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External an Internal Factors Influencing the Charring of Timber – an Experimental Study with Respect to natural Fires and Moisture Conditions

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ABSTRACT

The following publication summarizes the experimental work of fire tests as well as the accompanied analytical studies conducted by the author in order to assess the influence of the initial moisture content as well as varying temperature time scenarios, including the heating- and cooling phase of a fire on the charring of timber and on the temperature profiles within timber cross sections. The outcome of this research is a simplified design approach for calculating the charring depth, and an improved material model that can be used in numerical simulations.

INTRODUCTION

In recent years, an increased interest in using timber as a construction material has been noted all over the world, driven by a discussion of energy- and resource efficiency in the building sector. Despite political initiatives, which support the use of timber, concerns and gaps of knowledge still exist, particularly related to fire safety and the performance based design process. In case of a fire, failure of loadbearing elements may cause significant human and economic losses that are not tolerated by society. Considering these aspects, several design standards such as EN 1995-1-2 [1] have been developed to assess the fire safety of timber elements and structures. In general, the basic concept of these methods is the determination of the charring depth, followed by an assessment of the structural performance of the residual cross section. For unprotected timber elements exposed to standard fire, the reduction of the original cross section by charring has a larger influence on the load-bearing capacity as the thermal softening within the remaining cross section [2]. Considering this fact, the determination of the char depth is the key to a reliable structural fire design with timber. However, several experimental studies have shown that external and internal parameters influence the charring of timber and indicate for largely scattered results.
With respect to performance based design, it becomes ever more important to better understand how the charring of timber is influenced by specific parameters such as

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moisture content, permeability, incident heat fluxes or oxygen concentration in the fire compartment.

The following article comprises mainly the investigations and results of the conducted fire tests with varying temperature time scenarios and summarizes the general setup and results of the additional tests with varying initial moisture content. The numerical investigations including the derived material models, as well as detailed information of the test results for the charring behaviour of timber with individual initial moisture content, will be subject of additional articles by the author and will be published in due course.

EXPERIMENTAL INVESTIGATIONS

The following paragraphs provide details about the design of the fire tests. The tests were carried out at the fire testing facilities of the Leipzig Institute of Material Research and Testing (MFPA Leipzig).

Specimens

All specimens in the conducted fire tests were made out of glulam (strength class GL24) with lamellas that were graded visually prior to the examination. In all tests the specimen were 422 x 422 mm in size and exposed to fire from one side. The depth of all specimens was 140 mm. To avoid thermal exposure from the narrow sides, the specimens were lined sidewise with gypsum boards. The investigated glulam beams were composed of three individual beams (I – III) which were prepared in advance. To ensure similar quality and boundary conditions for the timber elements, all specimens were obtained from the same individual cross sections (lower part always from beam I, middle part always from beam II and upper part always from beam III). Hence, comparable lamellas of the test specimens originated always from the same beam. This procedure also ensured no branches being located in the area where the in-depth temperature measurement took place. The three parts of each specimen were glued with a melamine-urea-resin. All glulam specimens for the tests with varying temperature time scenarios consisted of spruce with a bulk density of 462 kg/m³ ± 10 and a moisture content of 12.5 M-% ± 0.2.

Instrumentation and Testing Facilities

In all specimens, Type K thermocouples (2 x 0.5) were installed at four positions (A – D) to continuously measure the temperature rise in steps of 6 mm throughout the thickness of the timber specimens during the fire tests, as shown in figure 1. In each specimen, 44 thermocouples were installed. The thermocouples were placed in 25 mm deep holes with a diameter of 2 mm, drilled-in from the top and bottom lamella of the middle section (II) of each specimen. To provide an even surface for proper gluing the thermocouples were fed in groves to the unexposed side. This procedure ensured that the thermocouples were aligned parallel to the isotherms under one dimensional fire exposure. The obtained measurements of these thermocouples were used to give an indication about the charring rate and thermal influenced area behind the char front during the fire exposure.

The specimens were placed in a diesel fired furnace as shown in figure 2 (left), and exposed from one side with varying temperature time scenarios, depicted in figure 2 (right). To control the furnace temperature, a plate thermocouple was installed in accordance with EN 1363-1 [3]. In addition, a 3 mm thick sheathed type K thermocouple was mounted besides the plate thermocouple in order to show the difference between the measurement systems for the gas furnace temperature. Furthermore, a sheathed thermocouple with 1 mm diameter was used to measure temperatures at the fire exposed surface of each specimen. Besides the temperatures, the atmospheric conditions were recorded during the tests.

Thermal Exposure

The temperature-time curves utilized in these fire tests represent a spectrum of heating- and decay phases of potential compartment fires, derived from a literature review and zone model simulations. These results cover opening factors varying from 0.04 $m^{1/2}$ to 0.12 $m^{1/2}$ in combination with a fuel load density of 500 MJ/m² and 1000 MJ/m² and a thermal inertia of well insulating enclosure materials (750 $J/(m^2Ks^{1/2})$). To allow a better comparison of the results, the maximum temperatures for all fire scenarios were assumed to occur after 30 and 60 minutes respectively, followed by three different types of decay phases (fast, medium, slow). Therefore the timber elements were ether exposed to low or high heating rates for a short and long period of time, combined with slow, medium and fast decay rates, in order to investigate resultant influences on the charring rate and the course of temperatures in the wooden cross sections. The chosen temperature time scenarios were intended to represent an upper and lower limit including a level of exposure similar to the standard fire. The resulting temperature time curves are shown in figure 2. In this context, it must be noted that a certain temperature time scenario is not solely defined by the three input parameters (opening factor, fuel load density and thermal inertia of the compartment) but is also influenced by the employed assessment method or simulation tool [5, 6, 7].

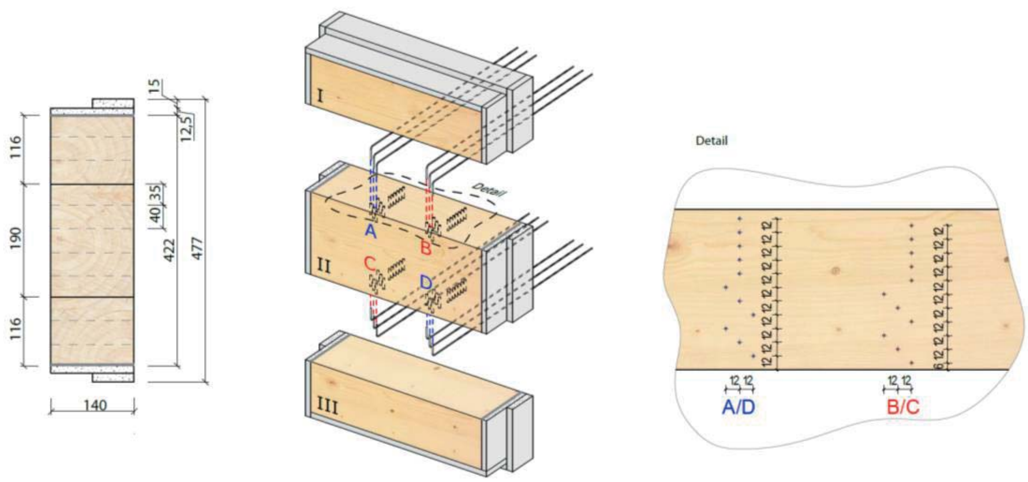

Figure 1. Setup of the specimens.

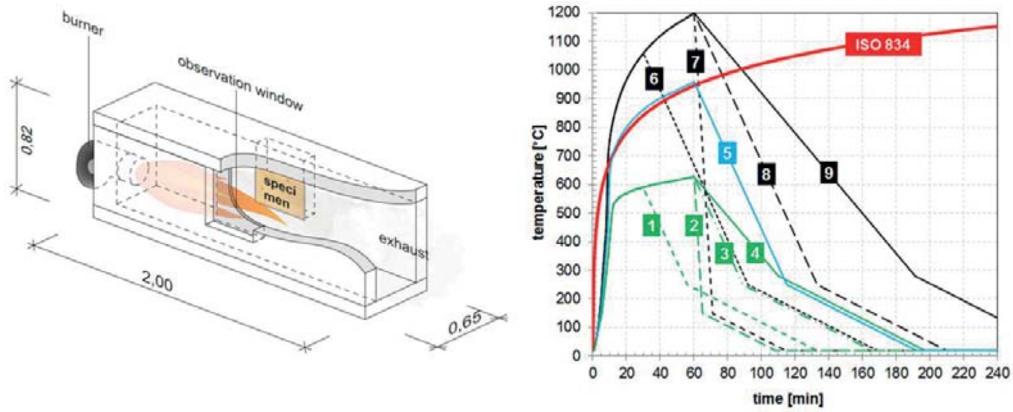

Figure 2. Test arrangement (left) and summary of temperature time scenarios (right).

Deviating from the specimens used in the tests to assess the influence of varying temperature time scenarios, the specimens for investigating the moisture influence were exposed to the standard fire curve in accordance with EN 1363 [3]. These specimens were conditioned in four different climates to reach constant moisture contents of 0 M-%, 6 M-%, 12 M-% and 18 M-%. The specimens were of the same size like the previous ones but with only a depth of 100 mm.

EXPERIMENTAL RESULTS

Temperature Time Scenarios

The comparison of the investigated temperature time scenarios showed significant differences between resulting charring and heating up behavior of the specimens. The magnitude and wide scatter of results is not known when examine other influencing factors under standard fire exposure. The tests suggested to distinguish between the heating and decay phase for assessing the data, due to the differences of the boundary conditions. An important aspect became evident from the comparison of temperature measurements at the surface of the timber elements with the plate thermocouple temperatures. During heating phases with low heating rates, temperatures up to 100°C above the furnace gas temperature were recorded on the surface. This was attributed to flaming combustion and exothermal reactions in the char layer. For a heating phase with heating rates similar to the standard fire and above, this difference became less evident and negligible. However, this phenomenon became more dominant for the decay phase particularly in combination with slow cooling rates. Figure 3 depicts an exemplary comparison of the temperatures measured during the tests No. 3 (low heating rate) and No. 8 (high heating rate) in combination with a medium duration of the cooling phase. The conducted tests show that exothermal reactions can significantly contribute to the charring process at the surface and must be taken into account in the heating- and most notably in a long cooling phase of the fire, when exothermal reaction in the char layer increases the affecting temperature. Within the cooling process an increase in oxygen concentration was recorded, which supports the exothermal reactions.

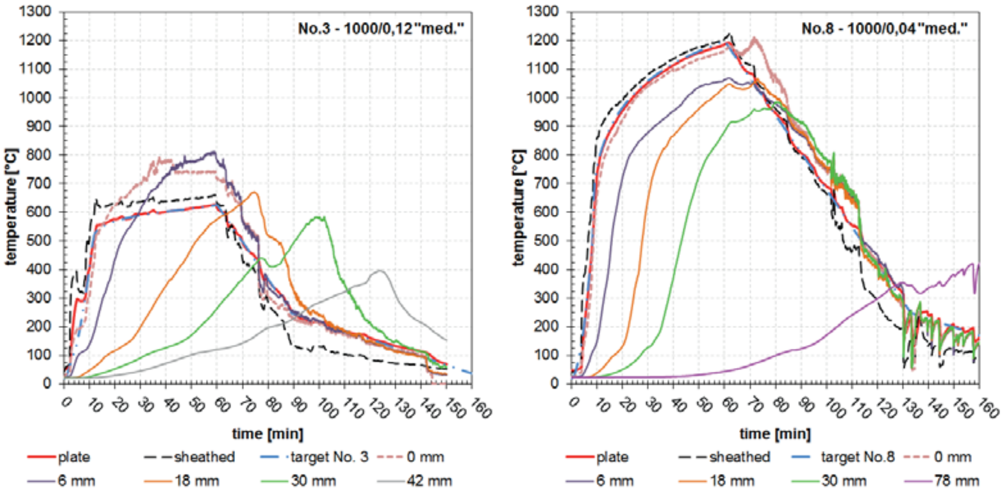

Figure 3. Comparison of surface temperature in tests No. 3 and No. 8.

The test results show that an increased heating rate results in an increased charring depth as well as an increased charring rate. The determination of the charring depth was based on the in-depth temperature measurements. The position of the char line was taken as the position of the 300°C isotherm, according to EN 1995-1-2. A comparison of the remaining cross sections with the temperature measurements confirmed that this assumption is also acceptable for the conducted series of fire tests. The examined "hot" fires (test No. 7, No. 8, No. 9) led, in the heating phase, to a charring rate almost twice as high as for the "cool" fire scenarios (test No. 2, No. 3, No. 4), see figure 4. Concurrently the temperature time scenario was not only influencing the charring rate but also had a significant impact on thermal affected region behind the char line. In this study, the depth between the 300°C and 60°C isotherm was estimated to be the thermally affected region behind the char line. Therefore, "hot" fire scenarios resulted in slender thermal affected zones as "cooler" fire scenarios as shown in figure 4.

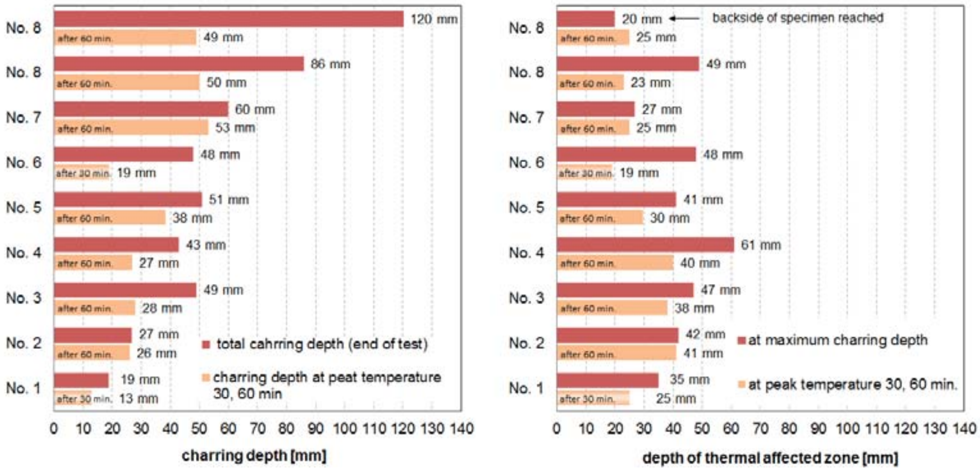

Figure 4. Comparison of the size of the charring depth and thermal affected zone.

These findings are attributed to two circumstances. On the one hand, a high exposure level leads to steeper temperature gradients behind the char line due to the increased charring rate. On the other hand, an additional mass transport into the cross section contributes to the heating up process, which is less distinct for a high exposure level compared to a lower one. After the maximum furnace temperature during the fire exposure was reached, previously described results begin also to be influenced by the duration and thermal exposure level of the cooling phase. As expected, the lowest increase in charring depth and thermal affected zone was realized for a rapid temperature decrease (test No. 2 and No. 7). In contrast, charring depths almost twice as high were recorded at the end of the fire exposure compared to the depth at the occurrence of the maximum furnace temperature for long decay phases. The additional influence of the cooling phase was also noticeable within the assessments of the size of the thermal affected zone. With an increased duration of the cooling phase, the depth of the thermal affected zone increased too. On note is the influence of the fire scenario on the cracking pattern within the formation of charcoal in the heating phase of the examined fire curves. “Hot” fires scenarios always led to deeper cracking and smaller sizes of the char blisters compared to “cooler” fire scenarios, see figure 5. However, these differences disappeared with an increase of the decay phase duration due to the surface oxidation and regression of the char coal.

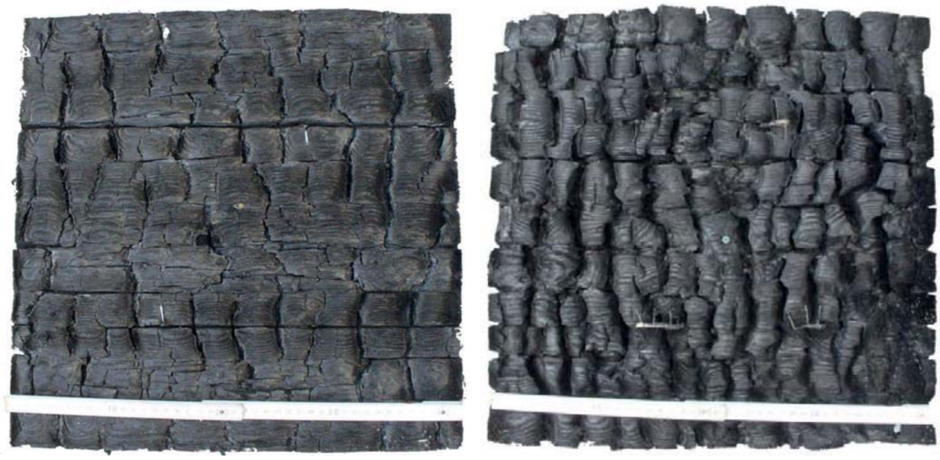

Figure 5. Char pattern after 60 minutes fire exposure (left - lower exposure level test No. 2; right – hot exposure level of test No. 7).

Moisture Influence

The results of the fire tests with different initial moisture contents showed that an increase in moisture content of about 1 M-% led to a decrease in the charring rate of 1 %. Mass transport processes with accumulation of liquids in the cross section and at the unexposed side of the specimens became evident during the tests. In the latter fact, this became particularly obvious at the end of the experiments. This effect became obvious from the in-depth temperature measurements too. Furthermore a reduction in the charring rate connected with an increased region affected by temperatures behind the char-line was observed in the specimens with increasing initial moisture content.

ANALYTICAL RESULTS

Based on the experimental examinations further analytical and numerical studies were conducted. The numerical investigations of the influence of moisture as well as fire scenarios are beyond of the scope of this article and will be subject of future publications by the author. An analysis of the data gained from the tests with different fire scenarios showed that the current design approach of EN 1995-1-2 Annex A [1] is not able to accurately predict the gained results, especially when the cooling phase was taken into account. However, a strong correlation between the charring depth and the received cumulative thermal exposure within all fire tests was established, in particular for the heating phase of a fire, as depicted in figure 6, The same correlation has been found for test results taken from literature.

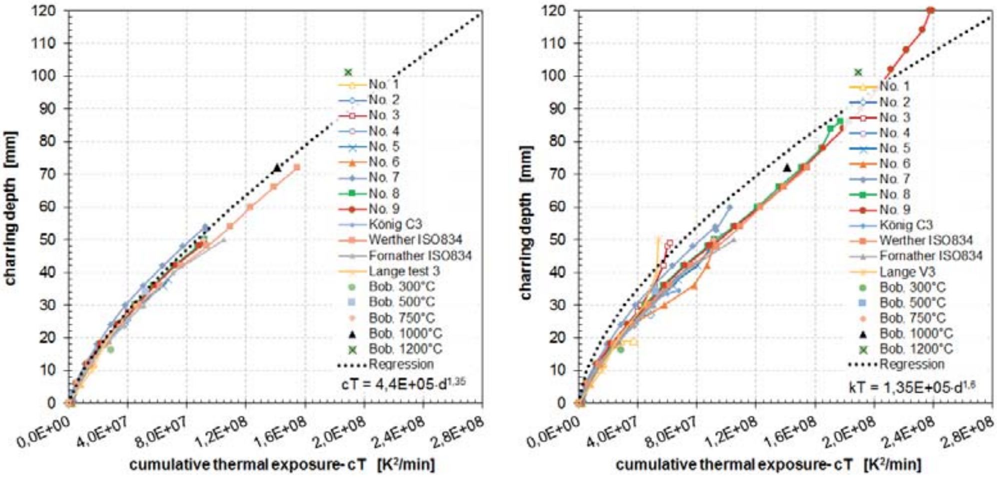

Figure 6. Charring depth vs. received cumulative thermal exposure for the heating phase (left) and for the entire fire duration (right). With König [8], Werther [9], Fornather [10], Lange [11], Bobacz [12].

Analyzing the results gained from the fire tests with varying initial moisture contents suggested the following equation (1) to describe the time dependent charring depth and the temperature distribution behind the char line, considering that an increase in moisture content of about 1 M-% led to a decrease in the charring rate of 1 % for β_u.

$$\vartheta_x = 20 + 280 \cdot \left(\frac{\beta_u \cdot t}{x}\right)^{\alpha} \quad (1)$$

with: $\alpha_t = 0.038 \cdot t + 1{,}22$
x – depth from original surface in mm
t – time in minutes

CONCLUSION

This article provides an overview of a series of fire tests with respect to the influence of different fire scenarios and the initial moisture content on charring and temperature development in timber elements exposed to fire from one side.

The tests and the accompanied analysis showed that temperature time scenarios above the standard fire curve led to an increased charring rate but at the same time to a slender thermal affected zone behind the char-line compared to the standard fire. Examining temperature time scenarios below the level of the standard fire led to opposite results. Both findings are relevant for the structural assessment of timber elements.

The tests also showed that mass transport processes contribute to an increase of temperatures within the cross section under fire exposure. In contrast, an increased moisture content reduces the charring rate. However the investigation revealed that for practical applications, the moisture influence on charring can be neglected compared to the influence of the potential fire scenario.

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