Research Article

Joachim Schmid* and Andrea Frangi

Structural Timber In Compartment Fires – The Timber Charring And Heat Storage Model

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Abstract: The influence of exposed timber surfaces on compartment fires has been well documented in various studies in recent decades. Yet available design concepts still typically neglect the influence of an additional fire load from linear structural timber elements such as beams and columns. As rules for large shares of exposed timber surfaces, *e.g.* by panels, are rare, authorities and fire safety engineers demand often mock-up compartment fire experiments to estimate the fire safety of a particular design. Such experiments, however, are costly, time consuming, and give limited insights into the potential fire scenarios and may fail to represent properly the fundamental effects arising from exposed structural timber elements in a fire. An approach to overcome these existing limitations is presented, which is able to estimate the contributions from structural timber to a fire from its fully developed- and decay phase until burnout. The model input is developed from an experimental campaign where the relevant effects of fire exposed structural timber could be isolated and measured. It was found that the energy stored in the char layer is a key characteristic for describing the fire dynamics of compartment fires with exposed structural timber. Consequently, the proposed approach describes a framework for the Timber Charring and Heat storage, the TiCHS-model. The validation of the model is shown in this paper by means of existing compartment experiments. A current limitation is the bond line integrity of the fire exposed components as the combustion characteristics of failed char pieces on the floor are currently unknown.

Keywords: fire dynamics, timber, compartment fire, modelling

1 Introduction

The use of structural timber panels and panel-type products, such as cross-laminated timber (CLT) and solid timber panels, is currently booming in construction and rapidly expanding. The current revival of timber engineering is based upon three parallel developments: improved production techniques, interest in new architectural design potentials of solid timber products, and the general acceptance of combustible products in many building regulations. Today, it has become common practice for designers to typically neglect the additional fire load contribution from post-and-beam timber structures. Alternatively, the entire volume of such structures can be considered as structural fire load. While the inclusion of the structural fire load is in accordance with current definitions of the fire part in Eurocode 1 [1], therein-specified design models do not explicitly consider the actual combustion behaviour of structural timber in compartment fires. Neglecting the structural fire load may risk for significantly under predicting the fire duration and may consequently lead to false information about the structural survival. A correct approach would consider the volume of the structural timber, which is involved in the fire dynamics, i.e. the char layer volume. However, from previous research, it appeared that this implies a conservative approach. In this paper, it is shown that a significant share of the embedded energy originating from the structural timber is not directly released but (temporarily) stored in the char layer. Considering two materials, i.e. the structural timber and the char layer, a model is presented to describe the actual combustion behaviour of structural timber. The combustion behaviour of structural timber in compartment fires entail an increased external flaming [2, 3]. Therefore, only a certain share of the charred timber volume contributes to the energy released inside the compartment [3–6]. Existing models ascribe this reduced share directly to an increased external heat release exterior of the compartment [4, 5] but fail to predict a share. A previous study found that the documented combustion behaviour is strongly related to the creation of a char layer, which is a material significantly different from timber, with a knowingly different density and heat content [6]. This heat content is sometimes re-

***Corresponding Author: Joachim Schmid:** ETH Zürich Zurich, Switzerland; Email: schmid@ibk.baug.ethz.ch
Andrea Frangi: ETH Zürich Zurich, Switzerland

ferred to as calorific or heating value corresponding to the embedded energy [6]. As the density of the char layer may be different from zero, the amount of energy stored in the char layer can therefore influence the overall fire dynamics, and requires close consideration to understand correctly the contribution of structural timber elements in compartment fires. Brandon [4] has proposed a concept adapting the method of the parametric fire design [1] for compartments with exposed structural timber. The concept allows for the calculation of a charring depth corresponding to the actual design fire using Eurocode 5 [7]. This concept is based on an iterative design procedure originally mentioned by Friquin [8]. Here, only the volume corresponding to the charring depth and not the entire volume of the structural timber member represents the structural fire load. The latter would imply the collapse of the structure due to the consumption of the member. Brandon [4] based his concept on a comparison of the heat release rate (HRR) measured in a large series of compartment experiments. The basis of the comparison by Brandon [4] was the HRR of cone calorimeter tests with timber specimens, where also the charring rate was measured [9, 10]. Comparing the measured HRR and the charring rates observed in the compartment experiments, a significant difference between the estimated and the measured HRR was observed. Consequently, Brandon [4] introduced a fitting factor to reduce the structural fire load in a fully developed post-flashover fire. A reduction proportionately to the energy embedded in the charred depth gave a good fit when using the model for parametric fire exposure provided in Eurocode [1]. Therefore, a reduction of 70% of the energy in the structural timber and the actual charring depth, respectively, was proposed [4]. More recently, Wade [5] has proposed the introduction of a fuel excess factor (GER) for compartments with exposed timber surfaces. The factor describes the share of the structural fuel load which combusts inside the compartment. Wade found the factor in the range of about 1.0 and 3.0. A factor of $GER = 1.7$ is similar to the fitting factor proposed by Brandon [4] suggesting that 70% of the structural fuel combusts exterior. Both approaches fitted calculation results to compartment experiment with exposed timber surfaces documented in the literature. Following Wade's methodology, a parameter study would be required between the bounds while Brandon's approach is stated to be conservative for the evaluated compartment experiments. Yet, as the significant reduction of the structural fuel was not apparent, the approach using a fitting factor was further studied by Schmid *et al.* [10]. Schmid *et al.* analysed the char layer with respect to its yield profile and the corresponding heat content. They found that a justifiable range of the reduction is caused by the energy stored in the char layer and could result conservatively in a reduction factor of 0.85. However, there is a risk that the factor may exceed 1.0 in certain situations. For example, when a timber product is fire exposed, thermally modified and a char layer is created. The so created new material exhibits a higher heat content and may release energy at a higher rate. Knaust *et al.* [11] observed such behaviour in single burning item (SBI) tests for medium density fibre boards. Knaust *et al.* found that the combustion efficiency of MDF boards exceeded 1.0 in later stages of the SBI test. This exceedance can be explained by the comparison of the measured heat release rate with the heat content of the source material, i.e. 17.5 MJ/kg. In general, the application of a conservative fitting factor or the need for a parameter study can be considered as unfavorable situation. Consequently, in this study, we investigated the contribution of the char layer to the fire dynamics.

First, we review relevant physics and offer a description of a fire environment. Both of these aspects were important considerations when designing the innovative experiments conducted in this work. The results of such experiments can accurately represent the behavior of structural timber in compartment fires and lead to new insights for modelling compartment fires. Comparing our proposed approach using the developed model and a conventional one-zone model with the data from compartment experiments, we found a good agreement for the direct prediction of the compartment fire without using constant fitting factors nor a parameter study. Current model limitations are the unconsidered re-radiation of surface flaming considered important in corners of combustible walls, and the bond line integrity as a condition for layered timber products such as cross-laminated timber (CLT).

2 Method

2.1 Combustion physics

To consider the additional fire load from structural timber, Schmid *et al.* [12] presented a physically based approach for the definition of the structural fuel load by timber. Based on the energy content of structural timber, two general relationships were presented. The relationships assumed an upper heating value of dry wood of 17.5 MJ/kg, a reference density of 450 kg/m^3 and a moisture content (MC) of 10%. It was proposed to depict the contribution to the fire load by structural timber related to the charring rate, which varies in general throughout the fire exposure. Consequently, the fuel load related to the fire exposed surface area of structural timber involved in the fire dynamics of a compartment

can be specified to:

$$s_{st,10} = \Delta H_0 \cdot \rho_{10} \cdot \alpha_{MC} \cdot \frac{1}{1000} \cdot \beta_{st} \quad (1)$$
$$= 17.5 \cdot 450 \cdot 0.886 \cdot \frac{1}{1000} \cdot \beta_{st} = 7.0 \cdot \beta_{st}$$

$$s_{st,10,ef} = s_{st,10} \cdot \chi \cdot \alpha_{st} = 7.0 \cdot \beta_{st} \cdot \chi \cdot \alpha_{st} \quad (2)$$

where:
$s_{st,10}$ is the specific fuel load of structural timber per square meter, in MJ/m^2;
$s_{st,10,ef}$ is the effective specific fuel load of structural timber per square meter, in MJ/m^2;
ΔH_0 is the heat of combustion of dry wood, assumed to be 17.5 MJ/kg;
ρ_{10} is the density of wood at 10% moisture content, in kg/m^3;
α_{MC} is the factor to compensate for the lower heat of combustion of moist wood, 0.886 for 10% moisture content;
χ is the factor to consider the combustion efficiency, for cellulosic based fuel loads this is typically assumed to 0.8 [1];
β_{st} is the variable charring rate of structural timber in a design fire event, in mm/min;
α_{st} is the factor to consider the combustion behaviour of structural timber taking into account the energy storage in and the heat release of the char layer.

It should be highlighted that the charring rate is not a constant but highly dependent on the fire exposure. Further, it should be noted that the factor α_{st} remains undefined. Correspondingly, the HRR by structural timber can determined to:

$$\dot{q}''_{st,10} = s_{st,10} \cdot \frac{1}{60} = 7.0 \cdot \beta_{st} \cdot \frac{1}{60} = 0.12 \cdot \beta_{st} \quad (3)$$

$$\dot{q}''_{st,10,ef} = s_{st,10} \cdot \frac{1}{60} \cdot \chi \cdot \alpha_{st} = 7.0 \cdot \beta_{st} \cdot \frac{1}{60} \quad (4)$$
$$= 0.12 \cdot \beta_{st} \cdot \chi \cdot \alpha_{st}$$

where:
$\dot{q}''_{st,10}$ is the specific heat release rate from structural timber, in MW/m^2;
$\dot{q}''_{st,10,ef}$ is the effective specific heat release rate from structural timber, in MW/m^2.

In Eq. (1) to (4), the basic relationships are proposed which are in line with the general terminology of Eurocode [1, 7]. Following the proposals by Brandon [4] and the analysis by Schmid *et al.* [6], the factor α_{st} to consider the combustion behaviour of the structural timber may be in a range of 0.30 – 0.85. Higher values exceeding 1.0 may be reasonable if the energy stored in the char layer would be released disproportionately. Thus, even a larger parameter study seems to be unreasonable for the definition of a project specific design fire. To address the shortcomings of the actual design methods and the application of Eq. (2) and (4), a large experimental campaign was conducted comprising of experiments in small-, medium- and full-scale. The experiments and results are presented in this study after the definition of the terms thermal and fire exposure.

2.2 Thermal exposure and fire exposure

The thermal exposure is sometimes described as the thermal load, *e.g.* Putynska CG *et al.* [13], which can be misleading as the heat transfer to a solid is influenced by its thermal properties. Consequently, in fire safety engineering, the terminology thermal exposure is rather used implying a more complex process rather than a load comparable to static loading in structural engineering. In an attempt to define the term thermal exposure, the conditions in fire resistance furnaces were compared when testing combustible and non-combustible specimens. The thermal exposure can be understood as the radiation and gas temperature combined with a proper thermal boundary condition [14, 15]. However, when combustible components are studied, the environment of the exposure becomes relevant as the existence of oxygen has significant influence on the combustion physics. Similarities of furnace testing and fully developed ventilation controlled compartment fires of combustible components can be concluded using the fire exposure, see Figure 1.

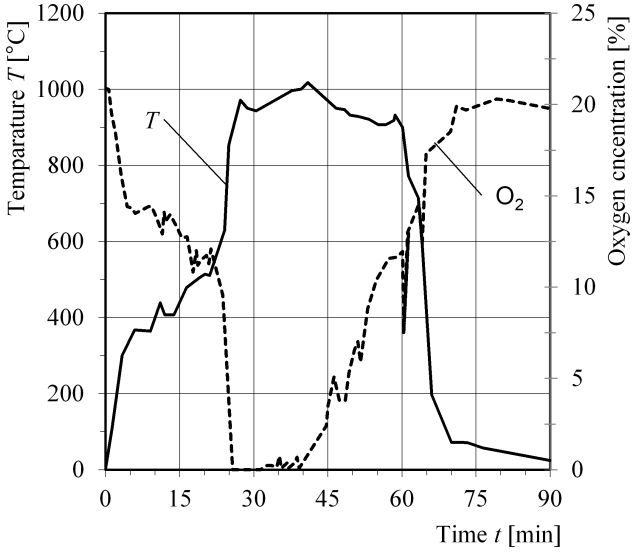


Figure 1: Compartment temperature and oxygen concentration in a compartment fire experiment [17].

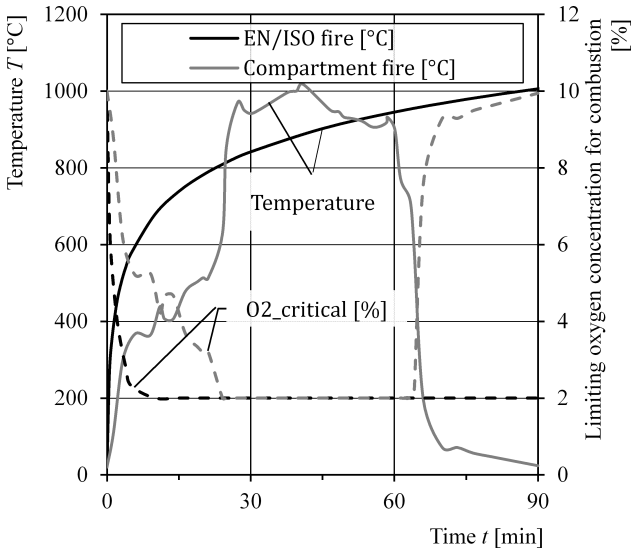


Figure 2: Application of the combustion limits (broken lines) for the EN/ISO fire and the compartment fire in Figure 1.

Figure 1 shows that the oxygen concentration in the fully developed phase, about between 25 min and 40 min is similar in fire resistance furnaces, i.e. less than about 5% [14]. After the maximum temperature has been reached, the oxygen concentration changes which is not reflected in standard fire resistance tests. To allow the comparison of the environments and the related behaviour of combustible components, Schmid *et al.* [14] proposed to extend the terminology of the *thermal exposure* to *fire exposure* including the description of the gaseous environment. Further, the need for this definition appeared when the char layer reaction was observed in various environments. For oxygen concentrations higher than 15%, char layer regression was observed, i.e. the recession of the original surface [10]. Wade *et al.* [16] describe the combustion limit as function of the gas temperature and the oxygen concentration, simplified given in Eq. (5) to:

$$O_{crit} = \frac{873 - T_g}{580} \cdot 8 + 2 \tag{5}$$

where:
O_{crit} is the critical oxygen concentration for combustion, in % by vol.;
T_g is the gas temperature, in K.

The critical oxygen concentration as given in Eq. (5) is exemplarily applied in Figure 2 on the EN/ISO standard fire and the compartment fire shown in Figure 1.

2.3 Experimental Setups

The conducted experimental campaign and for the setup of the Timber Charring and Heat Storage Model (TiCHS)-model are presented. Beside the data from the experiments described here, available data from the corresponding tests and experiments were used. These external data is described in the literature where details are given. These external data comprise compartment experiments conducted by McGregor [18], Medina [19], Su *et al.* [20] and the analysis of the char layer with respect to the density and heat content profile by Schmid *et al.* [6].

The experimental campaign summarized here consisted of three main parts, schematically shown in Figure 3. Furnace experiments were performed in two different scales. The furnace experiments were performed in fire resistance furnaces typically used for classification of construction but exceeded the standard instrumentation. Besides additional temperature measurements in the furnace compartment, the mass loss of the structural timber element was recorded

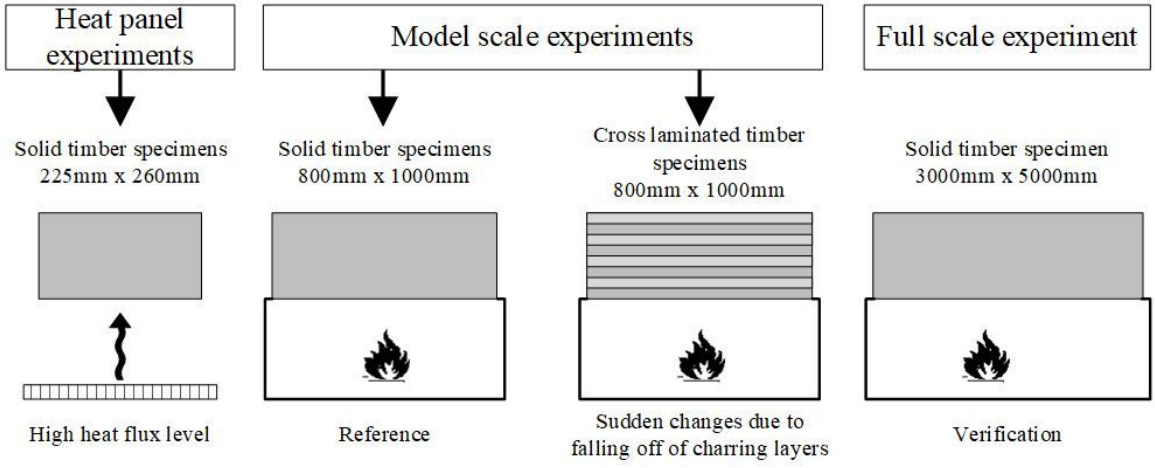


Figure 3: Experimental setups performed in the presented campaign.

during the experiments. Further measurements were the thickness of the residual virgin section and the char layer. For char material of the experiments, the density and the heat content of the char layer was directly measured after the experiments. Furnace experiments were conducted in a model scale fire resistance furnace at the laboratory of VKF, Swiss association of Cantonal Fire Insurance companies, in Dübendorf, Switzerland. One furnace experiment was conducted in the framework of a related study at Rise, Research Institutes of Sweden, Boras, where the results were already presented by Schmid *et al.* [14]. and Lange *et al.* [21].

2.3.1 Full-scale experiment

A solid timber panel (STP) was exposed to EN/ISO [22, 23] standard fire for 90 min. The panel with approximate dimensions of 5 m x 3 m (length x width) was assembled with thirteen glulam beams with a moisture content (MC) of 12%. They were orientated flatwise to exclude any influence of the bond lines and fire exposed on their lower side. The STP was supported by a steel frame resting on three load-cells to record the change of the specimen mass. Apparently, one load cell was affected by heat and delivered a significantly different signal than the pendant load-cell on the same end of the panel. Consequently, the signal was corrected and a mass-loss rate of 14.1 kg/(m^2·h) was estimated. Further determined values were the mass of the char layer (about 85 kg/m^3) and the charring rate (0.59 mm/min). Besides the temperature measurements with control plate thermometers (PTs) in the furnace compartment, further PTs close to the surface were installed to capture potential surface flaming. No differences from measurements with a non-combustible reference specimen were observed [21]. Sample gas was extracted from various positions in the furnace compartment, i.e. close to the combustible surface and away from it. An average oxygen concentration of 5% was measured in the furnace compartment and a significantly lower concentration near the surface. Near the surface, a noteworthy amount of carbon monoxide was detected indicating smouldering combustion of the specimen. Furthermore, the gas velocity was measured close to the specimen surface, which resulted in an average velocity of about 1 m/s.

2.3.2 Model-scale experiments

Eight panels made from structural timber at 12% MC were exposed to EN/ISO [22, 23] standard fire for up to 120 min. Six panels were made from CLT and two were made from STP. One STP specimen was initially fire protected with an incombustible fire protection system. All panels had dimensions of about 1.0 m x 0.8 m (length × width). The two STPs were edgewise assembled from solid timber beams to exclude any influence of the bond lines. All specimens were supported by a frame resting on three load-cells to record the change of the specimens mass. For the STP I, the mass loss of the specimen was determined as 15.4 kg/(m^2·h). The char layer material was collected and dried at 105°C to determine the dry density of the char layer. The density was determined about 35 kg/m^3. Material of the char layer was analysed by bomb calorimetry which gave the similar results as for the char layer material from other origins (radiant heat panel and full-scale fire resistance tests), i.e. about 31 MJ/kg. The specimens made from CLT experienced fall-off of charring layers and exceeded the mass loss rate of the STP by up to about 170%. Results are reported in Klippel *et al.* [24]. The temperature measurements were made with control plate thermometers (PTs) in the furnace compartment. In addition, measurements with a water-cooled heat-flux sensor (HFS) were made at various locations (horizontal variation; above and away from the burner) and the positions (vertical variation; flush with the specimen surface, behind and in level of the PTs). The HFS measurements in various positions were conducted to detect potential surface flaming. No difference between the measurements flush with the specimens surface and at the level of the PTs (100 mm away from the specimen

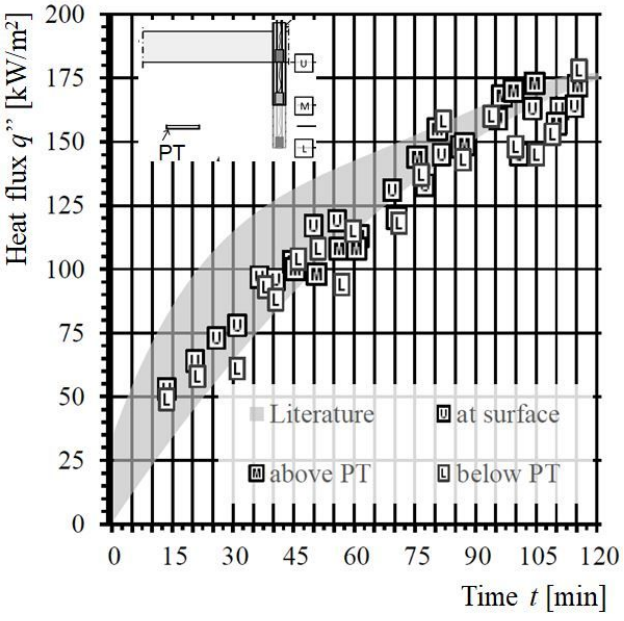


Figure 4: Measurements of the HFS at the positions "Upper" "Medium" and "Lower" in comparison to results available in the literature [14].

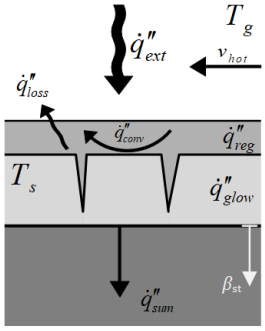
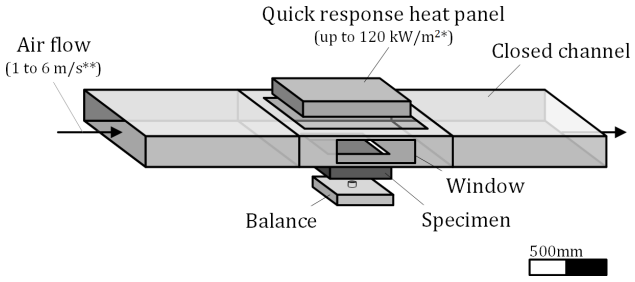


Figure 5: Heat transfer elements contributing to superimposed heat flux $\dot{q}_{sum}$ relevant for the charring rate β_{st}.



* variable external heat flux

** reference velocity at normal temperature

Figure 6: The Fire Apparatus for Non-standard heating and Charring Investigation (FANCI).

surface) were measured, see Figure 4. Sample gas was extracted from various positions in the furnace compartment, i.e. close to the combustible surface and away from it. An average oxygen concentration of 5% was measured in the furnace compartment and a significantly lower concentration near the surface. Furthermore, the gas velocity was measured close to the specimen surface, which resulted in an average velocity of about 2 m/s.

2.3.3 Heat-panel experiments

Several existing methods were analysed with respect to the suitability for the analysis of the behaviour of structural timber representative for compartment fires. 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. The criteria for the experimental setup was the measurement of (i) the mass loss, (ii) the charring, i.e. the charring rate and depth, (iii) the char layer surface regression, (iv) the temperature distribution in the specimen and (v) the char layer density. 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 6 m/s. Subsequently, the cone calorimeter according to ISO 5660 [25], the fire propagation apparatus according to ASTM E2058 [26], fire resistance furnaces according to EN 1363-1 [22] and the fire tunnel presented by Schmid *et al.* [10] were found unsuitable. Reasons are the limitations of the gas flow control with respect to the possible velocity range and degree of turbulence, the limited specimen size and the difficulties to measure the char layer surface regression during the exposure. Thus, a novel Fire Apparatus for Non-standard heating and Charring Investigation (FANCI) was developed at ETH Zürich. The setup is shown schematically in Figure 6.

The FANCI-setup represents a channel section with a cross-section of about 500 mm x 200 mm with calming units before and after the central combustion unit. The top of the combustion unit was closed by the radiant heat panel while the specimen closed the unit from its bottom. The specimen rested on an adjustable support to allow for the exposure of the specimens surface flush with the bottom of the channels. The channel was fed by ambient air with various gas velocities and different characteristics with respect to its turbulence. The specimens were made from spruce wood representing STPs with dimensions of 260 mm × 225 mm. The nearly defect-free specimens had a MC of 12% at the date of the experiment. The specimens exhibited annual rings perpendicular to the external heat flux provided by an electrical quick response radiant heat panel. The external heat flux was controlled by the current, a calibration was performed using a HFS. Experiments were either performed with a constant set-point, a temperature ramp according to EN/ISO standard time-temperature at the specimen surface or with two set-point levels to investigate the self-extinction behaviour. The experiments were conducted with reference gas velocities between 1 m/s and 6 m/s. The hot gas velocity, the specimens surface temperature and temperatures at various locations in the setup were measured. Further, the static pressure near the surface recorded the fluctuation of the velocity, defined as the degree of turbulence. Two major setup-types were used using two different fans to allow for the creation of “moderately turbulent” and “highly turbulent” gas flow. The exposure time was between 15 min and 40 min. Including the calibration runs, about 80 experiments were conducted in the FANCI-setup during ten experimental series.

Table 1: Set points and measurements of the experiments performed with the FANCI-setup.

Experimental series no.	External heat flux $\dot{q}''_{ext}$ [kW/m^2]		Reference gas velocity v_{gas} [m/s]		Charring rate β_{st} [mm/min]		Char layer surface regression rate β_{ch} [mm/min]		Mass loss rate Δm [kg/(m^2·h)]	
	min	max	min	max	min	max	min	max	min	max
1	25	115	1.5	1.5	0.9	1.3	0.3	0.8	n.a.	
2	35	120	2.0	2.5	1.1	1.8	0.4	0.9	n.a.	
3	50	100	2.5	2.5	1.4	1.9	0.5	1.2	32	58
4	75	90	1.0	2.5	1.3	1.8	0.5	0.9	28	47
5	50	100	1.0	6.0	1.0	2.3	0.4	1.5	21	44
6	75	120	1.0	5.0	1.2	2.2	0.3	1.8	29	48
7	50	100	2.5	6.0	0.6	1.4	0.0	1.8	25	34
8	45	120	2.5	5.0	0.5	1.6	0.4	1.8	29	43
9	<5	100	1.0	5.0	0.0	2.0	0.0	1.8	3	37
10	<5	100	1.0	5.0	0.0	0.7	0.0	1.4	1	3
n.a.	Not available									

3 Analysis of the experiments

Experimental set points and results are provided in Table 1.

Typically, in the literature, the charring rates of experiments with a radiant heat source are correlated with the external heat flux. This method was found to give a poor fit, for the experiments presented in Table 1. The limited correlation between the charring rate β_{st} and the external radiant heat flux $\dot{q}''_{ext}$ of the experiments in the FANCI-setup is given in Figure 7. Considering the additional characteristics measured in the FANCI-setup, the prediction of the charring rate could be improved significantly, see Figure 8.

The improved fit of the Figure 8 was achieved by the consideration of the characteristics apparently important to estimate the behaviour of structural timber in fires, graphically shown in Figure 5. These characteristics are (i) the char layer surface regression, (ii) the char layer density, (iii) the conversion of wood to char including the release of combustible gases and conversion losses and (iv) the gas characteristics in the environment including the film temperature between the surface and the moving gas. By systematically analysing the elements (i) to (iv), a general framework for the estimation of the contribution by structural timber could be setup which is presented in Section 3.1. In the experiments, char layer density losses were identified as key elements for the estimation of the amount of smouldering and glowing combustion. Analysing the thickness of the char layer and its relation to the density, a clear systematic trend was observed, see Figure 9.

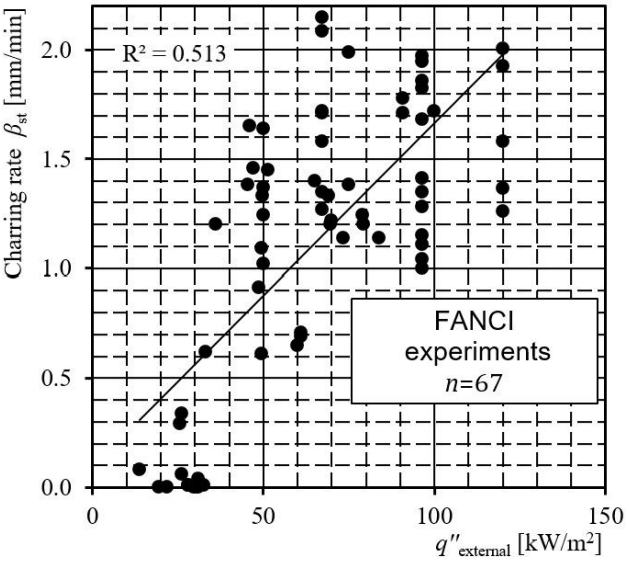


Figure 7: Observed charring rate vs. external heat flux and the correlation coefficient (least squares method).

The trend of the relationship observed in Figure 9 can be described by the following simplified function:

$$\rho_{ch,0} = \frac{230}{\sqrt{h_{ch}}} \tag{6}$$

where:

$\rho_{ch,0}$ is the density of the char layer, in kg/m^3;

h_{ch} is the thickness of the char layer, in mm.

The relationship described by the Eq. (6) as the model for the prediction of the char layer density was tested against the measurements. The results of the comparison are presented in Figure 10, which shows a good agreement. In Figure 10, additional data from the furnace and the

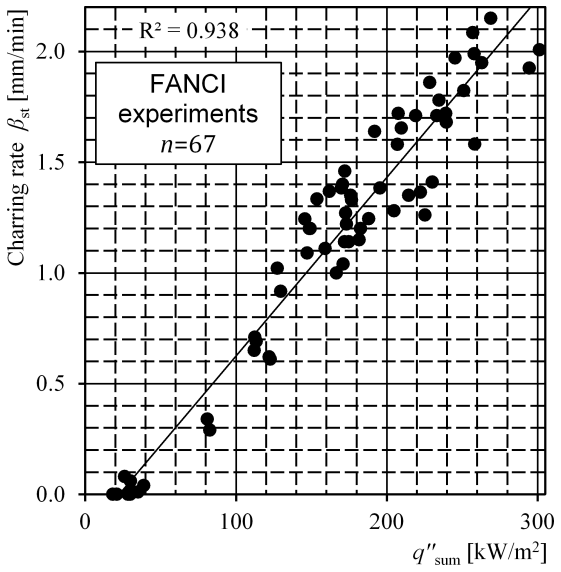


Figure 8: Observed charring rate vs. the superimposed heat flux and the correlation coefficient (least squares method).

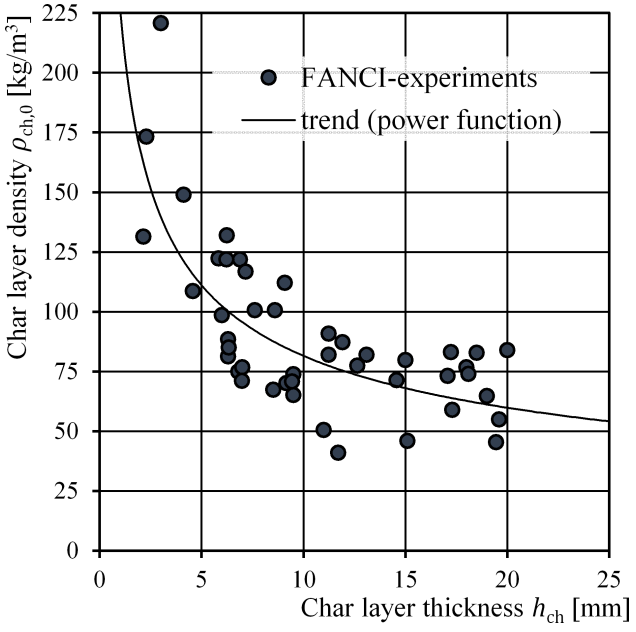


Figure 9: Developed relation for the char layer density (dry) as function of the char layer thickness.

compartment experiments are included (filled squared). By trend, the additional data show that Eq. (6) delivers a slightly conservative prediction.

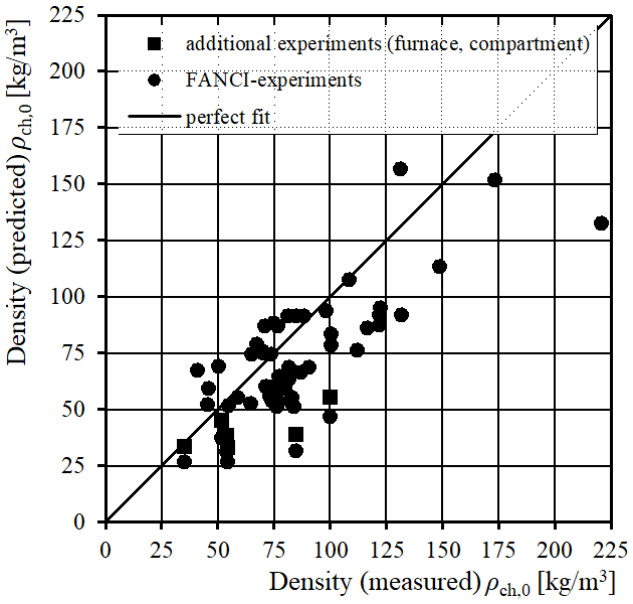


Figure 10: Measured vs. predicted char layer density.

3.1 Timber Charring and Heat Storage model (TiCHS-model)

The TiCHS-model is setup as a framework to describe the behaviour of structural timber in compartment fires. It uses seven elements based on physics applied on a charring material, wood, and the dependencies of the characteristics of major influence factors. The seven elements are

1. the energy provided by structural timber e_0;
2. the progression of the char line β_{st};
3. the energy released during the conversion of timber to char e_1;
4. the energy needed for the conversion of timber to char e_2;
5. the energy released during the degradation of the char layer e_{ch};
6. the char layer surface regression β_{ch};
7. the consumption of the char layer e_3.

Capital letter variables E_i refer to the total energy amount while lowercase letter variables e_i refer to the specific energy related to one millimetre depth of the material in consideration. With the seven elements, described in the following, the TiCHS-model is able to describe the contribution of structural timber to a compartment fire including the influence of the gas velocity caused by the natural pressure difference in a compartment. In the future, the superimposition with the externally imposed airflow (wind) should be possible which is currently under development. The seven elements of the TiCHS-model represent the energy content during various stages of the structural timber. The

energy content may be released as combustible volatiles, eventually combusted, or remain stored in the section. The elements of the TiCHS-model describe the changes in the timber section and the endothermal and exothermal reactions. The energy content is described using the specific energy content per square meter and millimetre section depth. The seven elements are described in the following paragraphs and are schematically presented for an example of a fire exposed timber section in Figure 11.

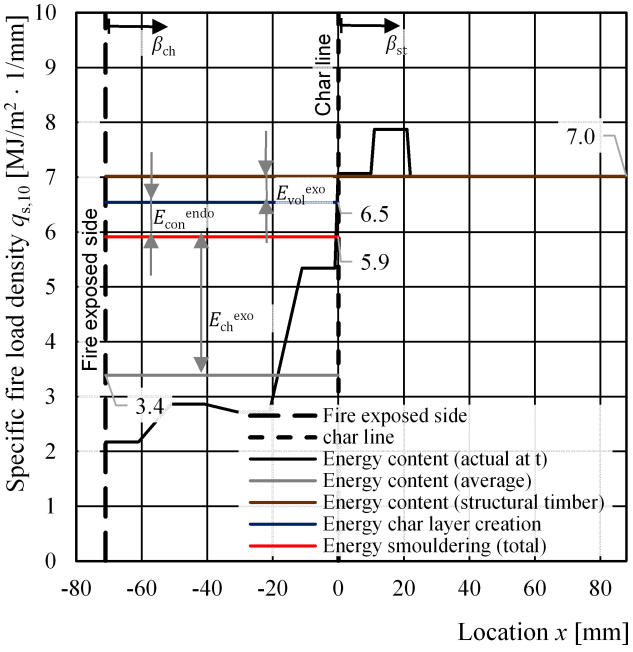


Figure 11: The TiCHS-model for a structural timber section exposed on one side.

1) Energy provided by structural timber e_0

The energy provided by structural timber is defined by its energy content depending on the specific heat content, the available density and its moisture content. For structural timber, the energy which can be released under ideal conditions is described in Eq. (1), $e_0 = 7$ MJ/m^2 per mm charring depth. This energy level is represented by the brown horizontal line in Figure 11. The corresponding structural fuel load $E_{st,10}$ can be derived taking into account the total depth of the section, which contributes to the fire.

2) Progression of the char line β_{st}

The TiCHS-model recognises the progression of charring by an appropriate charring model as sub-model. Currently, the progression of the char line is described by the cumulative temperature charring model proposed by Werther [27] which is implemented in the second draft of the revised Eurocode 5 [28]. The charring process of timber is temperature dependent, regardless the availability of oxygen. In general, combustion in the compartment occurs if the available oxygen concentration is sufficient, assumed to be limited by the oxygen concentration described by Eq. (5).

3) Energy released during the conversion of timber to char e_1

During the conversion of structural timber material to the char layer material, a certain amount of the potential energy is released as combustible volatiles. When oxygen is available, these gaseous pyrolysis products are combusted and the released heat contributes to the HRR. This combustion can occur directly at the structural timber surface as surface flaming, inside the fire compartment or latest at the façade implying increased external flaming. In the TiCHS-model, the condition for the HRR corresponding to e_{vol}^{exo} by flaming combustion (see Eq. 7) is assumed with 15% oxygen concentration as for the last element. This exothermal part of the pyrolysis process during the thermal modification of the timber to char can be specified to $e_{vol}^{exo} = 0.5$ MJ/m^2 per mm charring depth. This value for the exothermal amount of energy E_{vol}^{exo} was estimated based on the literature discussing the production of charcoal. Bunbury [29] reported that about 6% of the total energy stored in the timber are released during the modification process as volatiles. The available energy after the release of the volatiles can be derived to:

$$e_1 = e_{st,10} - e_{vol}^{exo} = 7.0 - 0.5 = 6.5 \text{ MJ/m}^2 \text{ per mm charring depth} \quad (7)$$

which is shown as blue horizontal line in Figure 11. It should be highlighted that this amount of volatiles is not the only volatiles created during the entire fire duration by structural timber. Apparently, during the subsequent smouldering and glowing combustion, the solid char is converted to volatiles. The smouldering and glowing combustion of the char layer is considered by further two elements in the TiCHS-model, presented in the following.

4) Energy needed for the conversion of timber to char e_2

The conversion of structural timber material to the char layer material requires a certain amount of energy, which is lost for the energy storage in the char layer. The literature reports a large range for energy needed to create combustible gases. It comprises the heat of gasification and the

energy to heat the solid, understood as the heat of pyrolysis. The values in the literature range between about 8% and 40% of the energy content provided by the source material, i.e. $E_{st,10}$ [29–32]. It remains unclear whether the energy released and discussed in the above paragraph (see e_1) is covered by the listed values. Furthermore, it remains unclear if the heat of gasification is depending on the specimen size, which would be relevant as the studies are normally performed on small-scale samples. If the previously presented amount of created volatiles during the modification process E_{vol}^{exo} would be a part of the heat of gasification or heat of pyrolysis, the energy content of the created char layer material would be up to about 92%. This value would represent an unrealistically high value for the degree of exploitation. The separate consideration of E_{con}^{endo} by about 8% in addition to E_{vol}^{exo} of 6% leads to a more realistic degree of exploitation of about 85%, which represents still a high value. Subsequently, the TiCHS-model recognises the conversion losses by $e_{con}^{endo} = 0.6$ MJ/m^2 and mm charring depth. The total losses by the conversion to the char layer material E_{con}^{endo} can be estimated taking into account the total depth of the section, which contributes potentially to the fire. The energy available for the smouldering and glowing combustion can be defined to:

$$e_2 = e_{st,10} - e_{vol}^{exo} - e_{con}^{endo} = 7.0 - 0.5 - 0.6 = 5.9 \text{ MJ/m}^2 \text{ per mm charring depth} \quad (8)$$

which is shown as the red horizontal line in Figure 11. This limit is the upper boundary for the potential combustion of the char layer, sometimes referred to as smouldering and glowing combustion or char layer oxidation.

5) Combustion of the char layer e_{ch}

The main contribution by structural timber to the fire dynamics in a compartment fire is the oxidation of the char layer. The oxidation of the char layer is addressed in the TiCHS-model by two reactions. The decomposition of the char layer is the superior combustion process represented by the loss of the density of the char layer. It appears that the density and, consequently, the losses in density correlate with the thickness of the char layer, see Figure 9 and Eq. (5). During the decomposition of the char layer, mainly hydrocarbons and carbon monoxide are released. The released gases may contribute to flaming, smouldering or glowing combustion. Contrary to the flaming combustion, the smouldering and glowing combustion is assumed to occur in oxygen lean environments as described in the literature, *e.g.* by Wade [5]. The upper limit for the energy available for the char layer combustion has been discussed as e_2 in the paragraph above. The lower limit is shown in Figure 11 as the grey horizontal line. For the example presented in the Figure 11, this limit is $e_3 = 0.9$ MJ/m^2 per mm charring depth for the char layer thickness of about 70 mm. By means of the FANCI-experiments, it could be shown that the actually released energy correlates to the external heat flux, the gas velocity and the degree of turbulence at the exposed surface. The limit of e_3 can be derived by the application of the default heat content of the char layer material of 31 MJ/kg and Eq. (3) to:

$$e_3 = \frac{230}{\sqrt{h_{ch}}} \cdot \frac{31}{1000} \approx \frac{7}{\sqrt{h_{ch}}} \quad (9)$$

where:
e_3 is the lower limit for the char layer combustion; in MJ/m^2 per mm charring depth;
h_{ch} is the thickness of the char layer, in mm.

Consequently, the limit for the combustion of the char layer can be determined combining Eq. (8) and (9) and further simplified to:

$$e_{ch} \approx 6.0 - \frac{7.0}{\sqrt{h_{ch}}} \quad (10)$$

where:
e_{ch} is the combustion of the char layer; in MJ/m^2 per mm charring depth;
h_{ch} is the thickness of the char layer, in mm.

6) Char layer surface regression β_{ch}

Typically, in fire resistance tests of solid timber products, no or a very limited char layer surface regression can be observed. Contrary, in experiments at ambient conditions, the char layer is consumed. Generally, the documentation of this characteristic is rare [33]. Schmid *et al.* [10] estimated a limit for the char layer surface regression at an oxygen concentration of 15% by volume. The FANCI-setup allowed the measurement of the char layer surface regression rate. Depending on the experimental set points, values up to 1.8 mm/min were observed, see Table 1. In ventilation controlled fire compartments, the oxygen concentration varies significantly. Typically, higher oxygen concentration can be expected in the inflow section and the lower zone before the available oxygen is consumed by the movable fuel arranged on the floor. On the other hand, in the upper zone, a limited oxygen concentration can be expected. In the TiCHS-model, the char layer regression is assumed to be dependent on the oxygen concentration. It is assumed that only the char layer of structural timber in contact with an oxygen rich environment will undergo char layer surface regression.

7) Consumption of the char layer e_3

Previously, it was predicted that the char layer is consumed by the smouldering and glowing combustion, see description of e_3 above. This consumption is referred back to the oxidation on the expenses of the char layer density. In an oxygen lean environment, the bulk volume of the char remains about constant or increases due to the movement of the char line into the virgin wood. When the compartment environment changes, char layer surface regression may occur. The changing point is typically when the fire starts to decays after reaching the maximum temperature in the compartment. Soon after this point, the oxygen concentration increases. From the observations in the fire tunnel [10] and similar literature results [34] it can be concluded that significant char layer surface regression occurs in oxygen rich environments. Consequently, the TiCHS-model recognises a further combustion mode where the remaining energy content e_3 may be consumed. The FANCI-experiments showed that highly turbulent environments are more aggressive than moderately turbulent flows. Subsequently, the final consumption of the char layer is dependent on the gaseous environment. Depending on the char layer surface regression rate β_{ch}, the energy stored in the density reduced char layer e_3 is consumed. Typical rates for β_{ch}, are given in Table 1.

4 Results

This section presents the utilisation of the findings of the experimental campaign and the accordingly developed TiCHS-model for compartment fires predictions. This is done together with a zone-model, which uses the TiCHS-model to consider the contribution by the structural timber to the fire dynamics. Required outcomes of the zone-model are the temperatures and the oxygen concentrations in the upper and lower zone. It is shown that it is possible to predict the temperature development and the progression of the charring of structural timber. A further outcome of the analysis presented in the subsequent sections are the modification factor α_{st} introduced in Eq. (4) to consider the combustion behaviour, the energy storage behaviour and the heat release of the char layer, respectively. For the validation, data from compartment experiments available in the literature were used.

4.1 Selection of benchmark experiments and general assumptions

Compartment experiments were selected for the comparison of measurements obtained in the experiments with the TiCHS-model predictions. The selection was done based on the availability of measurements and settings of the compartment experiments. The three essential requirements were (i) the availability of data for the total HRR, (ii) the availability of compartment temperature recordings, and, (iii) the inclusion of the performance of a baseline experiment of the particular compartment. A baseline experiment is understood as compartment experiment with similar geometry and movable fire load design but with zero structural fuel load, i.e. the ceiling and all wall surfaces

Table 2: Overview of the compartment experiments included in the validation.

ID	Compartment floor area	Ventilation Area [1)]	Exposed structural timber area	Exposed elements (ceiling | wall)	Reference
	A_f	A_v	A_{st}	(c | w)	
	[m × m]	[%]	[%]		
I	3.5 × 4.5	25	0	-	[McGregor 2013] Test 2 and 4
II	4.6 × 9.1	29	0	-	[Su *et al.* 2018] Test 1-1
III	3.5 × 4.5	25	30	w	[Medina 2015]
IV	4.6 × 9.1	29	100	c	[Su *et al.* 2018] Test 1-4
V	3.5 × 4.5	25	145	w	[Medina 2015]
VI	3.5 × 4.5	25	340	w, c	[McGregor 2013]

[1)] Face wall related

c ceiling

w wall(s)

encapsulated. The report of the charring depths is taken into account for further comparison. The experiments under consideration are compartment experiment campaigns with CLT panels. The use of CLT products, which exhibit bond line integrity throughout the fire duration, would allow for an improved comparison but due to currently available product limitations, such data are not available yet. In addition to experimental data, comparison to predictions presented by Wade and Wade *et al.* [5, 35] were made.

Subsequently, two experimental campaigns were identified appropriate for the validation of the TiCHS-model. The series have been performed and documented by McGregor [18], Medina [19] and Su *et al.* [20]. From the documented compartment experiments, a further selection was done to cover the range of combustible surfaces in the compartments. The description of the share of the combustible surface refers to the floor area as done typically for the movable fuel load. Table 2 summarizes details of the compartment experimental campaigns where baseline experiments have been performed with non-combustible (NC) enclosure surfaces prior to experiments leaving between 30% and 340% of the structural timber unprotected. It should be noted that in the experiments, various temperature measurements were taken. In the following, the reported mean gas temperature measurements were considered as benchmark. Further, it should be noted that the measurements of the HRR typically experience a time delay, which was considered by shifting the 1 MW point manually to the flashover time observed by the temperature measurements.

4.2 Baseline experiments

The experiments I and II were considered as baseline experiments which were similar to experiments III to VI but without any structural timber. The experiments with exposed structural timber showed increasing shares of the unprotected surfaces between 30% (experiment III) and 340% (experiment VI) referring to the floor area, see Table 2. The movable fire load of the corresponding experiments was similar, thus, it can be expected that the differences in the experiments can be attributed to the structural fire load.

In a first run, a zone-model was set up with appropriate enclosure materials, i.e. gypsum linings and softwood material. Subsequently, the temperature prediction for the HRR measured in the compartment experiment was done and reached a reasonable agreement when the heat of combustion was set to 12.1 MJ/kg, as suggested by Wade *et al.* [35]. No further reduction by *e.g.* a combustion efficiency was done. Thus, the combustion efficiency for the particular experiments can be estimated to:

$$\chi = \frac{\Delta H_{zm}}{\Delta H_{dw}} = \frac{12.1}{17.5} = 0.7 \tag{11}$$

where:

χ is the combustion efficiency factor;

ΔH_{zm} is the heat of combustion used in the zone model, in MJ/kg;

ΔH_{dw} is the heat of combustion (upper heating value; dry wood) of the fuel load, in MJ/kg.

The heat of combustion of timber is taken from Eurocode [1], which refers normally to dry material. Thus, the combustion takes into account the reduced heat of combustion by non-dry material and the creation of soot by the combustion efficiency factor. In Figure 12 and Figure 13,

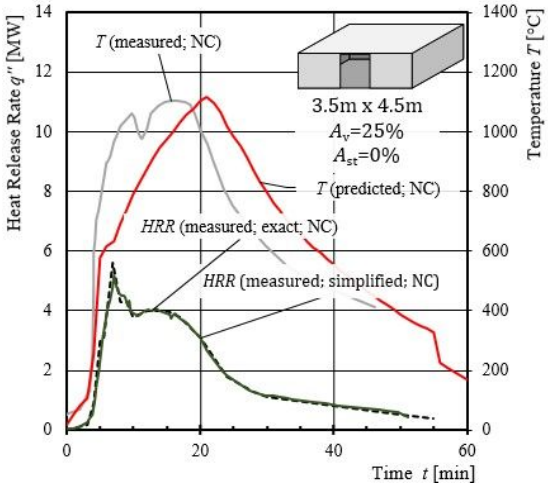


Figure 12: Predicted and measured temperatures for the HRR in baseline experiment I (NC).

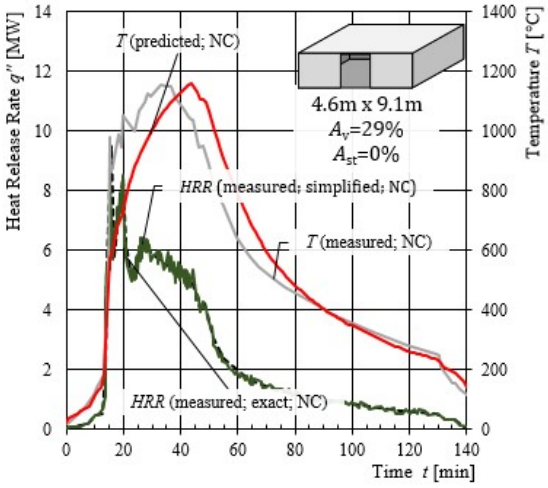


Figure 13: Predicted and measured temperatures for the HRR in baseline experiment II (NC).

the baseline experiments with the input to the zone-model (HRR simplified) and the predicted temperature for this non-combustible (NC) enclosures is provided in comparison to the measured compartment temperature. For both cases, the predicted temperature increase is slightly underestimated which is believed to cause the delay of the peak temperature. Overall, a good agreement of the prediction can be stated.

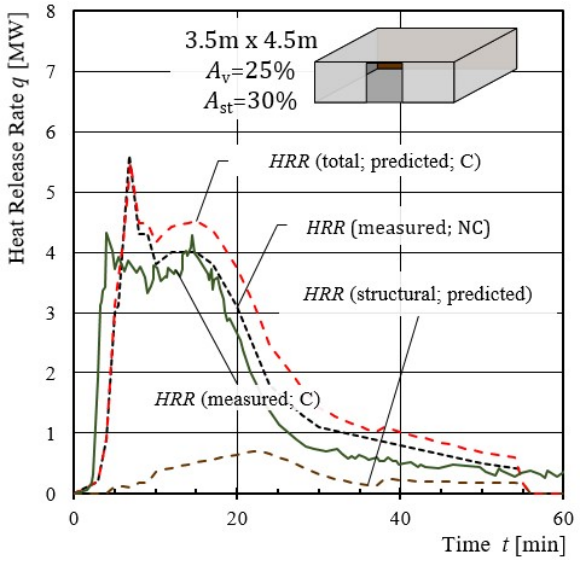


Figure 14: Predicted and measured HRR for experiment III.

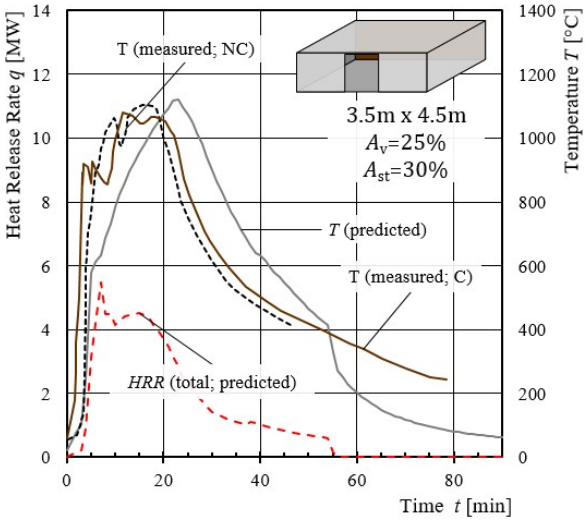


Figure 15: Predicted and measured temperatures for the predicted total HRR for experiment III.

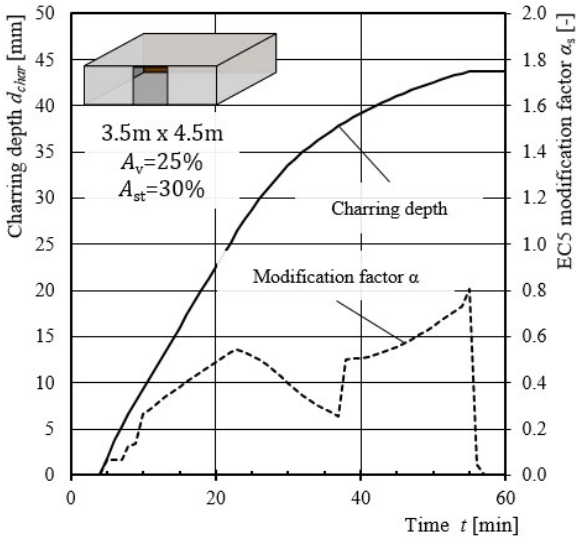


Figure 16: Predicted charring depth and modification factor α for considering the charring behaviour as function of time for the experiment III.

4.3 Exposed structural timber surface 30%

The experiment III had its rear wall exposed, which represents 30% of the floor area. Figure 14 shows the predicted HRR by the TiCHS-model in comparison to the HRR by the baseline experiment II and the measured HRR. Interestingly, it appears that the baseline experiment (NC) showed a HRR excessive the case with the exposed rear wall (C), the green curve in Figure 14. However, the agreement of the predicted HRR is still well and predicts the start of the decay very well. The temperature predictions by the zone-model are provided in Figure 15 and are in good agreement with the peak temperature slightly delayed as for the baseline experiment II (NC), see Figure 13. The development of the charring depth is shown in Figure 16 with a final value of about 44 mm. In the experiment III, the reported charring depth was between 21 mm and 44 mm.

4.4 Exposed structural timber surface 100%

The experiment III had its ceiling exposed, which represents 100% of the floor area. In the experiment, partial fall-off of the CLT's outer lamella was observed after about 40 min, which caused an increase of the HRR, see Figure 17. Until this point, the predicted HRR shows a good agreement. As observed already for the baseline experiment I, the peak temperatures are predicted with a delay, see Figure 18. In Figure 19, the development of the charring depth is given. The charring depth was simulated to reach about 78 mm while measurements indicated values

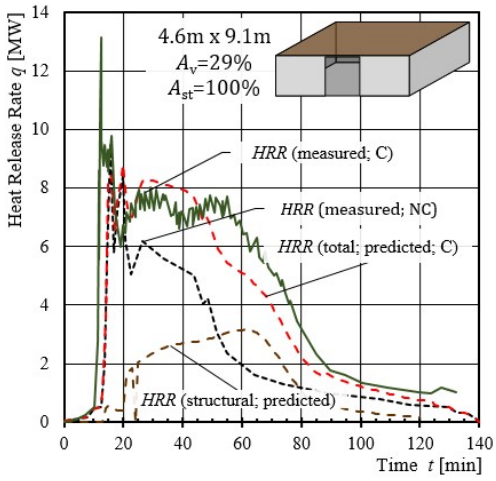


Figure 17: Predicted and measured HRR for experiment IV.

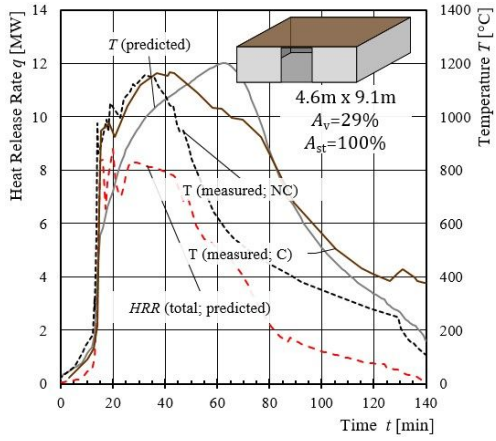


Figure 18: Predicted and measured temperatures for the predicted total HRR for experiment IV.

between about 65 mm and 90 mm. The modification factor for the structural fuel load increases after about 85 min when the char layer starts to get consumed due to the increased oxygen content in the compartment. Apparently, the temperature drop is superior the contribution by this process and the compartment would reach burnout under the condition that the CLT product shows intact bond lines which is not described by the TiCHS-model in its current version.

4.5 Exposed structural timber surface 145%

The experiment V had two opposite walls exposed, which represents 145% of the floor area. In the experiment, fall-off of the CLT's outer lamella was observed after about 40 min, which caused an increase of the compartment temperature, see Figure 21. The recording of the HRR failed after about

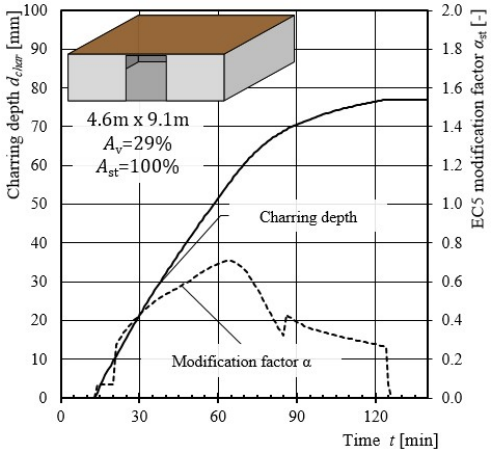


Figure 19: Predicted charring depth and modification factor α for considering the charring behaviour as function of time for the experiment IV.

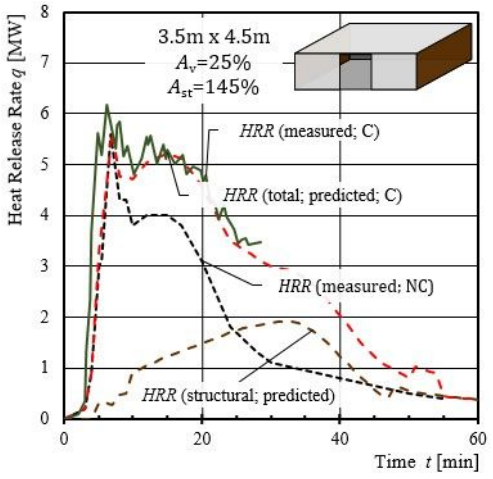


Figure 20: Predicted and measured HRR for experiment V.

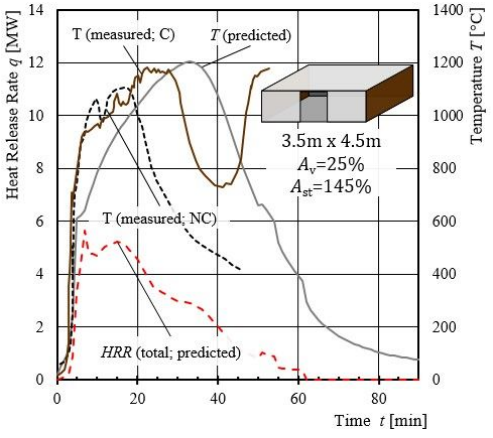


Figure 21: Predicted and measured temperatures for the predicted total HRR for experiment V.

30 min but, until this point, it shows a good agreement with the predictions by the TiCHS-model. The begin of the decay could be predicted fairly well considering the delay of the HRR and the peak HRR and peak temperature, see Figure 20 and Figure 21, respectively. In Figure 22, the development of the charring depth is given. The modification factor for the structural fuel load increases after about 45 min when the char layer starts to get consumed due to the increased oxygen content in the compartment. Apparently, the temperature drop is superior the contribution by this process and the compartment would reach burnout if no fall-off of CLT layers would occur.

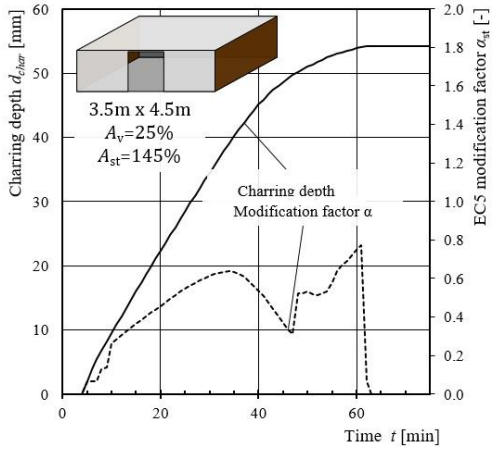


Figure 22: Predicted charring depth and modification factor α for considering the charring behaviour as function of time for the experiment V.

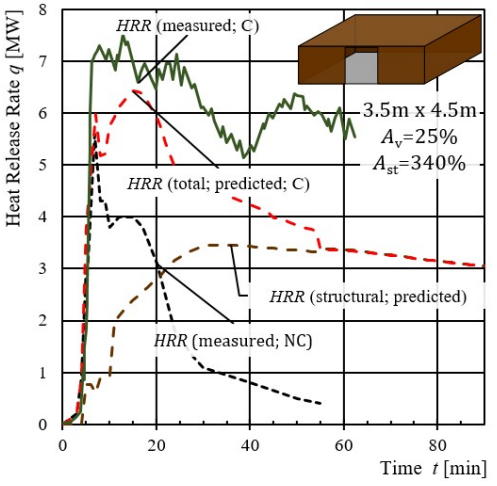


Figure 23: Predicted and measured HRR for experiment VI.

4.6 Exposed structural timber surface 340%

The experiment VI had its ceiling and all walls exposed, which represents 340% of the floor area. This means, all structural timber was left unprotected. In the experiment, fall-off of the CLT's outer lamella was observed after about 40 min, which caused an increase of the HRR, see Figure 23. The predicted HRR underestimates the measured HRR to a limited extent. The decay could be predicted fairly well until the fall-off of charring lamellas caused re-growth of the fire, which was terminated manually after about 60 min. The corresponding temperature measurements are given in Figure 24, which agree well with the measured results. In Figure 25, the development of the charring depth is given. Apparently, no decay of the charring can be expected. The prediction of no burnout is in agreement with corresponding simulations by Wade [5]. The modification factor for

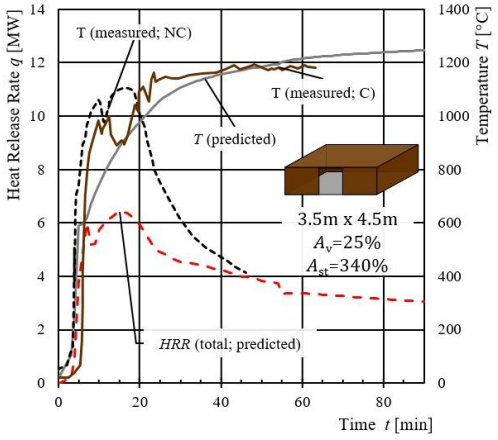


Figure 24: Predicted and measured temperatures for the predicted total HRR for experiment VI.

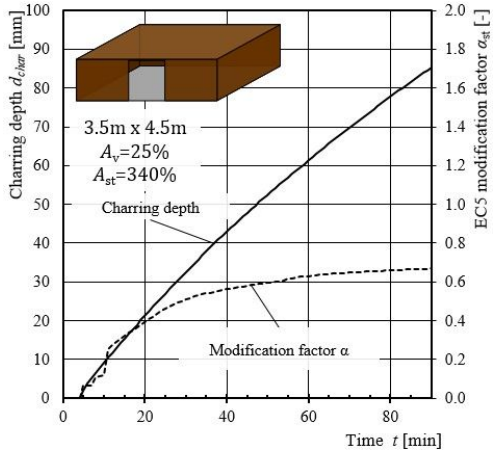


Figure 25: Predicted charring depth and modification factor α for considering the charring behaviour as function of time for the experiment VI.

the structural fuel load does not exceed $\alpha_{st} = 0.7$ during the 90 min. However, it should be observed that no phase with oxygen concentration exceeding 15% was observed during this time. Then, the consumption of the char layer thickness (element 7 in the TiCHS-model) would begin to increase α_{st}.

5 Discussion

A simplified engineering model for the consideration of structural timber in compartment fires was presented in this study. It considers the conversion of the source material, i.e. the structural timber, to a thermally modified layer, commonly known as char layer. The release of combustible volatiles occurs only to a small amount directly from the structural timber but mainly by the decomposition of the char layer. The modification of the structural timber implies the creation of a new material with a significantly less density, about 55% of the dry source material, but a significantly higher heat content, about 170% of the dry source material. From a study on the char layer material by bomb calorimetry [6] it became evident that, the heat content can be assumed to be constant but the density of the char layer density varies between experiments and over its depth. The density of the char layer is reported in literature with a large range, about 50% by Hankalin *et al.* [36] and between 30% and 20% for pine by Tran *et al.* [37]. The application of advanced methods in Eurocode [7] suggests a variable density over the char layer depth with a mean density of about 23% after two hours of standard fire exposure [6]. Considering the large range of data between 50% and 20% and the importance of the char layer acting to the energy storage, the char layer was deeper analysed in this study. A dependency on the decay, i.e. the loss of density, of the char layer was observed. A relationship was determined between the decay and the char layer depth implicitly related to the fire exposure and duration. The dependency was developed by data from char layer characteristics from experiments in fire resistance test furnaces, under a radiant heat panel and a compartment experiment. Together with data available in the literature documenting the pyrolysis and the well-documented production of char coal, a framework was developed to describe the behaviour of structural timber in fire. The mass loss and the specific heat content related to the density can be utilized to describe the potential energy release. Consequently, the developed Timber Charring and Heat Storage model (TiCHS-model) can describe the contribution to the fire dynamics by the structural timber and the char layer, respectively. The TiCHS-model comprises seven elements. The most important contribution to the compartment fire by combustible volatiles originates by the char layer during its decay. It appears important that smouldering and glowing combustion, in contrast to flaming combustion, is insignificantly dependent on the availability of oxygen. The limited dependency of the char combustion by the oxygen concertation can be observed by a slightly reduced fit of the additional data obtained in compartment experiments in comparison to heat panel experiments. The TiCHS-model is able to assess the contribution of structural timber to the fire dynamics by the determination of the structural HRR. Consequently, an iterative approach is followed based on the prediction of the compartment environment, i.e. the temperature and the gas characteristics in the compartment. Calculations were presented comparing the total HRR and the compartment temperature of the proposed procedure and experiments available in the literature. The results in terms of charring depth are about ± 5 millimetre compared to the experimental results. The predictions achieve an overall good agreement unless fall-off of charring layers induce a re-growth of the fire due to the sudden change of the combustion characteristics. These effects can be attributed to the sudden direct exposure of virgin wood and the significantly changed fire exposure of the fallen char layer. By fall-off, the char material is suddenly exposed to an oxygen richer environment at multiple sides. For the correct description of the combustion of char material on the floor, further information is essentially needed. The radiation from the surface flaming to other combustible members than the origin is currently not explicitly considered. Consequently, the model should not be used for compartments with exposed structural timber walls that are narrower than in the experimental data used for validation. The consideration of the relative arrangement of structural timber walls will be implemented when further data is available. In the calculations presented in this publication, a combustion efficiency of $\chi = 0.7$ is used while for design purposes a deviating factor may be used to allow for a conservative result. This combustion efficiency factor χ does not cover the factor α_{st} to consider the combustion behaviour of structural timber. The latter describes the delayed combustion caused by the char layer creation.

6 Conclusions

After the validation of the TiCHS-model by means of compartment experiments, the following statements can be made:

- The TiCHS-model can be used to predict the HRR together with a zone-model;
- The TiCHS-model is able to predict burn-out and the charring-depth;
- The TiCHS-model did predict the charring depth slightly conservative but in good agreement with the observations in the experiments;
- The TiCHS-model allowed the determination of the factor α_{st} to describe the combustion behaviour of structural timber.

It should be noted that the TiCHS-model in its current form does not consider a potential failure of the bond line, i.e. fall-off of charring layers. In a future model, it is planned to implement this feature although it is considered of minor interest as the adhesive industry is about to introduce improved adhesives. An important element to be studied prior to the intended implementation is the combustion characteristics of failed layers, which have been thermally modified sticking to the CLT, partly decomposed in the original location and suddenly exposed to multiple sides and oxygen-rich environments at the floor of the compartment after its fall-off.

In general, it was shown that the predictions using the TiCHS-model reach a good agreement with the measurements in the compartment experiments. Further, a good agreement with the prediction of corresponding simulations available in the literature was achieved. Here it should be noted that the TiCHS-model does not require the definition of a fuel access factor or a corresponding parameter study. Currently, the model is validated for the gas velocities, which occur in compartments with openings on one side. In the future, it is expected that the requirements will be set for superimposing the natural gas flow with imposed gas flow by wind. This is believed to be an important task for medium and high-rise buildings with potential cross-flows.

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