forests

MDPI

Article

Fire Resistance of One-Sided, Surface-Charred Silver Fir and European Ash Timber

David Hans Ebner [1], Marius-Catalin Barbu [2,3], Ondřej Prokop [1] and Petr Čermák [1,*]

1 Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic; xebner@node.mendelu.cz (D.H.E.); ondrej.prokop@mendelu.cz (O.P.)
2 Forest Products Technology & Timber Construction, Salzburg University of Applied Sciences, Markt 136a, 5431 Kuchl, Austria; marius.barbu@fh-salzburg.ac.at
3 Faculty for Design of Furniture and Wood Engineering, Transilvania University of Brasov, B-dul. Eroilor nr. 29, 500036 Brasov, Romania
* Correspondence: xcerma24@mendelu.cz

Abstract: The aim of this work was to investigate the fire resistance of silver fir (*Abies alba* L.) and European ash (*Fraxinus excelsior*) boards charred using the traditional yakisugi method and to compare the results with the fire resistance of non-charred boards as a reference and exploit its potential as a material with fire protection properties. After the boards were surface-charred on one side, specimens with different char thicknesses, resulting from their different position in the chimney, were selected from each wood species and subjected to analysis. Specimens with dimensions of 250 × 90 mm underwent a small flame test, those of 220 × 170 mm received indirect flame exposure by constant heat flux radiation from an infra-red emitter and those of 600 × 600 mm were subjected to a fire resistance test according to EN 1363-1:2020. The results of the small flame tests showed statistically significant fire resistance enhancement of specimens with 6 and 3 mm char-layer thickness in fir and ash wood, respectively, and a 110% and 75% improvement when compared to reference specimens. The constant heat flux radiation tests did not reveal any significant differences between the reference and charred specimens. The up-scaled fire resistance test, in which an assembled panel was exposed to flame, also indicated significant improvement. The reference burn-through time of fir and ash specimens was improved significantly with increasing char layer thickness, resulting in 10%–26% of fire resistance improvement for fir and 5%–12% for ash wood specimens. These results, based on the tests performed, suggest that the one-sided surface-charring of wood can enhance its fire resistance; however, this was mostly achieved in boards with the thickest char layer in both wood species studied and not all fire resistance indicators were considered. Further in-depth studies are required to better understand the complex behaviour of charred wood in response to fire.

Keywords: fire resistance; wood modification; small flame test; surface treatment; wood charring; yakisugi method

check for updates

Citation: Ebner, D.H.; Barbu, M.-C.; Prokop, O.; Čermák, P. Fire Resistance of One-Sided, Surface-Charred Silver Fir and European Ash Timber. *Forests* **2024**, *15*, 1109. https://doi.org/10.3390/f15071109

Academic Editors: Zeki Candan and Mehmet Hakki Alma

Received: 8 May 2024
Revised: 17 June 2024
Accepted: 25 June 2024
Published: 27 June 2024

1. Introduction

The European Green Deal emphasises the significance of forestry and the use of wood as an eco-friendly building material. Sustainable forestry practices play a key role in carbon storage and provide habitats for diverse tree species. As a renewable resource, wood resonates with the principles of the circular economy, which endeavours to reduce waste and resource use by reuse, recycling and energy conversion [1].

One effective carbon sequestration strategy involves retaining wood in built structures for extended periods. This ensures that, as long as the timber neither decays nor ignites, the carbon originally extracted from the air remains trapped and does not re-enter the atmosphere as carbon oxide (CO_2), thus avoiding adding to atmospheric CO_2 levels.

However, this method offers only a temporary solution, as the wood may degrade over time without consistent care and maintenance [2–5].

To optimally protect timber structures from external environmental threats, i.e., biotic and abiotic factors, it is essential to incorporate an external protective layer (façade), preferably made of wood, and preferably fire-resistant. The rising demand for sustainable wooden materials, coupled with intensifying urbanisation due to population growth [6], calls for the closer examination of wood in the context of fire safety regulations. The challenge extends beyond leveraging wood to curb the incidence and spread of fire; it also involves conserving resources while adhering to contemporary building codes [7]. This focus, however, introduces its own set of eco-centric challenges that require green solutions [8,9].

As a result of increasing attention on sustainability in architecture and building design, professionals tend to favour environmentally friendly materials and technologies. The "shou sugi ban" approach, a well-known Japanese tradition of charring wood surfaces known also as "yakisugi", is gaining in popularity. This technique usually involves tying three boards together to make a triangular prism that serves as a chimney to promote combustion. This method is described in detail by Ebner et al. [10–12]. It not only modifies the aesthetics, durability and eco-friendly characteristics of wood but also avoids the need for chemical treatments. The resulting one-sided, surface-charred boards are used primarily in exterior façades, but there is an increasing trend to use them in interior applications [13,14]. Such façades are increasingly chosen by innovators pioneering sustainable solutions in construction and design.

The yakisugi charring process involves attaining high temperatures in a short time. To produce a weather-resistant façade, Kymäläinen et al. [15] suggest that temperatures exceeding 320 °C may be required. While the present study explored significantly higher temperatures, it must be noted that precise temperature control is challenging. As a result, the boards develop a thicker carbon layer at the bottom than at the top, which is attributed not only to the treatment method but also to the heating rate, temperature, initial moisture content, density and wood species [10,11]. The degradation process starts with hemicellulose, the first component of wood to deteriorate, typically decomposing within the temperature range 120–300 °C [16–20]. Subsequently, cellulose decomposition starts within the range 240–400 °C, while lignin degradation occurs at 280–500 °C [21]. At temperatures of 400–450 °C, approximately 20%–35% of cellulose and half of the lignin transforms into char. Due to the higher lignin content of softwood than hardwood, the resulting carbon layer is also notably thicker [21,22].

Despite the growing interest in one-sided, surface-charred wood façades, there is a clear lack of detailed information about their properties. In this study we set out to understand the fire resistance of this kind of treated wood. We hypothesised that the one-sided surface-charring of wood improves its natural ability to resist fire if it has a sufficiently thick layer of char. The main scientific questions we aimed to answer were: Does the charred layer protect the wood underneath from catching fire and slow the spread of flames? How does the depth of charring affect fire resistance? It is hypothesised that softwood species may char faster and deeper, while hardwood species may take longer and gain a thinner but more compact char layer.

2. Materials and Methods

For this study, we chose silver fir (*Abies alba* L.; ρ_{12} = 441 kg·m^3) as the softwood representative and European ash (*Fraxinus excelsior;* ρ_{12} = 640 kg·m^3) as the hardwood representative. The wooden boards with dimensions 24 × 170 × 4000 mm were of standard quality for construction. The moisture content (MC) was determined using a dielectric constant and high frequency device (NDI 20, Lombach, Germany) immediately before the charring process. The average MC (with standard deviation) of the fir boards was 11.0% (2.5%), and of the ash boards 33.5% (8.3%). The charring process was carried out at an outside temperature of 21 °C, according to Ebner et al. [11], using the traditional yakisugi method enhanced with gas burner to start ignition. The charring process time was 240 s. The thickness of the charring layer was measured with a digital calliper (accuracy 0.01 mm) at various positions within charred boards, according to the methodology published by Ebner et al. [10,11]. The charred wood was subjected to a small flame test, infra-red emitter test and fire resistance test with 3 repetitions of each test. Data were processed, evaluated using one-factor analysis of variance (ANOVA) and completed with Tukey's honest significance test (HSD). Differences were considered statistically significant at $p \leq 0.05$.

2.1. Small Flame Test No. 1 with Different Char Layer Thickness and Different Residual Wood Thickness

The small flame test no. 1 was adapted from the ISO standard "Reaction to fire tests—Ignitability of products subjected to direct impingement of flame" [23]. Specimens of dimensions 250 × 90 mm, with different charred layer thicknesses corresponding to different positions in the vertical chimney, were studied. Fir specimens with a char layer 0 mm (reference), 2, 4 and 6 mm thick were analysed. For the ash specimens the char layers were 0 mm (reference), 1, 2 and 3 mm thick (Figure 1). The hardwood had a thinner char layer than the softwood—despite undergoing the same treatment—because of the inherent differences in density and structure between ash and fir. Before charring, the samples were conditioned at 20 °C and 65% relative humidity (RH). The thickness of the remaining wood and the charred layer were measured.

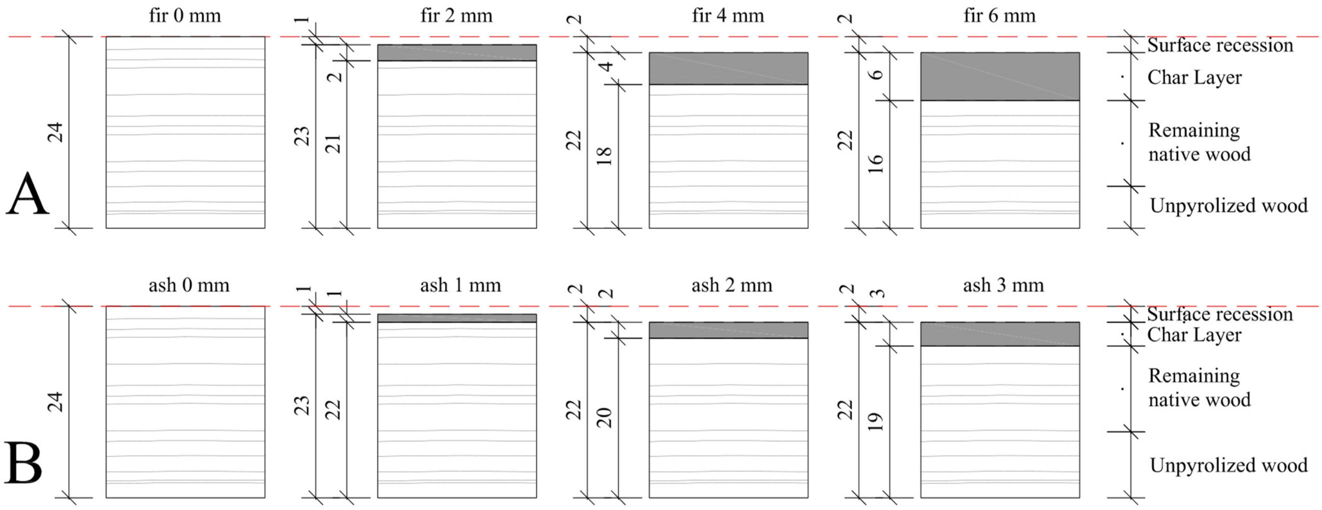

Figure 1. Fir (**A**) and ash wood specimens (**B**) with different char layer thickness resulting from different time of exposure.

After fixing the sample into a device conforming to the standard, the specimen was flamed with a gas burner (Labogaz 206 Bunsenbrenner, Schwerte, Germany) using butane/propane.

The flame was approximately 20 mm in length (measured from the burner to the yellow tip of the flame) and applied at an angle of 45° placed 5 mm from the specimen (Figure 2). The temperature was measured using an infra-red temperature meter (Infra-red Thermometer testo 835-T2, Egg, Switzerland) behind the board every 5 min. The test was carried out until the specimen burned through.

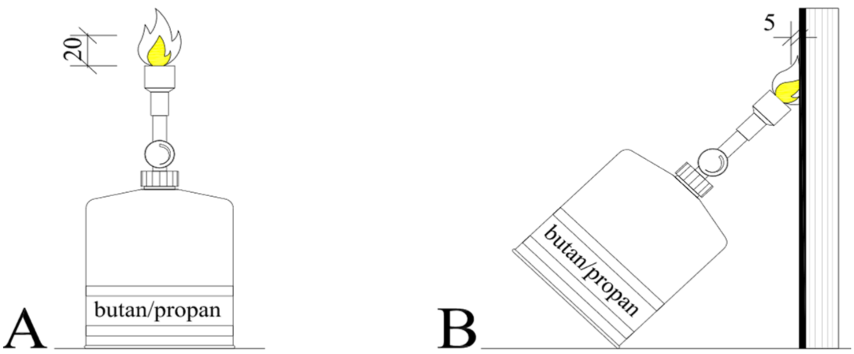

Figure 2. Small flame test set-up. Flame length to the yellow tip (**A**) and distance to the sample (**B**).

2.2. Small Flame Test No. 2 with Different Char Layer Thickness and Same Residual Wood Thickness

The small flame test no. 2 was carried out under the same laboratory conditions as no. 1, but with the difference that specimens were planed on the uncharred side until the remaining wood after charring had the same thickness. This thickness was 17 mm for the fir specimens and 15 mm for ash. The same char layer thicknesses were examined (Figure 3) as in flame test no. 1.

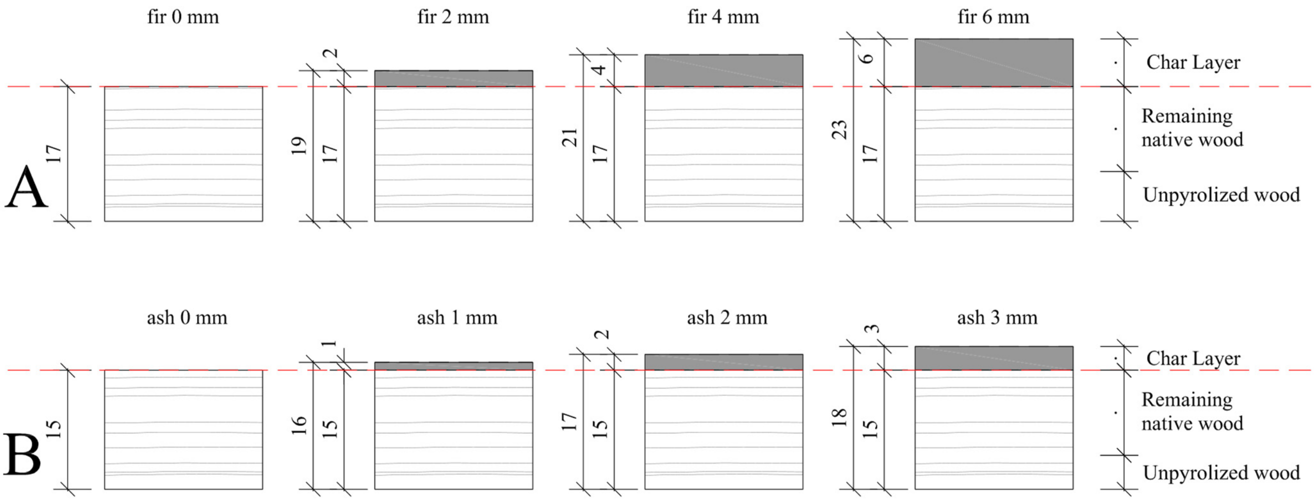

Figure 3. Fir (**A**) and ash wood specimens (**B**) with different char layer thickness and the same residual wood thickness.

2.3. Infra-Red Emitter Test

In this test, an infra-red emitter (G14-25 Mini, Egg, Switzerland), with power density up to 50 kW/m^2, was installed within a chamber built from fireproof bricks to serve as a wind barrier (Figure 4). Fir and ash specimens with dimensions 220 × 170 mm were tested as a reference and charred (fir with a 4 mm charred layer and ash with a 3 mm charred layer). The final thickness resulted from two boards glued together to allow them to stand during the test. Specimens were placed 80 mm from the infra-red emitter. All tests were conducted for three durations, i.e., 10, 20 and 30 min. The surface temperature was measured every five minutes on the exposed surface using an infra-red temperature meter (Infra-red Thermometer testo 835-T2, Egg, Switzerland). The specimens were extinguished with water spray after the time had elapsed and a few days later they were cut through the middle to measure the remaining residual wood thickness.

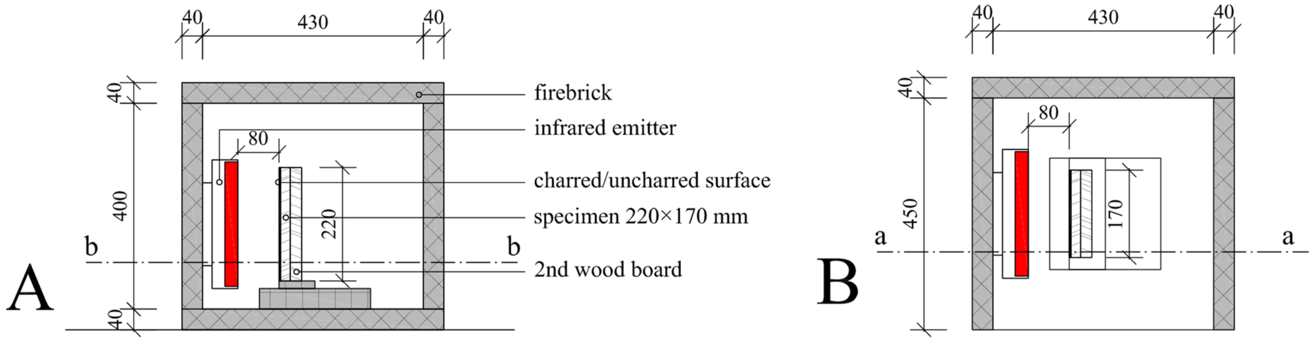

Figure 4. Infra-red emitter test chamber with the vertical (**A**) and horizontal section (**B**).

2.4. Fire Resistance Test

A fire resistance chamber, shown in Figure 5, was made according to the specifications of the EN standard "Fire resistance tests. General requirements" [24]. The chamber, made of aerated concrete blocks with airtight joints, was divided into three zones. A manually operated gas burner (RoMaxi, Kelkheim, Germany) was installed in the bottom zone, and the heat passed up through a 100 mm hole to the middle zone, where a gypsum plasterboard deflector shield was positioned to prevent the samples from being directly exposed to heat. In the top zone, there were two exhaust holes with a diameter of 50 mm to prevent excessive heat build-up. Two NiCr-Ni temperature probes (Type K), extending 80 mm into the chamber, were located 10 mm below the test panels to record the temperature. Within this zone, the test temperatures required by the standard were achieved.

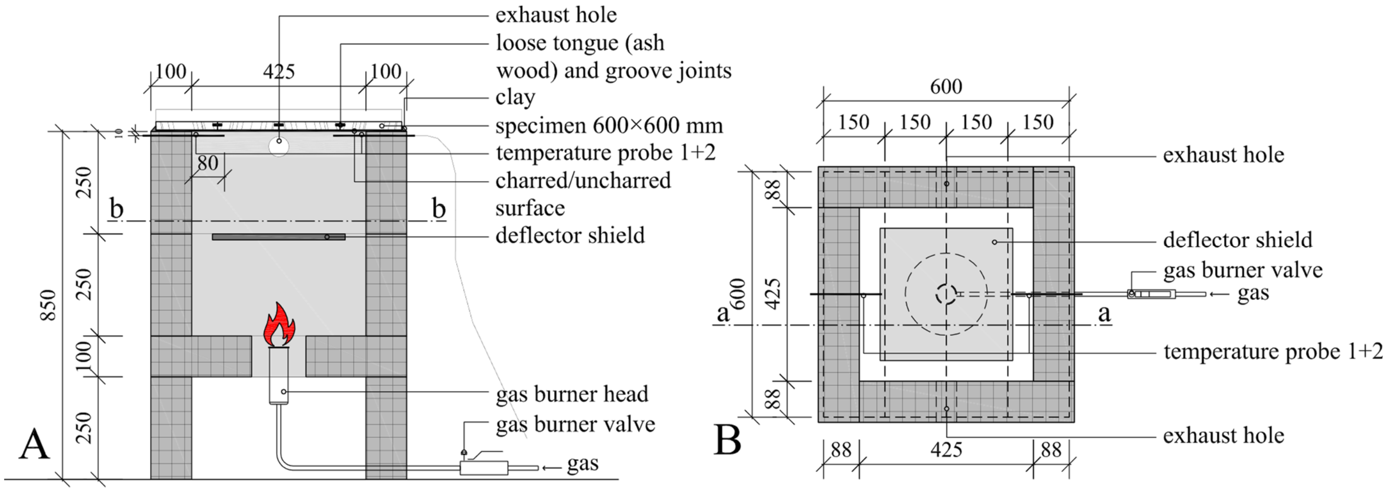

Figure 5. Fire resistance test chamber set up. Vertical section (**A**) and horizontal section (**B**).

The test panels were made from four boards connected using loose tongue (ash wood) and groove joints. The tongues (Figure 6) were glued (Super 3 Premium PVAc, Düsseldorf, Germany) into milled 5 × 11 mm grooves. The test panels with dimensions 600 × 600 mm were further protected from warping during the test using two 30 × 30 mm slats screwed to the side and not exposed to the heat.

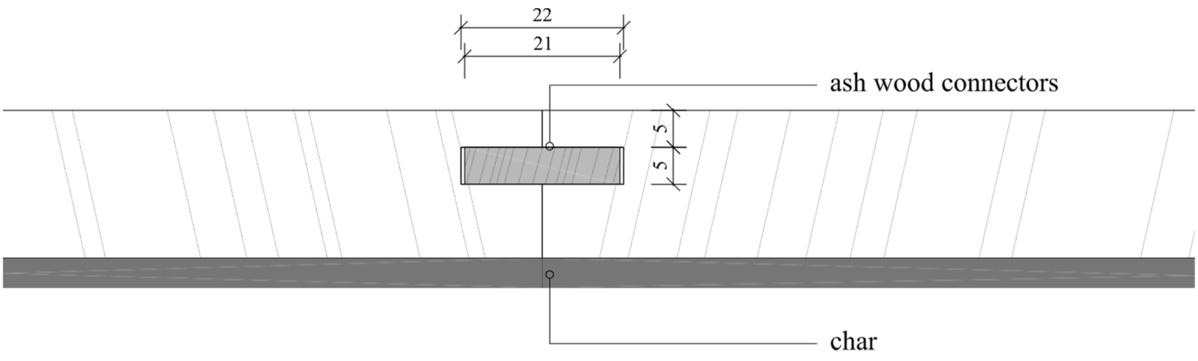

Figure 6. The groove and loose tongue joint detail of a test panel.

The fire resistance test was performed outside at a temperature of 10 °C. The test panels were sealed all around with clay to help regulate the temperature inside. The MC of the wooden panels was determined at two different locations on each panel using a moisture meter (NDI 20, Lombach, Germany) before the fire resistance test. At the beginning of each test, the internal chamber temperature was confirmed at less than 50 °C. As the test panel was placed on the top of the chamber and the fire started, the time was recorded. The gas supply was operated manually to keep the temperature on the standard curve (continuous line) as seen in Figure 7. The standard curve is considered to have been followed if the temperature stayed within the minimum and maximum deviation (dashed lines). The temperature was recorded every five minutes. The test was carried out until the panel failed and flames were seen on the upper side of the panel. The panel was then removed and extinguished and the exposure time rounded to the nearest minute. Similarly to the small flame tests, the fir wood samples had a char layer 0 (uncharred), 2, 4 and 6 mm thick; while the ash wood samples had 0 (uncharred) 1, 2 and 3 mm thick char layer.

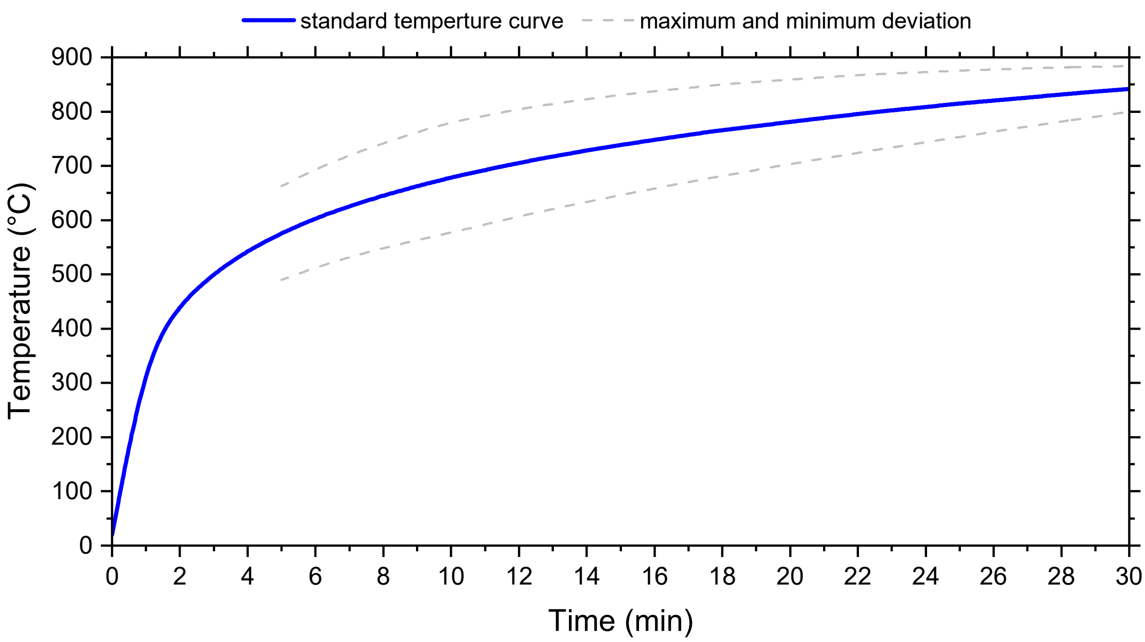

Figure 7. Standard time-temperature curve according to standard EN 1363-1.

3. Results and Discussion

3.1. Small Flame Test

The results of the tests on the fir and ash wood specimens according to adapted EN ISO 11925-2:2020 are presented in Figure 8 (test no. 1) and Figure 9 (test no. 2). The time-temperature profile from test no. 1 shows a statistically significant fire-resistant enhancement of specimens with 6 and 3 mm char layer thickness for fir and ash, respectively, while other samples, regardless of wood species and char layer thickness, appear similar to the reference specimens. The different burn-through times of the reference specimens are attributed to the different densities of different wood species [18,22,25,26]. While the temperature at the back of the specimen was almost identical at the time of burn-through for the reference fir and ash specimens (257 °C, standard deviation 8.5 °C), the time required was significantly longer for ash wood, i.e., about 20 min, corresponding to 25% of the total duration. It is evident from the literature that samples with higher density will generally char more slowly due to the greater mass of material to pyrolyse, as more energy is required to fuel this endothermic reaction [22]. Samples with lower density typically have lower thermal conductivity [27,28], resulting in a faster temperature rise at the surface and therefore pyrolysing and charring earlier.

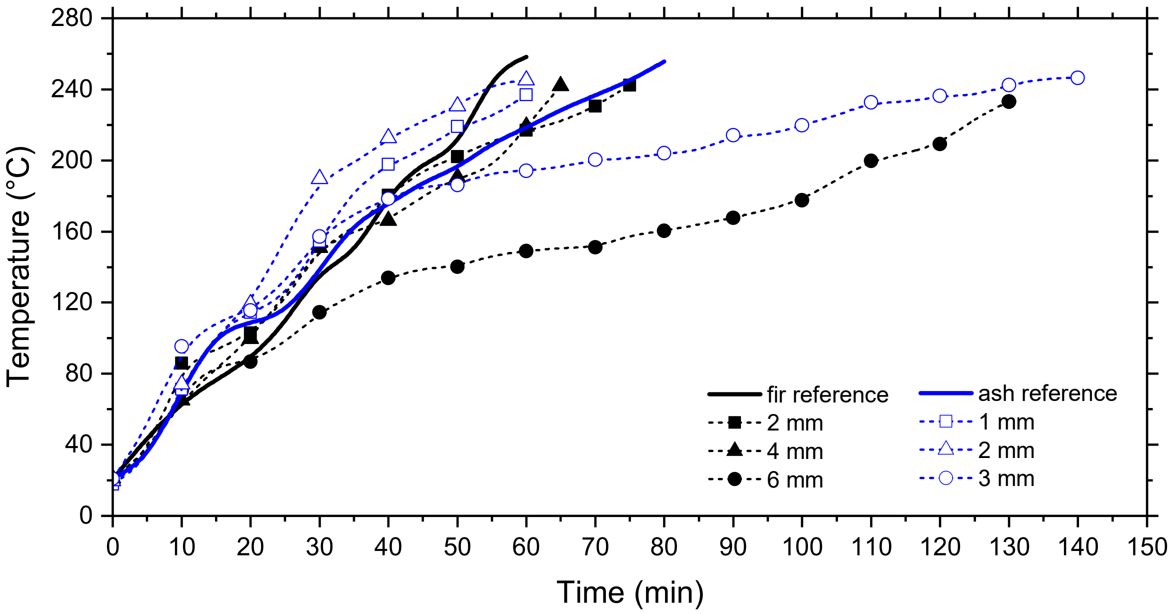

Figure 8. Time-temperature profile of fir and ash specimens during the small flame test no. 1.

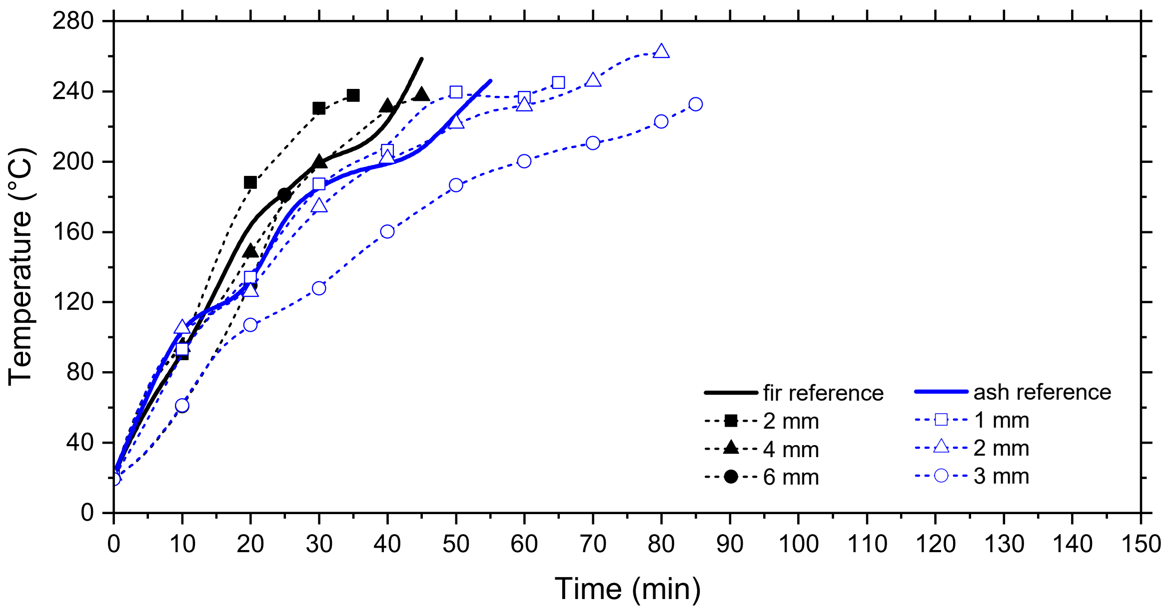

Figure 9. Time and temperature until the specimens burned through during the small flame test no. 2.

As mentioned above, the role of char as a thermal insulator was clearly evident in both fir and ash specimens with the thickest char layers. The charred fir and ash specimens gave burn-through times of 130 min and 140 min, which corresponds (with standard deviation) to 110% (3.2%) and 75% (4.7%) improvement when compared to those of the reference specimens. These results are in agreement with previous studies published by Lowden and Hull [19] and Bartlett et al. [22].

According to these results, the calculated charring rate (with standard deviation) for the reference fir specimens was 0.40 mm/min (0.09) and for ash specimens 0.30 mm/min (0.08). The one-sided, surface-charred specimens with the thickest char layer had a charring rate of 0.17 (0.05) and 0.16 (0.03) for fir and ash wood specimens, respectively. However, the charring rates typically presented in the literature vary between 0.4 and 0.8 mm/min, depending on the wood species, density and moisture content [29]. These results, published, for instance, by Friquin et al. [30], Yang et al. [31] and Liu and Fischer [32], evaluate charring rate under exposure to the standard time-temperature curve and therefore the charring rate values resulting from the small flame tests have a rather illustrative character and will be discussed further in the chapter on fire resistance tests according to EN 1363-1:2020.

The time-temperature profile of small flame test no. 2 shows the influence of the char layer of fir and ash wood specimens with the same residual wood thickness as shown in Figure 3. This approach should clarify how varying char depth affects fire resistance, independently of underlying residual wood variations [18]. According to the results of test no. 2, the reference fir and ash specimens' burn-through time (with standard deviation) was reduced by about 25%–30% (2.3%–3.5%), while maintaining a clear difference between species. This is simply a reflection of the reduced thickness of the tested reference boards. Surprisingly, the charred fir specimens gave very unclear and inconsistent results in test no. 2, and no conclusions can be drawn from them. Nevertheless, the charred ash specimens showed consistently better performance than the reference. Testing groups with 1 mm and 2 mm char layer thickness showed even better results than those from test no. 1.

The results of the tests show, at least partially, that surface-charring wood on one side has the potential to improve its fire resistance properties. According to the results, charring in both wood species slowed down the burning process and prolonged burn-through time significantly. However, this was only achieved by the thickest char layers, i.e., 6 mm for fir and 3 mm for ash specimens. This might be a first indication that a particular thickness of char is required and a layer thinner than 5 mm does not have an effect on fire resistance, as also suggested by various authors [15,33].

3.2. Infra-Red Emitter Test

The results of exposing fir and ash wood specimens to constant heat flux radiation by infra-red emitter are shown in Figure 10 and Table 1. Whereas the small flame test simulates the direct impact of flame on the material, this test simulates the indirect impact of heat flux without direct flame contact. The heat generated by the emitter can lead to a faster and more even temperature increase in the wood than the direct flame test, potentially resulting in different charring rates and burning behaviour.

Time-temperature curves of reference and charred specimens (Figure 10) do not show any major difference between the specimens. However, reference ash specimens always exhibited a significantly lower initial temperature than other test groups, though all groups were almost identical after 5 to 10 min. During the tests, the maximum temperature of the reference fir specimens was in the range 600–625 °C, while ash specimens were at 605–621 °C. Charred wood specimens, however, always showed a higher temperature—about 15–30 °C for fir and 2–15 °C for ash. This is not in agreement with the general finding that a charred surface provides a reasonable insulation layer for modified wood.

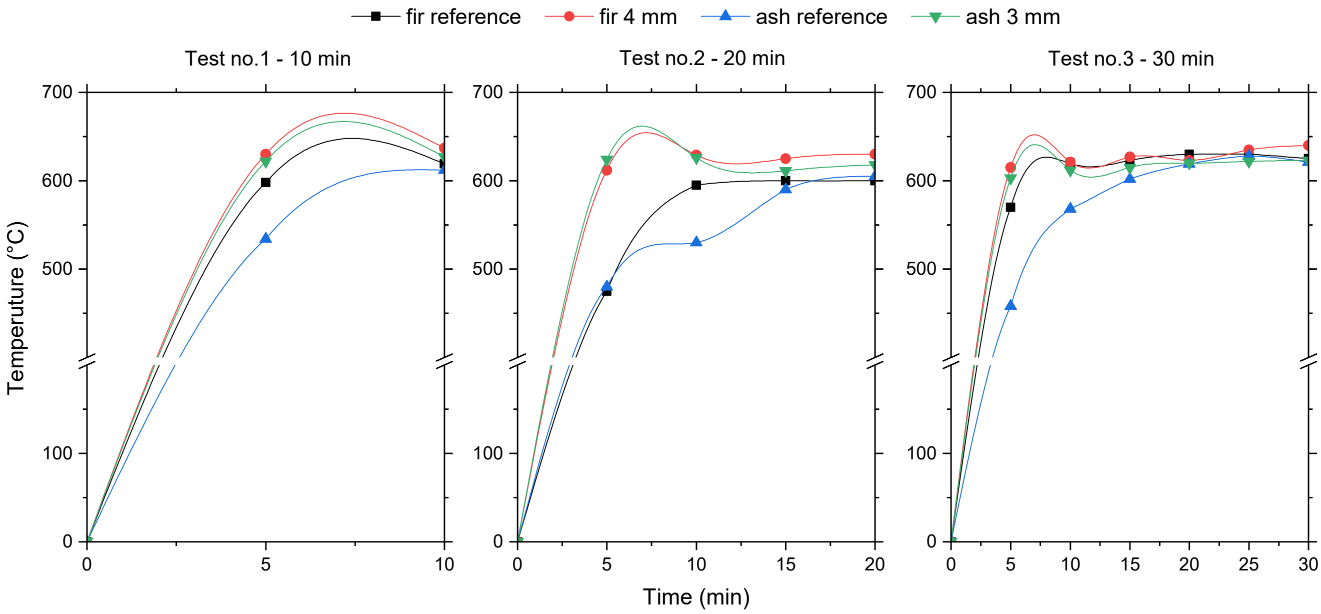

Figure 10. Time-temperature profiles of fir and ash specimens exposed to constant heat flux radiation by infra-red emitter.

Table 1. Results of fir and ash wood specimens exposed to constant heat flux radiation by infra-red emitter for different times.

	Test No. 1–10 min				**Test No. 2–20 min**				**Test No. 3–30 min**			
	Fir		Ash		Fir		Ash		Fir		Ash	
	Ref.	4 mm	Ref.	3 mm	Ref.	4 mm	Ref.	3 mm	Ref.	4 mm	Ref.	3 mm
Original thk. (mm)	22.0	19.0	22.0	17.0	22.0	19.0	22.0	19.0	22.0	20.0	22.0	20.0
Final thk. (mm)	16.8	14.9	18.1	11.9	14.5	9.5	15.3	9.0	5.7	4.2	8.2	3.5
Thickness loss (mm)	5.2	4.1	3.9	5.1	7.5	9.5	6.7	10.0	16.3	15.8	13.8	16.5
End test temp. (°C)	619	637	612	627	600	630	605	618	625	640	621	623

In accordance with the temperature results, and depending on the duration of the test, there was a significant decrease in the material thickness. After the first 10-min test, the thickness decrease was roughly the same in both wood species and treatments, i.e., 3.9–5.1 mm, which corresponds to 17%–30% of the original board thickness. The board thickness decreased significantly with increasing exposure time. After the 30-min test, the thickness decrease was in the range 13.8–19.0 mm, corresponding to 62%–82% of the original thickness. Similarly to the temperature measurements, a greater thickness decrease was observed in all charred specimens than in the reference.

According to the thickness loss results, the charring rate can be recalculated for each group. The charring rate tends to be 0.4–0.5 mm/min, while the reference hardwood specimens show slightly lower values than softwood. This is in general agreement with the literature, in which the wood species and its density are reported to play an important role [29]. In all tests, the one-sided, surface-charred specimens exhibit greater charring rate values, reaching 0.8 mm/min, with no measurable differences between species. This might be explained by the higher temperatures measured on the surface of the charred specimens. Despite the presence of a char layer, which is typically associated with thermal insulation properties, the reasons behind the greater charring rate of charred specimens, when constant heat flux radiation was applied, remain unknown.

This observation suggests that the char layer's insulating properties may be compromised under prolonged infra-red irradiation. For instance, according to Lin et al. [33], the minimum effective char-layer thickness is 6 ± 1 mm to achieve a fire-retardant effect. Such a charred layer could increase the thermal inertia of the wood, subsequently leading to improved fire performance by increasing the ignition times and temperatures required. However, according to their study, a char layer of 4.2 mm is not effective in improving fire resistance or reducing the flammability of wood material exposed to an irradiation of 40 kW/m^2. Similarly, Hasburgh et al. [14] conducted a fire performance test, in which 18–22 mm thick specimens were irradiated at 35 kW/m^2. The results showed that the charred wood specimens did not systematically improve the wood resistance against the fire. The thickness of the charred layer on the samples we tested was 4 mm for fir and 3 mm for ash, which would be predicted as non-effective according to the above-mentioned studies. Last but not least, it is believed that different original board thicknesses might affect the overall burning behaviour of wood during these tests.

3.3. Fire Resistance Test

The results for one-sided, surface-charred boards, tested for fire resistance in accordance with EN 1363-1:2020, are shown in Figures 11 and 12 and the key values are summarised in Table 2. When considering the application of one-sided, surface-charred wood as a fire protection barrier, it is crucial to take into account the optimal method for preparing a large fire-resistant area for testing. Our approach was to assemble boards joined by a loose tongue and groove to produce a sufficiently large testing area. This method not only ensures the scalability of charred wood, but also meets the requirements for comprehensive testing in practical applications, and ultimately contributes to fire safety improvements in construction.

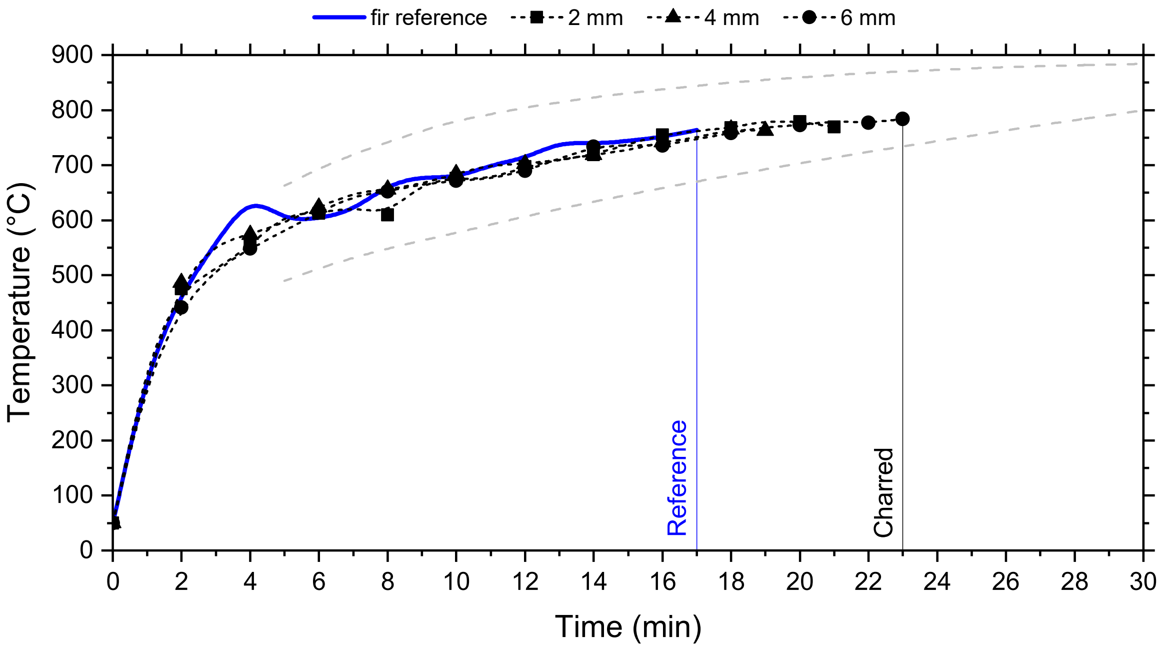

Figure 11. Time-temperature profiles of fir specimens in compliance with EN 1363-1:2020.

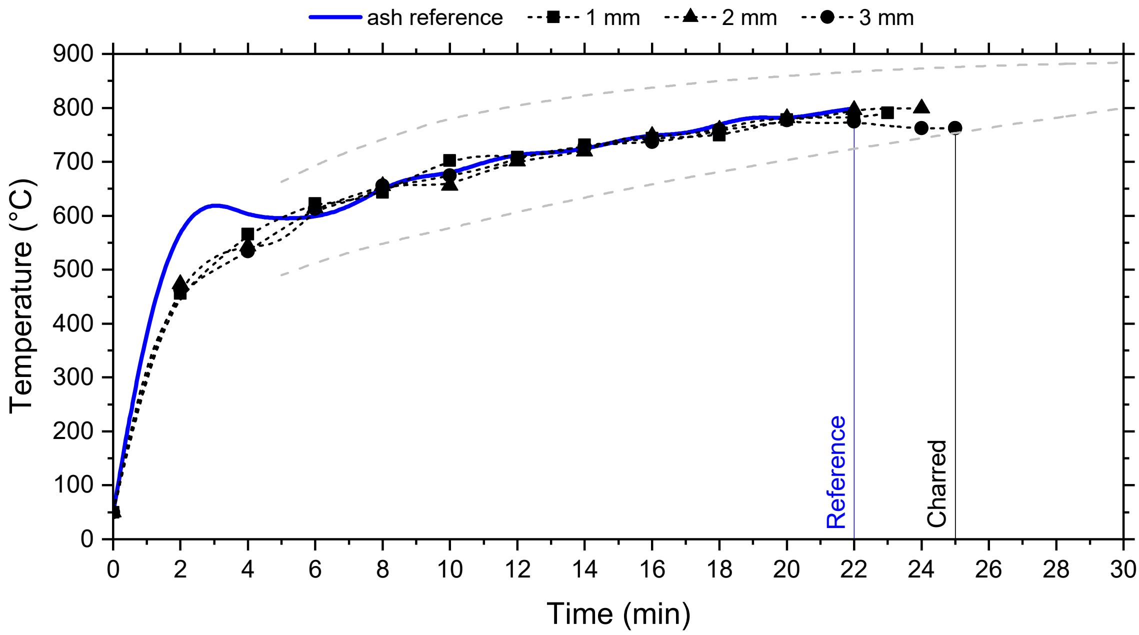

Figure 12. Time-temperature profiles of ash specimens in compliance with EN 1363-1:2020.

Table 2. Average burn-through times and temperatures for the fire resistance tests according to EN 1363-1:2020.

Wood Species	**Fir**				**Ash**			
Testing group	Ref.	2 mm	4 mm	6 mm	Ref.	1 mm	2 mm	3 mm
Temperature reached (°C)	764	769	762	784	799	791	799	762
Time till burn-through (min)	17	21	19	23	22	23	24	25

The time-temperature curves of tested reference and charred specimens show statistically significant improvements in burn-through time when reference and charred specimens are compared. The reference burn-through time (with standard deviation) of fir specimens was 17 (1.3) min, while charred specimens show 21 (1.2), 19 (0.8) and 23 (0.9) min for charred layers of 2, 4 and 6 mm thickness, respectively. These results vary inconsistently with charred layer thickness but, in general, represent 10%–26% fire resistance improvement. Additionally, the temperatures at burn-through time (Table 2) were all relatively high (ranging from 760 °C to 785 °C), with no clear correlation between char layer thickness and temperature.

The ash specimens show rather more consistent burn-through time increases with increasing char-layer thickness. The reference burn-through time of these specimens was 22 (0.5) min, while charred ash showed 23 (0.4), 24 (0.4) and 25 (0.6) min for charred layers of 1, 2 and 3 mm thickness, respectively. These results represent a 5%–12% fire resistance improvement. The temperatures recorded at burn-through time were similar to the fir specimens (ranging from 762 °C to 799 °C), also with no clear correlation between char-layer thickness and temperature.

There are several factors affecting the burn-through time and charring rate of wood, the main one of which is density [29,32]. In general, it has been found that charring rate under exposure to the time-temperature curve (to which the majority of recent studies refer) can vary from around 0.8 mm/min for light, dry softwood to 0.4 to 0.5 mm/min for dense, moist hardwood, with 0.6 mm/min being a reasonable average value. According to Eurocode 5 [34], the charring rate for solid softwood timber with a density over 290 kg·m^3 is 0.65–0.8 mm/min, and for solid hardwood timber with a density higher than 450 kg·m^3 the value is 0.5–0.55 mm/min. The faster charring rate of less dense wood species is due to an increase in void volume, reducing thermal conductivity. This produces localised heating and heat accumulation, resulting in an increased flame spread rate [22]. According to our results, the charring rate of tested specimens corresponds to 1.1 and 0.8 mm/min for fir and 0.9 and 0.7 mm/min for ash, for reference and charred wood, respectively.

The presence of moisture is widely considered to retard pyrolysis due to a heat sink effect, i.e., the higher the moisture content, the greater the energy required to evaporate the water, and thus less energy is available for pyrolysis. It can be seen that while there is strong agreement that increasing MC leads to a reduced charring rate due to the latent heat of the evaporation of the moisture, there is generally little agreement as to how much of an effect this has. This is most likely due to the presence of variable factors such as density and species overwhelming the effects of charring rate. For instance, Njankouo et al. [25] report tests on specimens with MC varying from 9% to 20%. Generally, the charring rate was found to decrease linearly from around 0.6 mm/min at 9% MC to 0.4 mm/min at 20%. Hugi et al. [26] measured the charring rate of several wood species, including fir (*Abies alba*, ρ = 388.0 kg·m^3) and ash (*Fraxinus excelsior*, ρ = 650 kg·m^3). According to their results, fir specimens tested at 7.5%–8.0% MC exhibited a charring rate of 0.7–0.8 mm/min and ash specimens tested at 7.3%–12.0% MC resulted in 0.6–0.7 mm/min. In this study, the moisture content of tested fir specimens varied in the range 15%–20%, while ash specimens had 22%–27% MC. Similarly, Li et al. [35] has reported charring rates for glulam columns for six wood species commonly used in China, i.e., poplar, Chinese fir, Douglas fir, hemlock, larch and spruce. Douglas fir conditioned to MC level between 10%–15%, with density of 550 kg·m^{-3} resulted in charring rate of 0.605 and 0.612 mm·min^{-1} after 60- and 120-min fire exposure duration, respectively.

Even though our results confirmed the general differences between softwood and hardwood charring rates, the values were slightly higher than those reported in the literature. It is very hard to compare our data with those in the literature as test panels are normally very homogeneous with no connections. However, the effect of MC is unlikely to be of much practical importance, as it is not a variable that can be controlled easily, but rather is dictated by the ambient temperature and relative humidity conditions [36].

Another factor affecting the burn-through time is the permeability of the wood, largely due to the grain direction. Increased permeability allows an increased flow of volatiles, thus also contributing to faster pyrolysis [26]. Another significant factor affecting the pyrolysis rate is the species of the wood, not only because it affects factors such as density, MC and permeability, but also due to its chemical composition (for instance, lignin content) and anatomy [18], which is also directly connected with the presence of the different cube-like distinctive patterns on the wood surface, i.e., the difference between hardwoods and softwoods. However, to quantify this would require an in-depth study of the influence of various factors. Last but not least, the scale of tested specimens, the airtight set up and testing method have effects on heat transfer and thus the charring rate. In summary, the measured data indicate that the presence of a char layer can influence the burn-through time (charring rate) and surface temperature of specimens exposed to fire. However, the relationship is not straightforward and is clearly influenced by the factors discussed above.

4. Conclusions

The findings from the small flame tests revealed a complex relationship between char layer thickness and the fire resistance of the tested wood specimens. A statistically significant fire-resistant enhancement of specimens with 6 and 3 mm char layer thickness for fir and ash wood was observed. The charred fir and ash specimens showed a prolonged burn-through time (130 min and 140 min), which corresponded to 110% and 75% improvements over reference specimens. Other studied groups did not show any statistically significant differences when compared to the reference specimens. Various burn-through times of reference specimens were attributed to the different density of the wood species as also suggested in the literature.

The constant heat flux radiation tests indicated that the presence of a char layer did not enhance the fire resistance of either fir or ash specimens. In fact, the charred specimens exhibited even higher temperatures, resulting in a greater decrease in the specimen thickness. Similarly to the small flame test, these observations suggests that a char layer thickness below 5 mm is not effective in improving fire resistance and does not protect underlying wood from thermal degradation.

The results of the fire resistance test, carried out according to EN 1363-1:2020 on both softwood and hardwood species, indicated a statistically significant improvement in burn-through time when reference and charred specimens were compared. The reference burn-through time of fir and ash specimens was improved significantly with increasing char layer thickness, resulting in 10%–26% of fire resistance improvement for fir and 5%–12% for ash. According to the time-temperature curves, the charring rates were calculated. The charring rates corresponded to 1.1 and 0.8 mm/min for fir and 0.9 and 0.7 mm/min for ash, for reference and charred wood, respectively. Even though the values presented were significantly higher than those in the literature, the effect of initial higher moisture content, as well as potentially non-airtight joints in the tested panels, could attribute to this.

All fire resistance tests presented in this study confirmed that various factors influence the fire resistance of wood, and even though increasing char layer thickness may improve fire resistance, this relationship is not straightforward. It is strongly affected not only by the charred layer itself but also by wood species, initial moisture content, permeability, the scale of the elements and other factors that were not taken into account in our study. Therefore, while increasing the char layer thickness could be a potential strategy to enhance the fire resistance of wood, it is not a universally applicable solution and should be considered in conjunction with other fire protection strategies. Moreover, further in-depth studies are needed to better understand the complex behaviour of wood in response to fire and to develop more effective and comprehensive fire protection solutions for wood-based products.

Author Contributions: D.H.E.—experimental analysis, data analysis, manuscript writing; M.-C.B.—experiment design, manuscript revisions; O.P.—data analysis, manuscript revisions, graphic preparation; P.Č.—graphic preparation, manuscript revisions and proofreading, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for funding received from the European Union's Horizon 2020 research and innovation programme under grant agreement N°952314.

Data Availability Statement: Who is interested can contact corresponding person or main author of given paper.

Acknowledgments: The authors would like to acknowledge the contribution of the students of the "Forest Products Technology and Timber Construction" of the Salzburg University of Applied Sciences at Campus Kuchl, namely M. Haushofer, C. Gruber L. Kainer and C. Michaelis.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. CEU; COMMU. Building and renovating. In *The European Green Deal*; European Commission: Luxembourg, 2019.
2. Kuittinen, M.; Ludvig, A.; Weiss, G. Tools, methods and applications. In *Wood in Carbon Efficient Construction*; CEI-Bois: Brussels, Belgium, 2013.
3. Oliver, C.D.; Nassar, N.T.; Lippke, B.R.; McCarter, J.B. Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. *J. Sustain. For.* **2014**, *33*, 248–275. [CrossRef]
4. Bergman, R.; Puettmann, M.; Taylor, A.; Skog, K.E. The Carbon Impacts of Wood Products. *For. Prod. J.* **2014**, *64*, 220–231. [CrossRef]
5. Ramage, M.H.; Burridge, H.; Busse-Wicher, M.; Fereday, G.; Reynolds, T.; Shah, D.U.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; et al. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev.* **2017**, *68*, 333–359. [CrossRef]
6. Ott, K.; Dierks, J.; Voget-Kleschin, L. *Handbuch Umweltethik*; J.B. Metzler Verlag: Stuttgart, Germany, 2016.

7. Österreichischen Instituts für Bautechnik. Brandschutz. In *OIB Richtlinie 2*; Österreichischen Instituts für Bautechnik: Vienna, Austria, 2019.
8. Schober, K.P. *Fassaden aus Holz, 3*; Überarbeitete Auflage, ProHolz-Information; ProHolz Austria: Wien, Austria, 2018.
9. Sikkema, R.; Styles, D.; Jonsson, R.; Tobin, B.; Byrne, K.A. A market inventory of construction wood for residential building in Europe—In the light of the Green Deal and new circular economy ambitions. *Sustain. Cities Soc.* **2023**, *90*, 104370. [CrossRef]
10. Ebner, D.; Barbu, M.-C.; Klaushofer, J.; Čermák, P. Surface Modification of Spruce and Fir Sawn-Timber by Charring in the Traditional Japanese Method—Yakisugi. *Polymers* **2021**, *13*, 1662. [CrossRef] [PubMed]
11. Ebner, D.H.; Barbu, M.-C.; Gryc, V.; Čermák, P. Surface charring of silver fir wood cladding using an enhanced traditional Japanese Yakisugi method. *Bioresources* **2022**, *17*, 2031–2042. [CrossRef]
12. Ebner, D.H.; Tortora, M.; Bedolla, D.E.; Saccomano, G.; Vaccari, L.; Barbu, M.-C.; Grzybek, J.; Schnabel, T. Comparative investigation of chemical and structural properties of charred fir wood samples by Raman and FTIR spectroscopy as well as X-ray-micro-CT technology. *Holzforschung* **2023**, *77*, 734–742. [CrossRef]
13. Japanese Wood Craftmanship. Available online: https://www.hughmillerfurniture.co.uk/wp-content/uploads/2016/04/WCMT-Report-Final-Online-v2.6-Spreads-Smallest-File-Size.pdf (accessed on 29 August 2023).
14. Hasburgh, L.E.; Zelinka, S.L.; Bishell, A.B.; Kirker, G.T. Durability and Fire Performance of Charred Wood Siding (Shou Sugi Ban). *Forests* **2021**, *12*, 1262. [CrossRef]
15. Kymäläinen, M.; Turunen, H.; Rautkari, L. Effect of Weathering on Surface Functional Groups of Charred Norway Spruce Cladding Panels. *Forests* **2020**, *11*, 1373. [CrossRef]
16. Beall, F.; Eickener, H. *Thermal Degradation of Wood Components: A Review of the Literature*; USDA Forest Service Research Paper; Forest Products Laboratory Service: Madison, MI, USA, 1970; Volume 130.
17. Tran, H.C. Experimental Data on Wood Materials. In *Heat Release in Fires*; Elsevier: New York, NY, USA, 1992.
18. Friquin, K.L. Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber. *Fire Mater.* **2011**, *35*, 303–327. [CrossRef]
19. Lowden, L.A.; Hull, T.R. Flammability behaviour of wood and a review of the methods for its reduction. *Fire Sci. Rev.* **2013**, *2*, 4. [CrossRef]
20. Bartlett, A.I.; Hadden, R.M.; Bisby, L.A.; Law, A. Analysis of cross-laminated timber charring rates upon exposure to nonstandard heating conditions. *Fire Mater.* **2015**, 667–681.
21. Drysdale, D. *An Introduction to Fire Dynamics*, 1st ed.; Wiley: Hoboken, NJ, USA, 2011. [CrossRef]
22. Bartlett, A.I.; Hadden, R.M.; Bisby, L.A. A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction. *Fire Technol.* **2018**, *55*, 1–49. [CrossRef]
23. *EN ISO 11925-2:2020-07*; Prüfungen zum Brandverhalten—Entzündbarkeit von Produkten bei direkter Flammeneinwirkung—Teil 2: Einzelflammentest (translation: "Reaction to fire tests—Ignitability of products subjected to direct impingement of flamePart 2: Single-flame source test") (ISO 11925-2:2020); Deutsche Fassung EN_ISO_11925-2:2020. Beuth Verlag GmbH: Berlin, Germany, 2020. [CrossRef]
24. *DIN EN 1363-1:2020-05*; Feuerwiderstandsprüfungen—Teil 1: Allgemeine Anforderungen (translation: "Fire resistance tests—Part 1: General requirements"); Deutsche Fassung EN1363-1:2020. Beuth Verlag GmbH: Berlin, Germany, 2020. [CrossRef]
25. Njankouo, J.M.; Dotreppe, J.C.; Franssen, J.M. Experimental study of the charring rate of tropical hardwoods. *Fire Mater.* **2004**, *28*, 15–24. [CrossRef]
26. Hugi, E.; Wuersch, M.; Risi, W.; Wakili, K.G. Correlation between charring rate and oxygen permeability for 12 different wood species. *J. Wood Sci.* **2007**, *53*, 71–75. [CrossRef]
27. Steinhagen, P.H. Thermal conductive properties of wood, green or dry, from −40° to +100 °C, A literature review. In *USDA Forest Service General Technical Report*; Forest Products Laboratory: Madison, MI, USA, 1977; Volume 9.
28. Chaouch, M.; Pétrissans, M.; Pétrissans, A.; Gérardin, P. Use of wood elemental composition to predict heat treatment intensity and decay resistance of different softwood and hardwood species. *Polym. Degrad. Stab.* **2010**, *95*, 2255–2259. [CrossRef]
29. White, R.H.; Dietenberger, M.A. *Encyclopedia of Materials: Science and Technology*; Elsevier: Amsterdam, The Netherlands, 2001; pp. 9712–9716. [CrossRef]
30. Friquin, K.L.; Grimsbu, M.; Hovde, P.J. Charring rates for cross-laminated timber panels exposed to standard and parametric fires. In Proceedings of the World Conference on Timber Engineering, Trentino, Italy, 20–24 June 2010; pp. 20–24.
31. Yang, T.H.; Wang, S.Y.; Tsai, M.J.; Lin, C.Y. Temperature distribution within glued laminated timber during a standard fire exposure test. *Mater. Des.* **2009**, *30*, 518–525. [CrossRef]
32. Liu, J.; Fischer, E.C. Review of the charring rates of different timber species. *Fire Mater.* **2023**, *48*, 3–15. [CrossRef]
33. Lin, S.; Qin, Y.; Huang, X.; Gollner, M. Use of pre-charred surfaces to improve fire performance of wood. *Fire Saf. J.* **2023**, *136*, 103745. [CrossRef]
34. *EN 1995-1-2*; Eurocode 5: Design of Timber Structures, 1-2. General—Structural Fire Design. European Committee for Standardization: Brussels, Belgium, 2005.

35. Li, X.; Yue, K.; Zhu, L.; Lv, C.; Wu, J.; Wu, P.; Li, Q.; Xu, C.; Sun, K. Relationships between wood properties and fire performance of glulam columns made from six wood species commonly used in China. *Case Stud. Therm. Eng.* **2024**, *54*, 104029. [CrossRef]
36. Simpson, W.T. *Equilibrium Moisture Content of Wood in Outdoor Locations in the United States and Worldwide*; US Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, MI, USA, 1998; Volume 268.