The behaviour of timber in the decay phase - Charring rates, char recession, heat release and glowing combustion under various exposure levels and gas velocities

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THE BEHAVIOUR OF TIMBER IN FIRE INCLUDING THE DECAY PHASE - CHARRING RATES, CHAR RECESSION AND SMOULDERING

Joachim Schmid[1], Antonio Totaro[2], Andrea Frangi[3]

ABSTRACT

For the assessment of the fire resistance of timber members, the depth of the virgin wood has been documented as crucial parameter in numerous scientific experiments in the past; results have been used primarily for the load-bearing resistance verification. An excessive number of tests with timber members have been performed with various products (e.g. glulam, cross-laminated timber) in furnace environments showing a consistent one-dimensional charring rate of 0.65 mm/min ± 0.1 for standard fire exposure. More severe fire exposure (e.g. hydrocarbon fire) showed a moderate increase of the charring rates to about 1.4 mm/min. The interest for performance-based design (PBD) moved the focus away from the fully developed fire phase and included other conditions, where further parameters are relevant. In furnaces, mainly the charring rate has been observed while in oxygen rich environments further a reduction of the char layer can be observed. This paper presents results from a novel charring investigation apparatus where exposure levels up to 120 kW/m2 and gas velocities up to 8 m/s (heated gas) in moderately and highly turbulent conditions were investigated. Typically, the prediction of the charring rate is done using the external heat flux, which resulted in poor fit for the observed charring rates up to 2.4 mm/min. The predictions could be significantly improved if further characteristics were considered. The most significant characteristic was the smouldering combustion of the char layer. Findings of the experimental campaign can describe the contribution of the timber to the fire dynamics and are expected to be used in future calculation models.

Keywords: Fire; Timber; Charring; Cooling phase; Oxygen; Turbulence; Heat Release Rate

1 INTRODUCTION

The fire resistance and its verification is of high importance regardless the structural material. The use of timber structures has been limited in many countries due to its combustibility. Improved products, the request for sustainable buildings and new boundary conditions such as improved fire service performance, fire safety systems and the increased reliability of heating systems led to an opening of building regulations for timber structures. The recently introduced cross-laminated timber elements stimulated the marked and further raised questions about the fire safety of these structures and the validity of the fire resistance framework for combustible members in general.

A performance based design (PBD) has been requested of structures with a significant share of combustible surfaces contributing to the fire development, see e.g. Su et al. [1]. To allow for PBD, further knowledge is

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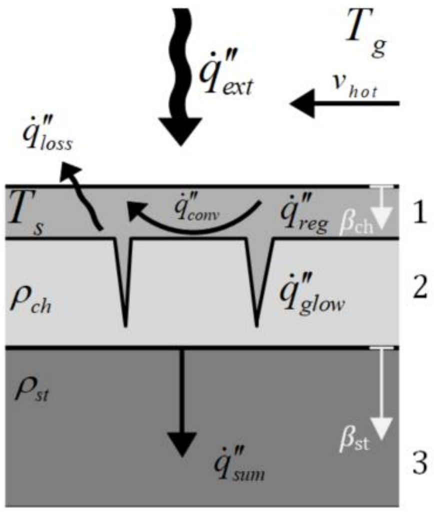
needed exceeding the well-documented behaviour of timber structures in the fully developed fire phase, see e.g. Buchanan et al. [2].

From numerous compartment experiments documented in the literature, it is apparent that the contribution of exposed timber to the compartment fire cannot be described with actual design models. In earlier work, the authors investigated the influence of the gas velocity and the oxygen concentration on the charring behaviour [3,4] and proposed how the heat release rate (HRR) of structural timber can be determined, i.e 5.4 MJ/m2 per mm charring. Here it should be noted that the actual 2nd draft for the revision of Eurocode 5 contains rules for the consideration of structural timber as part of the total fire load. Comparing HRR measurements of compartment experiments with calculations for the particular compartment, Brandon [5] proposed a fitting factor to consider the apparent contribution of the structural timber in the fully developed fire phase. In a recent study, Schmid et al. [6], showed that the afore mentioned fitting factor can be traced back to (a) the combustion efficiency and (b) the combustion behaviour of structural timber. The latter is understood by the authors as the pyrolysis of the virgin wood releasing a limited amount of combustible volatiles and the modification of the virgin wood to a new material, the char layer. Apparently, this thermal modification from wood to char goes along with a significant reduction of the density and increase of the heat content. The char layer is involved in the following in the compartment fire.

So far, the charring rate has been the only input parameter for the description of the combustion of structural timber in compartment fires. Traditionally, the charring rate is correlated with a fire temperature, e.g. the EN/ISO standard fire exposure [7.8] or an external heat flux, typically done for cone calorimeter tests. In this paper, it is shown that the description of the charring rate can be significantly improved by considering further parameters. Those additional parameters can be used to describe the contribution of structural timber in a fire.

2 METHOD

In this Section, the background of the experimental campaign is presented resulting in a novel test method. In the context of a research study at ETH Zürich, several existing methods were analysed with respect to the suitability for the analysis of the behaviour of structural timber representative for compartment fires. Model- or bench scale setups were preferred as they allow to isolate characteristics and their cost efficiency allows for the performance of a large number of experiments. Contrary to the post-flashover environments where the oxygen concentration is limited, it was aimed for an oxygen rich experimental environment with controlled gas flow.



Key:

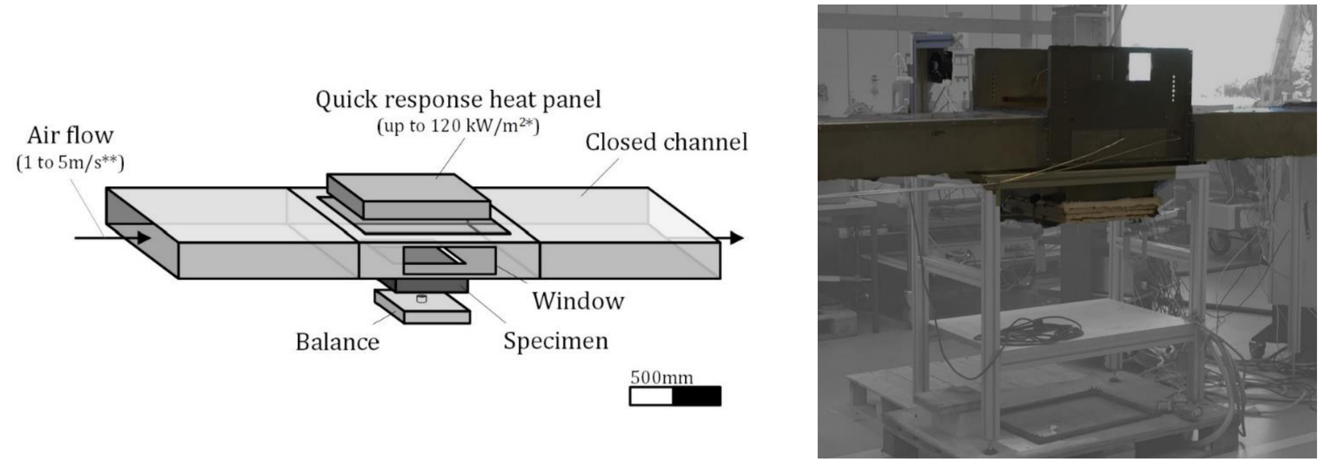
T_s	surface temperature;	T_g	gas temperature;
$\dot{q}''_{ext}$	external heat flux;	v_{hot}	gas velocity;
$\dot{q}''_{loss}$	heat losses;	β_{st}	charring rate;
$\dot{q}''_{conv}$	convective heat flux;	β_{ch}	char layer surface regression rate;
$\dot{q}''_{reg}$	HRR by char layer surface regression;	$\dot{q}''_{glow}$	smouldering;
$\dot{q}''_{sum}$	Heat flux into the virgin wood;	ρ_{ch}	char layer density;
ρ_{st}	wood density.	1	consumed char layer;
2	char layer;	3	wood.

Figure 1. Characteristics to describe the general charring behaviour of timer in fire.

The study presented in this paper included various requirements for the experimental setup to allow the measurement of (i) the mass loss (rate), (ii) the charring (rate), (iii) the char layer surface regression (rate), (iv) the temperature distribution in the specimen and (v) the char layer density. Furthermore, the criteria for the description of the environment were (vi) the exposure with a potentially variable external heat flux exceeding 100 kW/m^2 and (vii) the controlled gas flow with gas velocities up to 5 m/s (reference velocity at normal temperature). After a review of the characteristics and available methods, the cone calorimeter according to ISO 5660 [9], the fire propagation apparatus according to ASTM E2058 [10], fire resistance furnaces according to EN 1363-1 [7] and the fire tunnel presented by Schmid et al. [3,4] were found unsuitable. Thus, a novel Fire Apparatus for Non-standard heating and Charring Investigation (FANCI) was developed at ETH Zürich.

3 EQUIPMENT AND MATERIAL

A custom-made experimental setup, shown in Figure 2, the Fire Apparatus for Non-standard heating and Charring Investigation (FANCI-setup), was developed to systematically investigate characteristics, which were found to appear as variables in experiments in large, medium and small-scale experiments when timber members were heated or fire exposed. Contrary to existing methods, the experimental apparatus should be able to simulate realistic conditions by the environment with respect to the fire exposure of the member. The *fire exposure* is understood by the authors as the *thermal exposure* (gas and radiation temperature) and the *gas characteristics* (oxygen concentration and movement of the hot gas), compare Schmid et al. [3,4]. Existing setups show limitations with respect to the specimen dimensions, which should allow for the investigation of the one-dimensional heat transfer and the one-dimensional charring in the specimen. Furthermore, the energy supply power, its modification during the experiment, the applicable gas velocities and its control, the measurement possibilities of the char layer recession and the mass loss of the specimen experience typically limitations.



* variable external heat flux

** reference velocity at normal temperature

Figure 2. Experimental setup developed in this study to investigate the charring behaviour of timber under realistic fire conditions. Schematic view (left) and photo of the setup at ETH Zürich (right).

In the developed FANCI-setup, a specimen with an area of about 250 mm×250 mm surface area is installed on a load-cell-supported lab platform. The adjustable specimen support allows to keep the surface of the specimen flush with the closed channel and in constant distance to the radiation source. This allowed the estimation of the char recession during the experiment. The char recession is described by the char layer surface regression, i.e. the reduction of the char layer thickness. Previously, this characteristic was observed for environments with oxygen concentrations above about 15% (Schmid et al. 2018).

As fires produce a severe incident heat flux in the range of about 120 kW/m^2 (rough equivalent for the incident heat flux for standard fire exposure at 60 min) and exceeding 200 kW/m^2 (rough equivalent for real compartment fires at its maximum) an electric quick response radiation panel was installed. The device induces an external heat flux exceeding 120 kW/m^2 considered representative for real fires. The actual setup allows the control of the actual power, which was initially checked with several heat flux sensors (HFS). Among others, for the calibration measurements of the incident heat flux, a novel device was used which allows the exclusion of the convective heat transfer. The HFS was a modified water-cooled HFS of Schmidt-Boelter-type. The modification concern the protection of the sensor by a glazing to prevent any disturbing influence of the measurement by convection, see Figure 3. The convective heat transfer is highly dependent on the surface temperature of the specimen when the surface temperature and the gas temperature would be significantly different.

The FANCI-setup, was fed with ambient air using two types of fans producing (i) moderately or (ii) highly turbulent conditions at the specimen's surface. The degree of turbulence, understood by the authors as standard deviation of the velocity vector in the combustion chamber, was measured using a dynamic pressure device at ambient conditions in the calibration runs and three Pitot tubes in the combustion chamber above the specimen during the experiments, see Figure 4.

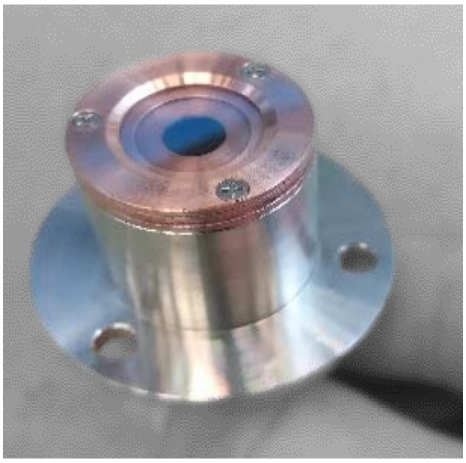


Figure 3. Novel heat flux sensor for the exclusion of the convective heat transfer.

Figure 4. Installed specimen (FH03) during the exposure with surface thermocouples and the three fixed installed Pitot-tubes to measure the static pressure changes near the specimen surface.

Except some calibration runs, all experiments were performed with clear wood specimens, see Figure 6, produced from wood from five trees with annual rings perpendicular to the default heat flux. The specimens were assembled from five beams (width ca. 45 mm). The beams were arranged edgewise to simulate an infinitely wide solid timber panel (STP), see Figure 5. The arrangement with vertical bond lines (one-component adhesive) was chosen to exclude any potential influence of the adhesive with respect to the bond line integrity in fire (sometimes referred to as debonding in fire). The specimens' density was determined based on the mass measurements. The material for assembling the specimens and the specimens were conditioned to 12% equilibrium moisture content and 20°C. In total, about 80 experiments were conducted including calibration and test runs. Finally, 67 specimens were produced; about 50% were instrumented with thermocouples arranged in a way to minimize the measurement error (Fahrni et al. 2018).

4 EXPERIMENTS

The experiments were conducted in ten series between 2015 and 2020. The horizontally arranged laminate specimens, see Figure 6, were exposed on their upper side. Some comparative experiments were conducted with fitting mineral insulation between the incombustible lower surface in the combustion unit while for most of the experiments a gap of 1 mm to 2 mm was designed between the specimen and the setup to allow for undisturbed horizontal movement of the specimen. The experimental series had different objectives and can be grouped to experiments A, B and C as follows:

A. ISO fire temperature at the exposed surface;

B. Constant exposure levels (i.e. constant energy supply from the heat panel) between 50 kW/m^2 and 120 kW/m^2;
C. Multi-level exposure: initially exposure at 100 kW/m^2, subsequently a lower limit to investigate smouldering combustion including self-extinguishment.

The measurements taken during and after an experiment included the gas temperature in the combustion chamber, the gas velocity of the supplied air and in the combustion chamber above the specimen, the time to ignition, the surface temperature by means of indicative measurements using sheathed thermocouples and the mass loss (rates). Experiments lasted between 15 min and 40 min. After an experiment, the specimen was removed from the FANCI-setup, its final mass was checked by a lab balance and the specimen was extinguished with water. This procedure took less than 90 sec. Subsequently, the specimen was dried, its geometry was 3D-scanned before and after the removal of the char layer. The difference between the geometries was used to determine the char layer thickness and the residual virgin section. The procedure of the 3D-scanning was always checked with manual measurements. The mass of the char layer was determined using the bulk volume of the char layer. The following analysis of the char layer comprised the heat content of the char layer material. Corresponding results including the comparison to data of char layer originating from furnace and compartment experiments and including the density profile of the char layer are presented in another paper by the author (Schmid et al. 2020).

5 EXPERIMENTAL RESULTS

Results are the rates for (a1) the char layer surface regression, (a2) the charring, (b) the heating within the solid and at the surface of the specimen and the (c) the mass loss.

Figure 5. Specimen JF01 before exposure.

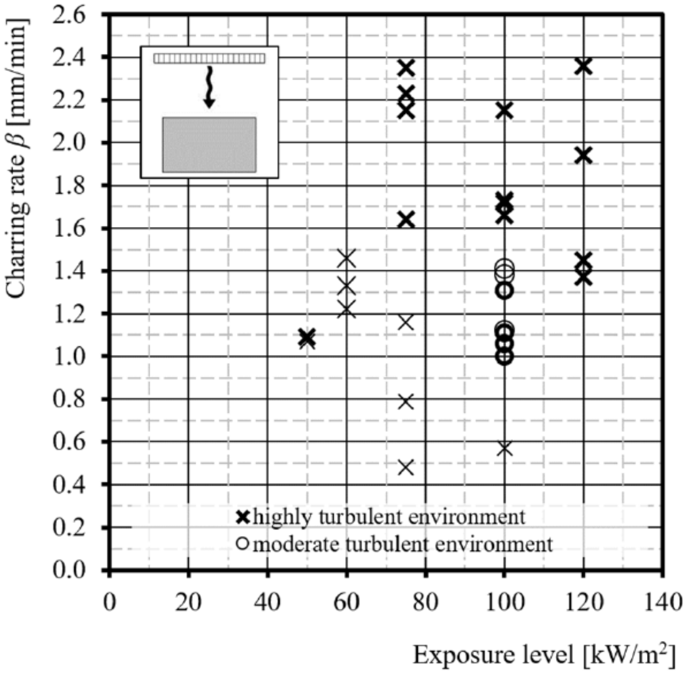


Figure 6. Results for the charring rates in oxygen rich environments. Highly turbulent (crosses) and moderate turbulent gas flow (circles).

In Figure 6, the charring rates are plotted for Series B (constant exposure level) for highly turbulent (ht) and moderate turbulent (mt) gas flow. The scatter of the results is significant. In general, the trend shows that results for the charring rates exceed the charring rates typically observed in furnace tests. Results are further dependent on the degree of turbulence, which is apparently responsible for the intensity of the contact of the char layer and the moving gas (ambient oxygen concentration). The results from the mass loss measurements (e.g. equivalent to 37 kg/m^{2}h for 100 kW/m^2 and about 5 m/s) exceed known values from furnace tests in various scales of about 14 kg/m^{2}h ± 1, see Klippel et al. [11] and Lange et al. [12].

The mass loss measurement were used to detect the ending of the smouldering combustion. Dependent on the gas velocity, mass consistency (no further mass loss) was observed between about 4 kW/m^2 (1 m/s) and about 2 kW/m^2 (5 m/s) incident radiant heat flux.

Further characteristics measured were the char layer surface regression up to 1.8 mm/min and the density of the char layer between about 220 kg/m^3. and 40 kg/m^3. The density of the char layer is understood as the bulk density of the char layer including visible and invisible cracks and voids. The density was determined using the dry mass of the char layer (0% MC), the surface area of the specimen and the difference between the virgin wood thickness after the exposure and the total thickness of the specimen after exposure. Exemplarily, results with respect to the change of the geometry for two experiments (MH14 and LA17) are given in Table 1.

Table 1. Examples of results of FANCI-experiments with respect to the charring and char recession. Characteristics in line with Figure 1.

#	β_{st} [mm/min]	β_{ch} [mm/min]	ρ_{ch} [kg/m^3]	$\dot{q}''_{ext}$ [kW/m^2]	v_{hot} [m/s]
MH14	1.5	0.7	74.2	47.2	2.5
LA17	2.0	1.5	70.8	120.0	5.0

6 ANALYSIS

In Figure 7, the charring rates of all experiments regardless the degree of turbulence are plotted against the external heat flux as typically done in the literature, see e.g. Tran et al. [11]. A moderate fit can be observed quantified by $R^2 \sim 0.5$ (method of least squares). Tran et al. [11] showed that the fit can be improved for their experimental results from a cone-calorimeter, when the density of the timber is considered. For the presented correlation in Figure 8, no influence of the density has been considered. In the analysis presented in this paper, the fit was improved considering further elements contributing to the heat flux $\dot{q}''_{sum}$ at the char line, see Figure 8.

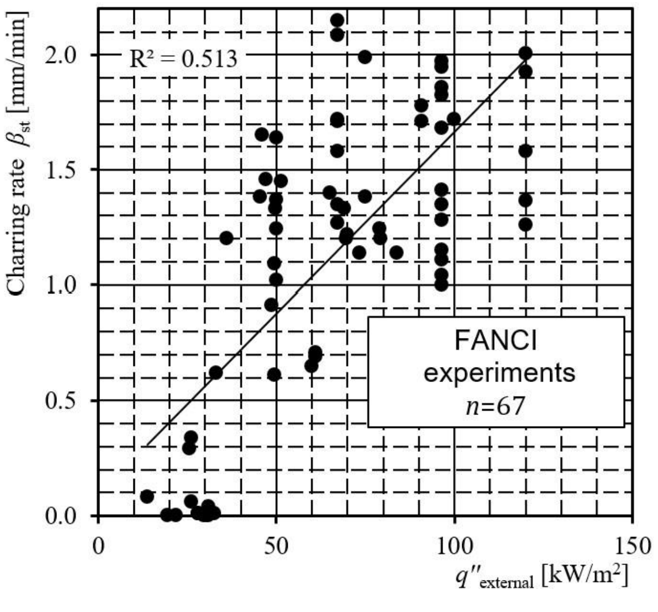


Figure 7. Analysis of charring rate observed in the FANCI-experiments; correlation with the external heat flux.

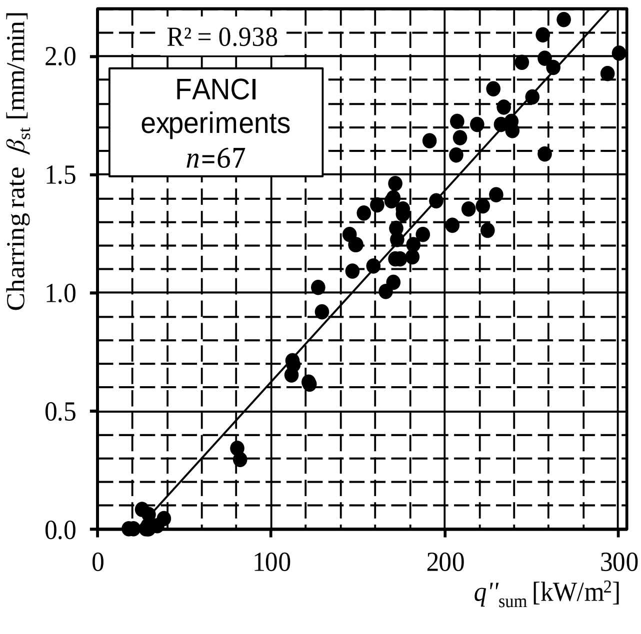


Figure 8. Analysis of charring rate observed in the FANCI-experiments; correlation with the superimposed heat flux at the char line.

6.1 Conversion and combustion behaviour of timber and the char layer

In the following, the elements are described which contribute to the charring. It is assumed that the heat flux $\dot{q}''_{sum}$ at the char line can be estimated by superimposing the contributions, which appear in the experiments.

6.1.1 Initially available amount of energy

The initial energy amount to consider is the heat content of structural timber, which deviates slightly from the dry wood heat content, usually referred to 17.5 MJ/kg. Schmid et al. [14] proposed a modification factor for considering the water stored in moist wood and proposed to consider structural timber in heated indoor climates with 10% MC. This is slightly deviating from the MC in the FANCI-experiments, i.e. 12%.

6.1.2 Release of combustible volatiles during thermal modification of the virgin wood

The first part for the improvement of the correlation is the consideration of flaming combustion. In the experiments, flaming was apparent in the initial phases but for external heat fluxes greater than 75 kW/m^2 difficult to detect, by a HFS (fluctuation and location appeared to be challenging) and visual observations (radiation of the radiant panel outscored the flames). It was assumed that the oxygen concentration in the ambient air (21%) allows for flaming combustion as observed by Jervis [15]. Subsequently, after the ignition, recorded for all experiments, the combustible volatiles are met by favourable conditions for flaming combustion. Thus, it can be assumed that the volatiles created during the thermal modification process of the virgin wood (pyrolysis) were combusted in the combustion chamber near the surface, contributing to the radiation received at the specimen’s surface (radiative feedback). It is assumed that the combustible volatiles consist mainly from hydrocarbons. The amount of appearing volatiles can be estimated by the corresponding losses described for the char production, quantified to 6% of the energy available in the source material [16]. This part of the heat release considered for the superimposition is indicated as $\dot{q}''_{vol}$. It should be highlighted that the combustion process requires oxygen while the creation of the volatiles is assumed temperature dependent only.

6.1.3 Smouldering combustion during the combustion of the char layer

After the char layer has been created in parallel to energy losses due to the conversion of the material and the release of combustible volatiles (see Section 6.1.2), the char layer gets consumed. It should be noted that the char layer represents a new material with different characteristics. It appears to be relevant to refer to the significantly different decreased density (about 50% to 10% of the source material) and the significantly increased heat content (about 200% of the source material). Schmid et al. [6] have observed the robustness of the heat content provided by the char layer material. Consequently, the energy of the char layer is released as heat dependent on the mass loss of the char layer. Apparently, the latter can be observed as density loss determined in the FANCI-experiments. From the experimental data, this part of the heat release considered for the superimposition, indicated as $\dot{q}''_{glow}$, is the most relevant parameter, partly superior of the external heat flux.

6.1.4 Consumption of the char layer

From tests in cone-calorimeters and also from the experimental series conducted by Schmid et al. [3,4] it is known that the char layer can be reduced in its thickness. Friquin [17] summarized the documentation available in the literature with respect to this characteristic, sometimes referred to as char oxidation or char contraction. In this paper, the char layer surface regression is understood as part of the smouldering combustion of the char layer but described separately. In the experiments, it was observed that the char layer was reduced in its depth, in general, dependent on the fire exposure and, in particular, dependent on the description of the gas movement at the specimen’s surface. The analysis of the dependency of the characteristic will be content of a future paper and is not further discussed here. In the FANCI-experiments, this characteristic was directly measured with values up to 1.8 mm/min, understood as char layer surface regression rate. This part of the heat release is considered for the superimposition, indicated as $\dot{q}''_{reg}$.

6.1.5 Heat losses

The heat losses of the char layer were considered for the improvement of the correlation presented originally in Figure 8. These losses are the heat transfer from the hot surface of the char layer to the environment of the combustion chamber. For the FANCI-experiments, this is possible as (indicative) surface temperature measurements were done with two surface thermocouples. The mean of both were used together with the estimated compartment gas temperature (mean of the in- and outflow gas temperature) to derive a film temperature. Furthermore, the hot gas velocity was used to calculate the losses according to well-known heat transfer methodologies, see e.g. Wickström [18]. In general, for the FANCI-experiments, the losses were of minor magnitude and are indicated as $\dot{q}''_{loss}$, for the superimposition.

6.2 Heat flux at the char line

The heat flux at the char line, describing the conductive heat transfer into the solid virgin wood, is indicated as $\dot{q}''_{sum}$ in Figure 1. It is considered as relevant parameter to describe the reaction of the wood, i.e. the conversation to the char layer material (pyrolysis). It is determined calculating the sum of the energy stored and heat released as described in the Sections 6.1.1 to 6.1.5. For the exemplarily presented results in Table 1, the elements are specified in Table 2. After the consideration of the aforementioned characteristics, a significantly increased fit can be observed quantified by $R^2 \sim 0.94$ (method of least squares), see Figure 9.

Table 2. Elements shown in Figure 1 used for the superimposition of the heat flux at the char line for two experiments in the FANCI-setup. Heat flux in kW/m^2.

#	$\dot{q}''_{ext}$	$\dot{q}''_{vol}$	$\dot{q}''_{glow}$	$\dot{q}''_{reg}$	$\dot{q}''_{loss}$	$\dot{q}''_{sum}$
MH14	47.2	10.2	90.0	33.4	8.7	172.0
LA17	120.0	14.0	127.3	55.9	16.1	301.0

7 DISCUSSION

The FANCI-setup allowed for the measurements of additional parameters, which are often not available. However, the non-availability can be traced back to the limited interest in the field of fire science when it comes to structural timber engineering.

From the literature review, the experimental campaign and the analysis of the experimental results it became apparent that the overall combustion behaviour of structural timber can be solved only if the combustion of the char layer is understood. In the analysed, it was shown that the heat flux at the char line exceeds 300 kW/m^2. Also for lower exposure levels, see Table 2, the smouldering combustion reaches significant values exceeding the external heat flux. In the FANCI-experiments, the smouldering combustion was found as the most relevant contribution to determine the heat flux at the level of the virgin wood. However, the heat, which is made available by smouldering combustion, affects significantly the compartment of a testing unit or a compartment. As observed in the experiments, the contribution by the char layer combustion, subdivided in (a) smouldering combustion measured as the density loss of the char layer and (b) the complete consumption of the char layer, the char layer surface regression. Both elements are needed to improve the description of the heating of the timber section. The char layer surface regression appeared to be a function of the gas flow. By trend, for more homogeneous gas flows (moderately turbulent environment), the char layer surface regression was significantly limited.

8 CONCLUSIONS

It appears that the charring rate, considered essential for the description of the general behaviour of structural timber elements, cannot be explained only with the applied external heat flux. The FANCI-setup allowed for further measurements, typically left unconsidered when experiments or tests are performed. Although e.g. the cone-calorimeter as the standard setup for the investigation of the reaction to fire properties is often used to determine a total mass-loss, the contribution by the combustion of the char layer has been often neglected. From the presented improvement of the fit, it can be concluded that the smouldering combustion is of superior influence and can not be neglected.

In the past, the combustion behaviour of timber in standard fire and deviating fires have been described by only the charring rate. Among others, this value has been used to verify the load-bearing capacity of structural timber members in fire the charring rates are considered as essential input parameters. When it comes to the assessment of the fire dynamics in compartment fires, the description of the contribution to the fire by the structural timber is needed. This can been done by the determination of the structural fire load as addition to the movable fire load corresponding to the charring depth. However, recent observations comparing the charring of timber panels with large exposed surfaces showed that the only use of the charring rate is sufficient. Thus, for description of the general behaviour of structural timber, further parameters are needed.

Unfortunately, measurement of the overall mass-loss is not sufficient to describe the combustion behaviour. This is as the loss of one unit mass may indicate the complete combustion of this unit mass or the conversion of e.g. two units mass to one unit mass of a new material, i.e. the char layer material. Consequently, the char layer mass has to be estimated separately. Thus, for future experimental series and tests it is highly recommended to measure the relevant characteristics (gas velocity) and density of the char layer.

Available literature results with respect to burnout and self-extinguishment could be improved and extended with the data provided here. It should be highlighted that both, the condition for self-extinguishment and the contribution by the char layer to the compartment heating are dependent on the external or incident radiant heat flux and the gas characteristics describing the movement of the gas. From a designers point of view, it should be highlighted that, in general, currently available tools neglect the gas movement and its impact on burnout and self-extinguishment. Using data and techniques presented in this study, the calculation tools can be improved.

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