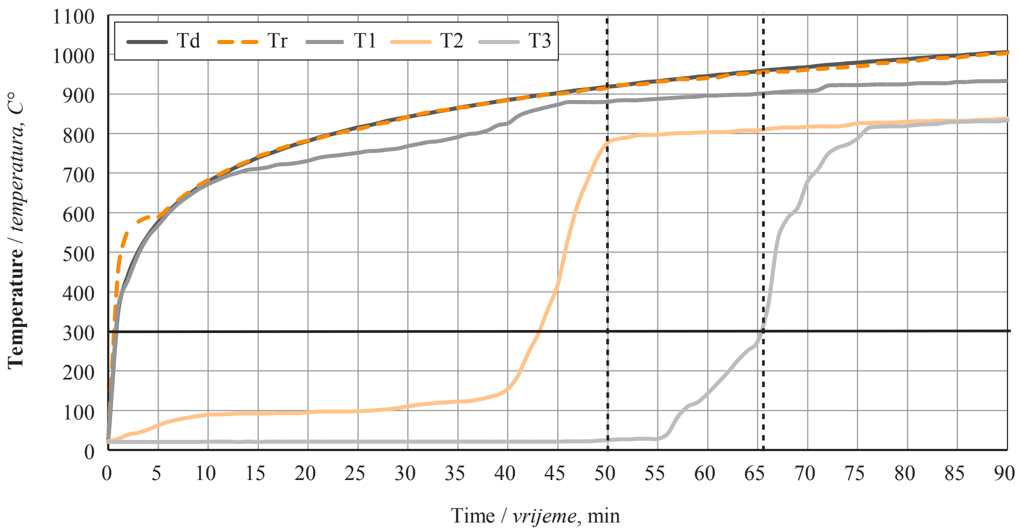

Figure 6 Temperature trends of test specimen TS1 in thermocouples T1 to T3 depending on actually reached temperature T_r in fire furnace with marked significant time points, T_d is fire furnace reference temperature
Slika 6. Temperaturni tokovi ispitnog uzorka TS1 u termoparovima od T1 do T3 ovisno o stvarno postignutoj temperaturi T_r u ložištu s označenim značajnim vremenskim točkama; T_d je referentna temperatura u ložištu

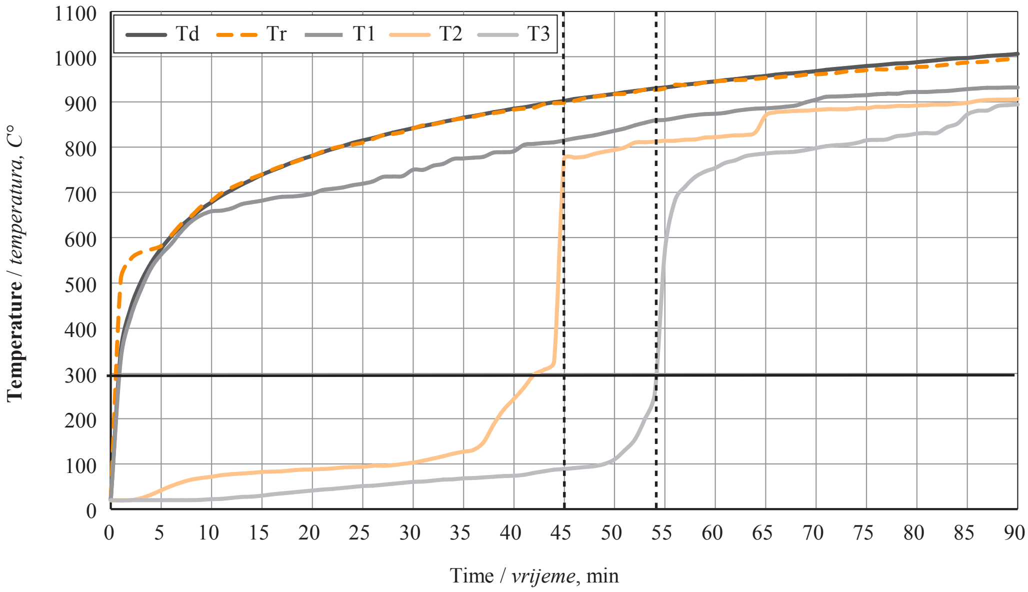

Figure 7 Temperature trends of test specimen TS2 in thermocouples T1 to T3 depending on actually reached temperature T_r in fire furnace with marked significant time points, T_d is fire furnace reference temperature
Slika 7. Kretanje temperature ispitnog uzorka TS2 u termoparovima od T1 do T3 ovisno o stvarno postignutoj temperaturi T_r u ložištu s označenim značajnim vremenskim točkama; T_d je referentna temperatura u ložištu

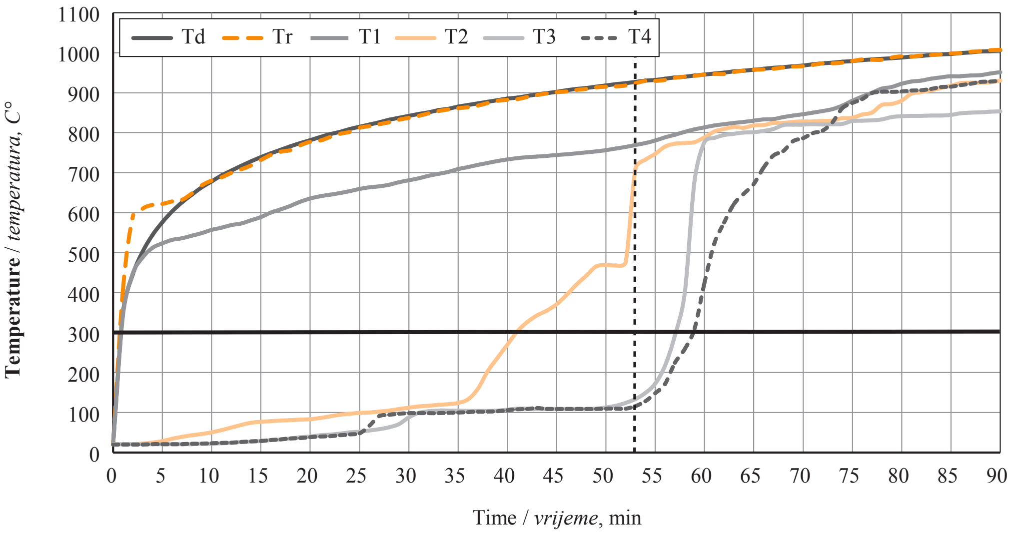

Figure 8 Temperature trends of test specimen TS3 in thermocouples T1 to T3 depending on actually reached temperature T_r in fire furnace with marked significant time points, T_d is fire furnace reference temperature
Slika 8. Temperaturni tokovi ispitnog uzorka TS3 u termoparovima od T1 do T3 ovisno o stvarno postignutoj temperaturi T_r u ložištu s označenim značajnim vremenskim točkama; T_d je referentna temperatura u ložištu

A temperature of 300 °C was reached in the T3 thermocouple on top of the particleboard (Euroclass B) in the 62th minute. This temperature in the T4 thermocouple located in the joint between the wooden prisms and the particleboard occurred with a delay of about one minute.

3.1.5 Other data obtained by testing of specimens
3.1.5. Ostali podatci dobiveni ispitivanjem uzoraka

Figures 6 to 9 provide other data on the behaviour of the test specimens. Temperature points with the sudden temperature change indicate the times of breaking of individual layers of the test specimens. The time interval between the termination of faster temperature increases in the T2 thermocouples and reaching the temperature of 300 °C in the T3 thermocouples reflects the effect that the layers placed over the gypsum-based panels have on the time of onset of charring in the individual specimens.

A comparison of the termination of faster temperature increases in T2 thermocouple and the time to reach the temperature of 300 °C in T3 for the test specimens TS3 and TS4 shows that the fire resistance of

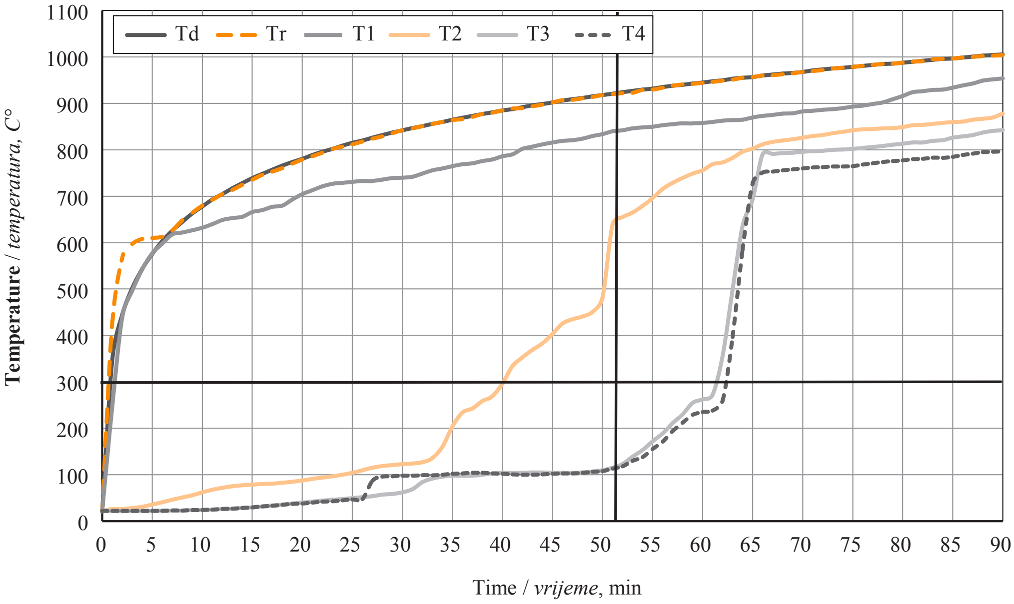

Figure 9 Temperature trends of test specimen TS4 in thermocouples T1 to T3 depending on actually reached temperature T_r in fire furnace with marked significant time points, T_d is fire furnace reference temperature
Slika 9. Temperaturni tokovi ispitnog uzorka TS4 u termoparovima od T1 do T3 ovisno o stvarno postignutoj temperaturi T_r u ložištu s označenim značajnim vremenskim točkama; T_d je referentna temperatura u ložištu

the particleboard of Euroclass B is clearly higher than that of the oriented strand board.

3.2 Analysis of fire test results in terms of fire protection
3.2. Analiza rezultata ispitivanja gorivosti u smislu zaštite od požara

3.2.1 Analysis of temperature trends measured by thermocouples
3.2.1. Analiza temperaturnih tokova mjerenih termoparovima

It is presumed that, when the temperature curves show a sudden rise in temperature, the beneficial effect of the fire protection cover is lost due to its collapse. It can then be considered that $t_f = t_{ch}$, which means that the time of failure of the fire protection cover t_f is equal to the time of charring onset t_{ch}.

The time of charring onset t_{ch} of gypsum plasterboard can be determined according to the formula in Eurocode 5 (EN 1995-1-2, 2004):

$$t_{ch} = 2.8\, h_p - 14. \qquad (2)$$

The variable h_p represents the thickness of fire protection cover in millimetres. If the protection cover consists of two layers of gypsum plasterboard, h_p is defined as the thickness of the bottom layer plus 80 % of the thickness of the top layer. However, for gypsum fibreboards, this formula does not apply.

The charring onset time calculated according to the standard procedure for a fire protection cover made of two layers of 12.5 mm gypsum plasterboard is t_{ch} = 49 minutes. This value is consistent with the results obtained from test specimens TS1 and TS2, whose fire protection cover failure time was $t_f = t_{ch}$ = 50 minutes and 45 minutes, respectively.

Test specimens consisting of two layers of 10 mm gypsum fibreboard had longer charring onset times than test specimens with two layers of 12.5 mm gypsum plasterboard. The failure time of fire protection cover of test specimens TS3 and TS4 was $t_f = t_{ch}$ = 53 minutes and 52 minutes, respectively. The temperature measurements taken by thermocouples on these specimens show that the composition of layers above the gypsum-based boards affects the results.

For test specimen TS1, which had 2 mm × 12.5 mm gypsum plasterboard cladding and mineral fibre thermal insulation on a steel grid, a 10 minute interval was recorded between the time the temperature suddenly started to rise (56 minutes) and the time when the 300 °C isotherm reached the top of the 15 mm thick oriented strand board (66 minutes).

For specimen TS2 with a fire protection cover made of 2 mm × 12.5 mm gypsum plasterboard and of 15 mm of oriented strand board, a 5-minute interval was recorded between the start of fast temperature increase (49 minutes) and the time when the 300 °C isotherm reached the upper side of the oriented strand board (54 minutes).

For test specimen TS3 with a fire protection cover made of 2 mm × 10 mm gypsum fibreboard and a 15 mm of oriented strand board, a 6-minute interval was recorded between the start of temperature rise (53 minutes) and the time when the 300 °C isotherm reached the upper side of the oriented strand board (57 minutes).

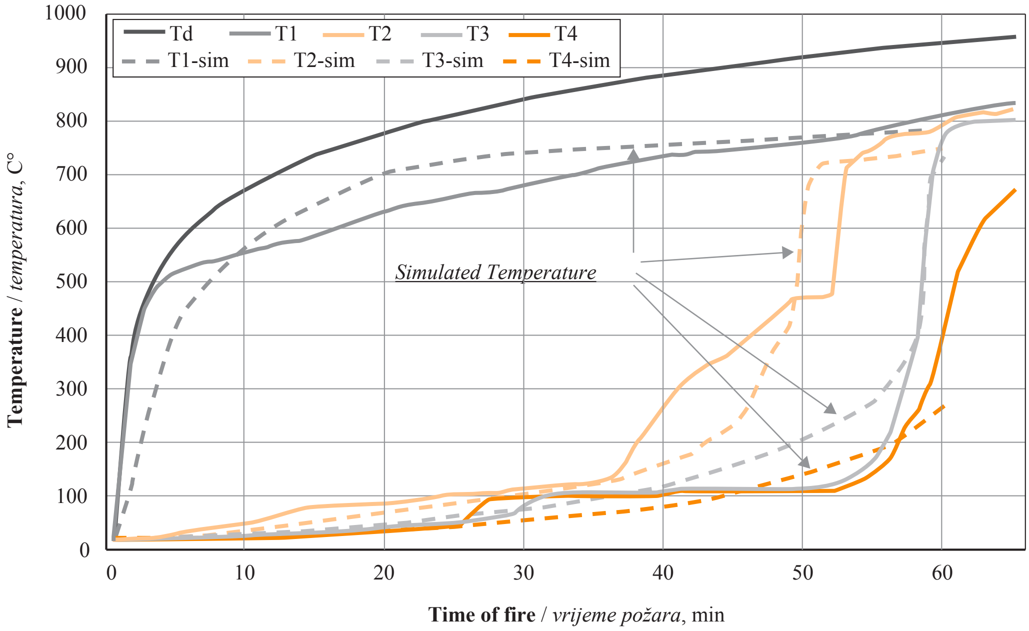

Figure 10 Comparison of numerical analysis and fire test results of test specimen TS3, where T_d is fire furnace reference temperature, T1 to T4 are temperatures measured by thermocouples, T1-sim to T4-sim are temperatures obtained by numerical analysis

Slika 10. Usporedba numeričke analize i rezultata ispitivanja gorivosti ispitnog uzorka TS3, pri čemu je T_d referentna temperatura u ložištu, T1 do T4 temperature izmjerene termoparovima, a T1-sim do T4-sim temperature dobivene numeričkom analizom

For test specimen TS4 with a fire protection cover made of 2 mm × 10 mm gypsum fibreboard and a 16 mm particleboard of Euroclass B, a 10-minute interval was recorded between the start of temperature increase (52 minutes) and the time when the isotherm of 300 °C reached the top side of the oriented strand board (62 minutes).

3.2.2 Numerical analysis
3.2.2. Numerička analiza

The application of the fire test knowledge is presented here (Figure 10) with a numerical analysis that simulates a real fire test, for a selected specimen TS3, which has a fire cover of gypsum fibreboard and oriented strand board.

The numerical analysis was performed using the boundary temperature conditions of the actual test and the material properties of the individual layers (Vimmrová, Krejsová, Scheinherrová, Doleželová and Keppert, 2020; Norgaard and Othuman Mydin, 2013). The dependence of the heat transfer coefficient, specific heat capacity and density of each material on temperature was respected for accurate simulations (Bergmann, Lavine, Incropera and DeWitt, 2018; Ezekoye, 2016). The simulation was performed using ANSYS software, which allows the solution of non-stationary and non-linear heat transfer problem using the finite element method (FEM). The first 60 minutes of the test were modelled with a step interval of 1 minute and a sub-step of 1 second.

The formula used to determine the heat transfer coefficient was taken from the literature (Peter, Veloo and Quintiere, 2013), according to which the heat transfer coefficient includes a radiative component that becomes more significant with higher temperatures. The effect of dropping the charred layers was expressed by increasing the thermal conductivity and decreasing the density and specific heat of the layer in order not to impede heat transfer. Overall, it can be concluded that the simulation is a suitable predictor of fire resistance results, despite some deviations from the actual test results.

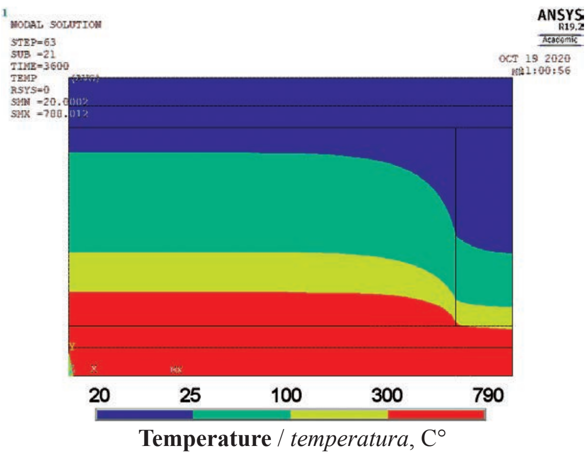

Figure 11 Temperature distribution in cross-section in °C at the end of simulation (after 1 hour)

Slika 11. Raspodjela temperature po presjeku (u °C) na kraju simulacije (nakon jednog sata)

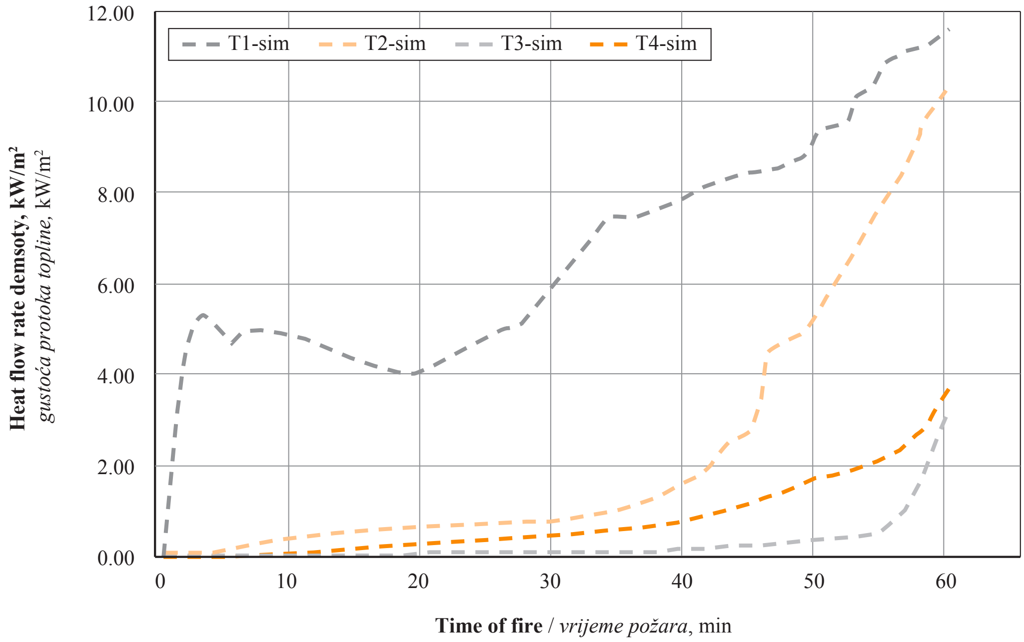

Figure 12 Heat flow rate density in measured points (simulation)
Slika 12. Gustoća protoka topline u izmjerenim točkama (simulacija)

Additionally, Figure12 displays the thermal loading of specimen surface in terms heat flow density (flux) with the maximum values reaching 11.6 kW·m^{-2}. For fires or larger scale experiments, thermal flow density values of 20 to 50 kW·m^{-2} are typically achieved.

The temperature distribution in the cross-section at the end of the simulation (after 1 hour) is illustrated in Figure 11.

4 CONCLUSIONS
4. ZAKLJUČAK

Assuming that the time of onset of charring t_{ch} occurs at the time of failure of fire protection t_f (König, 2004), the time of onset of charring can be determined as the moment when the 300 °C isotherm reaches the surface of the wooden structure, as mentioned above.

Table 1 provides an overview of the critical time points identified by the tests at the locations of the T2 thermocouples and the thermocouples above the wood-based boards.

The high temperature behaviour of the individual fire protection layers was derived from the temperature profiles of the test specimens, and it was assumed that the time point considered as the time of fire protection failure corresponds to the end of the faster temperature increase in the thermocouples T2. A comparison of the termination times of the faster temperature increase on the top side of gypsum-based boards shows that the time of failure of fire protection cover is shorter for gypsum plasterboard than for gypsum fibreboard. The average time to terminate the faster temperature increase in the T2 thermocouple for the gypsum plasterboard test specimens TS1 and TS2 was 47.5 minutes. Gypsum fibreboard test specimens TS3 and TS4 had an average time for the faster temperature increase to cease in thermocouple T2 of 52.5 minutes, which is approximately 10 percent longer than the gypsum plaster board test specimens. Considering that the thickness of gypsum fibreboard (10 mm) was less than that of gypsum plasterboard (12.5 mm), the fire resistance of gypsum fibreboard comes out approximately 12.5 percent higher than that of gypsum plasterboard. The higher fire resistance of the gypsum fibreboards is attributed to the fact that the reinforcement of the gypsum matrix is internal and therefore more protected against

Table 1 Overview of crucial time points
Tablica 1. Pregled ključnih vremenskih točaka

Test specimen *Ispitni uzorak*	**Time points in minutes** / *Vremenske točke u minutama*	
	Termination of faster temperature increase in T2 thermocouple / *Prestanak bržeg porasta temperature u termoelementu T2*	**Reaching temperature of 300 °C in T3 thermocouple** / *Postizanje temperature od 300 °C u termoparu T3*
TS1	50	66
TS2	45	54
TS3	53	57
TS4	52	62

high temperatures than the external reinforcement of the gypsum matrix of the plasterboards.

These numerical values should be considered indicative because the rate of reaching the isotherm of 300 °C in the thermocouples T3 and T4 is influenced by the thermal properties of the layers that are placed on the gypsum-based boards. This is especially evident from the difference in values between test specimen TS1 (50 minutes), where the layer is composed of mineral wool and an air gap, and test specimen TS2 (45 minutes), where the layer is composed of oriented strand boards.

Although the test results showed that gypsum fibreboards have better fire resistance than plasterboards, as can be seen in Table 1, the composition of gypsum plasterboards on a steel grid with mineral wool thermal insulation had the longest time to reach the temperature of 300 °C in the T3 thermocouple. It can be interpreted as the longest time needed to the onset of charring, i.e. the highest fire resistance. This confirms the fact that it is not only the material of the fire protection, but also the composition of its individual layers that matters.

Acknowledgements – Zahvala

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Corresponding address:

Ing. MARIE RUSINOVÁ, PhD

Brno University of Technology, Faculty of Civil Engineering, Institute of Building Structures, Veveří 95, 602 00 Brno, CZECH REPUBLIC, e-mail: rusinova.m@fce.vutbr.cz