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Complete List of Authors:	McNamee, Robert; Brandskyddslaget AB, Zehfuß, Jochen; Technische Universitat Carolo Wilhelmina Zu Braunschweig Institut fur Baustoffe Massivbau und Brandschutz, Fachgebiet Brandschutz Bartlett, Alastair; University of Edinburgh School of Engineering, HEIDARI, MOHAMMAD; Centre d'Etudes et de Recherches de l'Industrie du Beton, ; Imperial College London, Robert, Fabienne; Centre d'Etudes et de Recherches de l'Industrie du Beton Bisby, Luke; The University of Edinburgh School of Engineering
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ENCLOSURE FIRE DYNAMICS WITH A CROSS LAMINATED TIMBER CEILING

Robert McNamee[1], Jochen Zehfuss[2], Alastair I. Bartlett[3], Mohammad Heidari[4], Fabienne Robert[4] and Luke A. Bisby[3]

[1]Brandskyddslaget, Sweden
[2]The Institute of Building Materials, Concrete Constructions and Fire Safety, Technische Universität Braunschweig (iBMB), Germany
[3]School of Engineering, the University of Edinburgh, UK
[4]CERIB Fire Testing Centre, France.

ABSTRACT

An experimental study of the influence of an exposed combustible ceiling on compartment fire dynamics has been performed. The fire dynamics in compartments with combustible cross laminated timber (CLT) ceilings versus non-combustible reinforced concrete ceilings in otherwise identical compartments, with three different ventilation factors were investigated. The experimental results are compared against predictions from two theoretical models for compartment fire dynamics: (1) the parametric fire model given in EN 1991-1-2, and (2) a model developed at Technische Universität Braunschweig (iBMB), which is the parametric fire model currently used in Germany. It is confirmed that the introduction of a combustible timber ceiling leads to higher temperatures within the enclosure, both under fuel-controlled and ventilation-controlled scenarios. It is also demonstrated that the theoretical models considered in this paper require refinement in order to adequately represent all relevant scenarios when combustible ceilings are present. A refinement of the German model, by adding the fuel from the combustible ceiling to the occupancy fuel load was shown to not adequately capture the response for the ventilation-controlled fires.

INTRODUCTION

The ‘Epernon Fire Test Programme’ is an experimental campaign aimed at studying the fire dynamics and structural response of compartments with ceilings consisting of two types of loaded one-way spanning slabs in different standard and compartment (i.e. ‘natural’) fire exposures: (1) those made from exposed (i.e. unencapsulated) cross laminated timber (CLT), and (2) those made from exposed reinforced concrete. These two types of slabs were tested both in standard fire resistance (i.e. furnace) tests, and in compartment fire experiments with timber crib fuel loads and different opening factors at the CERIB testing facility in Epernon, France. This paper focuses on the variations in fire dynamics observed when the natural fire compartments had ceilings made from CLT, and compares the experimental data against both theoretical calculations and notionally identical experiments performed with concrete ceilings.

The common reference for fire exposure during fire resistance testing internationally is a standard cellulosic fire time temperature curve[1], however this is strictly only a reference fire exposure; real fires may be less or more severe than the standard exposure, and may have lesser or greater rates of heating (or decay) . Real fires also include a decay phase, which is only very rarely considered in fire resistance testing in furnaces. The standard cellulosic temperature versus time curve was first defined a century ago by the American Society for Testing and Materials (ASTM). At that time, knowledge regarding fire dynamics in building enclosures was extremely limited, since few real fire dynamics experiments had been performed[2]. Ingberg later undertook seminal research in this area and developed the equal area concept to suggest an ‘equivalency’ between real burnout fires and a duration of standard fire exposure[3].

Ingberg's equivalency concept suggested that the severity of two fires could be assessed as equal if the area under the time temperature curve above a certain reference temperature was equal for both the real and standard fire gas phase temperature versus time curves. This equal area concept can of course be criticised on a number of grounds, for instance because different materials and cross sections respond differently to changes in thermal exposure, i.e. this type of transformation includes a material dependence that is not properly accounted for. Several alternative approaches to this time equivalence approach have subsequently been developed[4,5,6]. For instance, the method for time equivalence in Eurocode 1 Annex F[7] is based on work by Schneider using the MRFC (Multi-Room-Fire-Code) computer program developed at the University of Kassel[8,9]. This method is, by its nature, material dependent, and is not strictly applicable to composite steel and concrete or timber construction.

The primary factors influencing temperature development in fully developed fires in non-combustible enclosures are the fuel load (quantity and geometry), total size of the openings, the geometry of the compartment and its openings, and the thermal properties of the enclosure boundaries. Early models for fully developed fires including these important factors were developed around, both 1963 by Ödeen[10,11]and by Kawagoe[12]. During the 1960s Ödeen's model was further developed and validated against a set of experiments and by using computer calculations, resulting in the well-known "Swedish fire curves"[13]. These curves were subsequently parametrized by Wickström[14] and later included in EN 1991-1-2 with some further modifications. The Eurocode parametric fire curves, which assume uniform gas phase temperature, are generally considered valid for compartments with floor areas up to 500 m² and ceilings up to 4 m in height. The current paper compares experimental results from the Epernon fire test series against the Eurocode parametric fire model[7], and also against a more recently developed iBMB parametric model.

The iBMB parametric fire model[15] is a natural fire model which is more directly connected to the heat release rate in a fire. The model, defined in the national annex of the German Eurocode[16], is considered by its developers to be valid for floor areas up to 400 m² and ceilings up to 5 m in height. It describes the gas phase temperature-time curve in the growth, fully-developed, and decay phases of a compartment fire. The qualitative shapes of the of heat release rate (HRR) from the Eurocode and the temperature-time curve from the iBMB model are shown in Figure 1, where a temporal link between the two is evident.

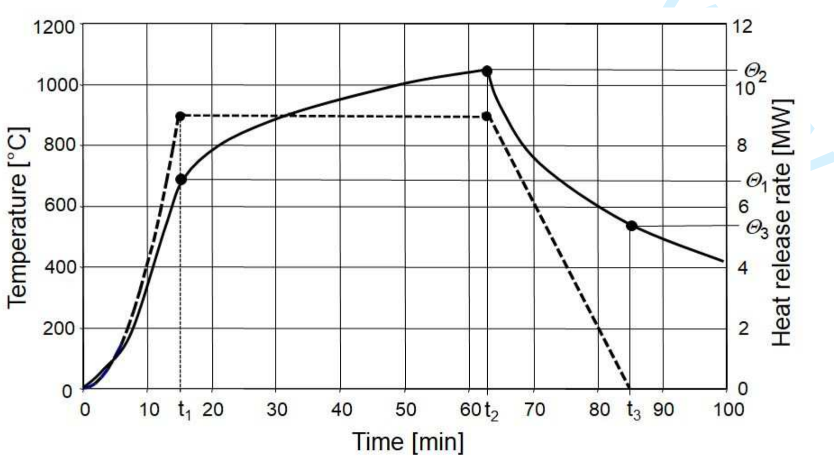


Figure 1. Temperature development in the simplified iBMB fire model (solid line) and the heat release rate (dashed line) from the Eurocode (principle).

The iBMB parametric fire curves[15,16] can be divided into three sections based on the heat release rate from the Eurocode (Figure 1 shows the development of gas phase temperature and heat release rate). From the beginning of the fire until time t_1 the temperature increases rapidly (representing the growth phase). At t_1 the maximum of the heat release rate is achieved, and it remains constant until time t_2

(representing the fully-developed phase). After t_1 the temperature increases more moderately. As 70 % of the fire load is expected to be consumed at time t_2, the HRR is assumed to drop off linearly (representing the decay phase) and the temperatures decrease. At time t_3 the fire load is assumed to be totally consumed and the HRR is thus zero. At this time the temperature-time curve changes in slope and is assumed to decay more gradually. To fully describe the temperature-time curve the associated characteristic temperatures Θ_1, Θ_2, and Θ_3 have to be determined (Figure 1). The HRR depends on the ventilation conditions, and a distinction must be made between ventilation-controlled fires and fuel-controlled fires. The iBMB model is presented in detail by Zehfuss and Hosser[15]; it is based on the heat release rates suggested in Annex E of the Eurocode[7], along with a best-fit of results from parametric studies[15] using the zone model CFAST.

For ventilation-controlled fires in residential and office buildings the maximum HRR inside the compartment is assumed, based on Zehfuss and Hosser[15] with $H_u = 17{,}3$ MJ/kg and $\chi = 0{,}7$, as:

$$\dot{Q}_{max,v} = 1.21\ A_w\sqrt{h_w}\ [\mathrm{MW}] \qquad [1]$$

For fuel-controlled fires in residential and office buildings the maximum HRR is assumed, according to EN 1991-1-2 Table E.5, as:

$$\dot{Q}_{max,f} = 0.25 \cdot \mathrm{A_f}\ [\mathrm{MW}] \qquad [2]$$

For ventilation-controlled fires the characteristic temperature values for a reference fire load density, q = 1300 MJ/m² are assumed based on a regression analysis of the CFAST zone model calculations[15] as:

$$\Theta_1 = -8.75 \cdot 1/\mathrm{O} - 0.1\ \mathrm{b} + 1175\ [°\mathrm{C}] \qquad [3]$$
$$\Theta_2 = (0.004\ \mathrm{b} - 17) \cdot 1/\mathrm{O} - 0.4\ \mathrm{b} + 2175\ [°\mathrm{C}] \qquad [4]$$
$$\Theta_3 = -5.0 \cdot 1/\mathrm{O} - 0.16\ \mathrm{b} + 1060\ [°\mathrm{C}] \qquad [5]$$

with:

opening factor	$O = A_w\sqrt{h_w} / A_t$ [m$^{1/2}$],
area of ventilation openings	A_w [m²],
averaged height of ventilation openings	h_w [m],
total area of enclosure including openings	A_t [m²],
fire compartment area	A_f [m²],
averaged thermal property of enclosure	b [J/(m²s$^{1/2}$K)].

For fuel-controlled fires the following temperature functions for a reference fire load density of q = 1300 MJ/m² are assumed:

$$\Theta_1 = 24000\ \mathrm{k} + 20\ [°\mathrm{C}] \text{ for } \mathrm{k} \le 0.04 \text{ and } \Theta_1 = 980°\mathrm{C} \text{ for } \mathrm{k} > 0.04, \qquad [6]$$
$$\Theta_2 = 33000\ \mathrm{k} + 20\ [°\mathrm{C}] \text{ for } \mathrm{k} \le 0.04 \text{ and } \Theta_1 = 1340°\mathrm{C} \text{ for } \mathrm{k} > 0.04 \qquad [7]$$
$$\Theta_3 = 16000\ \mathrm{k} + 20\ [°\mathrm{C}] \text{ for } \mathrm{k} \le 0.04 \text{ and } \Theta_1 = 660°\mathrm{C} \text{ for } \mathrm{k} > 0.04 \qquad [8]$$

with

$$k = \left(\frac{\dot{Q}^2}{A_w\sqrt{h_w} \cdot (A_t - A_w) \cdot b}\right)^{1/3} \qquad [9]$$

and maximum HRR $\dot{Q} = \mathrm{MIN}\ (\dot{Q}_{max,v}, \dot{Q}_{max,f})$ [10]

For fire load densities less than the reference value of 1300 MJ/m² the maximum temperature occurs earlier, when 70% of the fuel is consumed and the decay phase begins; this point can be determined from the HRR function.

For buildings with unprotected timber elements and fuel-controlled fire dynamics, the additional fire load from the burning timber must obviously be considered. Therefore, the iBMB model has been modified in the current paper using a simplified approach with an assumed linear burning rate for temperatures above 300°C based on an assumed charring rate. Charring rates are, of course, not constant in reality, however this is considered a reasonable first approximation and is indeed a fundamental assumption of the methods provided within EN 1995-1-2. This enhancement is marked in **bold** characters in the formulae below. Thus the total fire load density $q_{f,tot}$ becomes:

$$q_{f,tot} = q_{f,k} \cdot \chi + \boldsymbol{A_{tim}} \cdot \boldsymbol{d_{char,t}} \cdot \boldsymbol{h_{eff,tim}} \cdot \boldsymbol{\rho_{tim}/A_f} \quad [11]$$

with:

fire load density according to EN 1991-1-2 (only "mobile fire load")	$q_{f,k}$ [MJ/m²],
combustion efficiency	χ [-],
surface area of timber elements	A_{tim} [m²],
effective heat of combustion of timber	$h_{eff,tim}$ [MJ/kg],
density of timber	ρ_{tim} [kg/m³],
fire compartment floor area	A_f [m²],
charring depth $d_{char,t} = \beta_0 \cdot t_{>300}$ with $t_{>300} = \sum_{T \geq 300} t_T$	[m].

The charring depth is calculated from the charring rate multiplied by the time during which the enclosure temperature is calculated as being higher than 300°C.

The maximum heat release rate for fuel-controlled fires is then assumed as:

$$Q_{max,f,k} = HRR_f \cdot A_f + \boldsymbol{HRR_{tim}} \cdot \boldsymbol{A_{tim}} \quad [12]$$

with the heat released by timber = $HRR_{tim} = \dot{r}'' \cdot \Delta H_{c,tim}$ [MW/m²]
burning rate of the timber = $\dot{r}'' =$ 0.014 [kg/(m²s)][17]

$$HRR_{tim} = \dot{r}'' \cdot \Delta H_{c,tim} \approx 0.20 \text{ [MW/m²]} \quad [13]$$

COMPARTMENT FIRE EXPERIMENTS

Compartment fire experiments were performed on compartments 6000 mm x 4000 mm in plan and with a ceiling height of 2520 mm. The basic material of the walls of the fire compartment was aerated concrete with a nominal density of 350 kg/m³, and the floor was covered with calcium silicate boards on top of mineral wool insulation. Three experiments with unencapsulated CLT ceilings and three experiments with exposed concrete ceilings were performed.

For the CLT experiments the ceiling consisted of an assembly of two CLT slabs with dimensions 5900 mm x 1950 mm in plan and a thickness of 165 mm. These were joined together along the structural spanning direction and placed on top of the fire compartment. The CLT slabs were manufactured from five 33 mm thick spruce lamellae stacked and crossed at 90°. The adhesive used was a single-component polyurethane resin, designated HB S709 from the company PURBOND. The concrete slabs, with dimensions 5900 mm x 3900 mm in plan and with a thickness of 180 mm, were cast in-situ from C35/45 concrete with a welded reinforcement mesh (ST50C, 5.03 cm²/m, Ø8 mm every 100 mm in both directions) and a clear cover of 20 mm (axis distance 24 mm). Both the CLT and concrete slabs were loaded during the experiments – the mechanical behaviour of the CLT slabs has been discussed in a complementary paper[18,19]. Selected experiments included a façade mock-up to characterise the external fire plume, the data from which are also discussed in a complementary paper[20].

The fuel load during the experiments consisted of spruce wood cribs ignited using heptane accelerant, for a total moveable fuel load = 891 MJ/m². Three different opening factors were investigated, as shown in Table 1 and Figure 2. The opening factors were determined following the definition in EN 1991-1-2[7]. With an opening factor of 0.144 $m^{1/2}$ the fire was expected to be fuel-controlled, and in the two other cases, with opening factors of 0.050 $m^{1/2}$ and 0.032 $m^{1/2}$, respectively, the fires were expected to be ventilation-controlled. The opening factors for the three experiments were chosen based on the work of Thomas and Heselden, involving cellulosic fuels[21]. The average compartment gas phase temperatures of the two regimes, fuel- and ventilation-controlled, during steady burning as a function of their definition of opening factor, $A_T / A_w H^{1/2}$ [$m^{-1/2}$], are shown in Figure 3. In their definition, which is notably not the same as in the Eurocode, A_T, is the total area of the compartment excluding the ventilation area, A_w, and H is the height of the opening. The chosen opening factors are included in Figure 3 where Scenario 1 (blue line) was in the fuel-controlled regime according to these definitions, and the two other scenarios (red and green lines) were considered to be ventilation-controlled.

Table 1 Opening geometries in compartment fire experiments.

Scenario #	Number of openings	Height of opening [mm]	Width of opening [mm]	Opening factor [$m^{1/2}$]	Opening factor* [$m^{-1/2}$]
1	2	2000	2500	0.144	4.64
2	3	1200	1250	0.050	14.2
3	1	2000	1100	0.032	23.2

*Opening factor according to definition by Thomas and Heselden[21]

Figure 2. CLT slabs tested with three different opening configurations; opening factors were 0.144, 0.050, and 0.032 $m^{1/2}$.

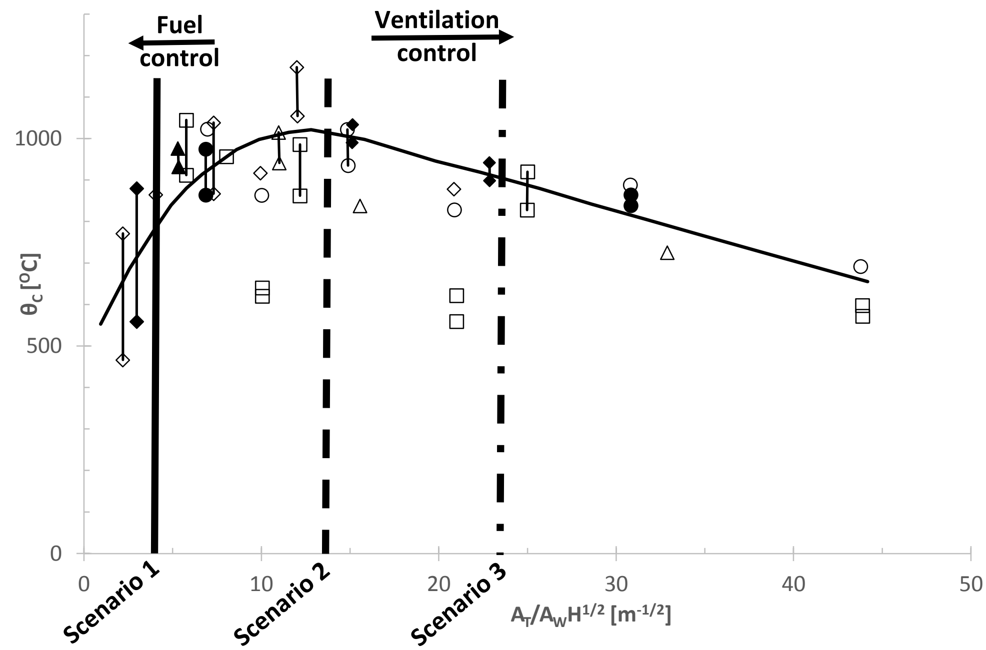


Figure 3. Average compartment gas phase temperatures during the steady burning period for wood cribs based on data from Thomas and Heselden[21], different symbols for different compartment shapes, and thin vertical lines indicate the span of temperatures recorded. The opening factors in the current study are included as three thick vertical lines (Scenario 1, 2, and 3).

Fifteen plate thermometers were placed at a distance of 100 mm below the slab soffit in the gas phase; the average, maximum, and minimum values from these are shown in Figure 4. In addition, shielded Type K thermocouples were used to measure the temperature at four locations, each including TCs at distances of 500, 1000, 1500, and 2000 mm below the slabs' soffits. Temperature measurements were also taken with embedded plate thermometers fitted flush within the fire-exposed surfaces of the slabs, as well as in-depth within the slabs using shielded thermocouples. The data resulting from these different measurements will be presented in more detail in a companion paper (under preparation). In the current paper, measurements from plate thermometers and shielded thermocouples at the distance 100 mm from the fire exposed slab soffit, and temperatures measured in the centre of the compartment 1500 mm below the soffit, are presented and discussed.

CALCULATIONS

The experimental results were compared with calculations according to the EN 1991-1-2[7] and the iBMB[15,16] parametric fire models. Both models were implemented assuming the thermal properties for compartment boundaries given in Table 2. The Eurocode model calculations do not include additional fuel from burning of the wood in the ceiling, however the iBMB model has been modified to include the contribution from the CLT, as already described.

Table 2. Material data used in calculations.

	Density $[kg/m^2]$	Specific heat [J/(kgK)]	Thermal Conductivity [W/(mK)]	Thermal inertia ("b" in fire model) $[J/(m^2s^{1/2}K)]$
Aerated concrete	350	1000	0.36	355
Calcium silicate board	900	1000	0.212	437
Mineral wool	96	1000	0.05	69
Wood	450	1530 (EC)	0.12 (EC)	287
Concrete	2400	900 (EC)	1.33 (EC)	1695

For application of the Eurocode method[7], the combustion efficiency was set to 0.8, gamma factors set to 1, and the fire development was defined as "fast" for the fuel-controlled fires, since 18 litres of heptane was used to ignite the timber cribs (the Eurocode prescribes "medium" fire development for dwellings but due to the experimental procedure "fast" was chosen as an initial assumption). A sensitivity analysis of the combustion efficiency, with values 0.7, 0.8 and 0.9, is provided later in this paper to show the resulting variation in the predictions using the Eurocode method. Also, a sensitivity analysis of the choice of fire development is included later in this paper.

RESULTS

A summary of results from all six experiments and calculations are provided in Figure 4.

<u>Scenario 1 – Opening factor 0.144 $m^{1/2}$</u>

When comparing the data between the compartments with CLT or concrete ceilings, in the case of the largest opening factor of 0.144 $m^{1/2}$, the largest temperature difference measured 100 mm beneath the slab soffit was around 200ºC. In this case the results from the calculations with the EN 1991-1-2 model indicated that the fire was fuel-controlled. Since this calculation was performed without including the contribution from the burning ceiling, this is clearly an incorrect assessment of the available fuel, however it indicates that more oxygen was available in this scenario than in those with lower opening factors. This additional available oxygen is considered to account for the more pronounced effect of the addition of a combustible ceiling (i.e. significantly increased peak gas phase temperatures as measured by plate thermometers within the compartment). During this experiment there was no structural collapse of the CLT slab.

<u>Scenario 2 – Opening factor 0.050 $m^{1/2}$</u>

With an opening factor 0.050 $m^{1/2}$ the CLT slab collapsed after 29 hours due to a reduced cross-section. This is thought to have resulted from continued localised smouldering of the CLT after extinction of flaming. At all four measurement stations with thermocouples in-depth at distances of, 4, 12, 23, 33, 44, 55, 66, 77 and 99 mm from the surface the temperatures measured within the CLT after 15 hours were less than 40°C. The data acquisition was then turned off; however smouldering appears to have continued in localised areas deeper in the slab where no temperature measurements were made. This ongoing in-depth heating resulted in a continued loss of load-bearing capacity, eventually resulting in structural collapse of the slab.

<u>Scenario 3 – Opening factor 0.032 $m^{1/2}$</u>

During the experiment with the lowest opening factor of 0.032 $m^{1/2}$, giving the longest duration of the fully developed phase, the CLT structure collapsed after 108 minutes of natural fire exposure. Whilst comparisons of fire resistance durations from natural fires cannot be compared with standard fire resistance durations, the fire resistance rating for this slab would have been REI 120 based on the applied loading and using the reduced cross-section method (RCSM) given in EN 1995-1-2.

The gas phase temperatures recorded in all experiments significantly exceeded those of the standard cellulosic fire curve during the steady burning phase.

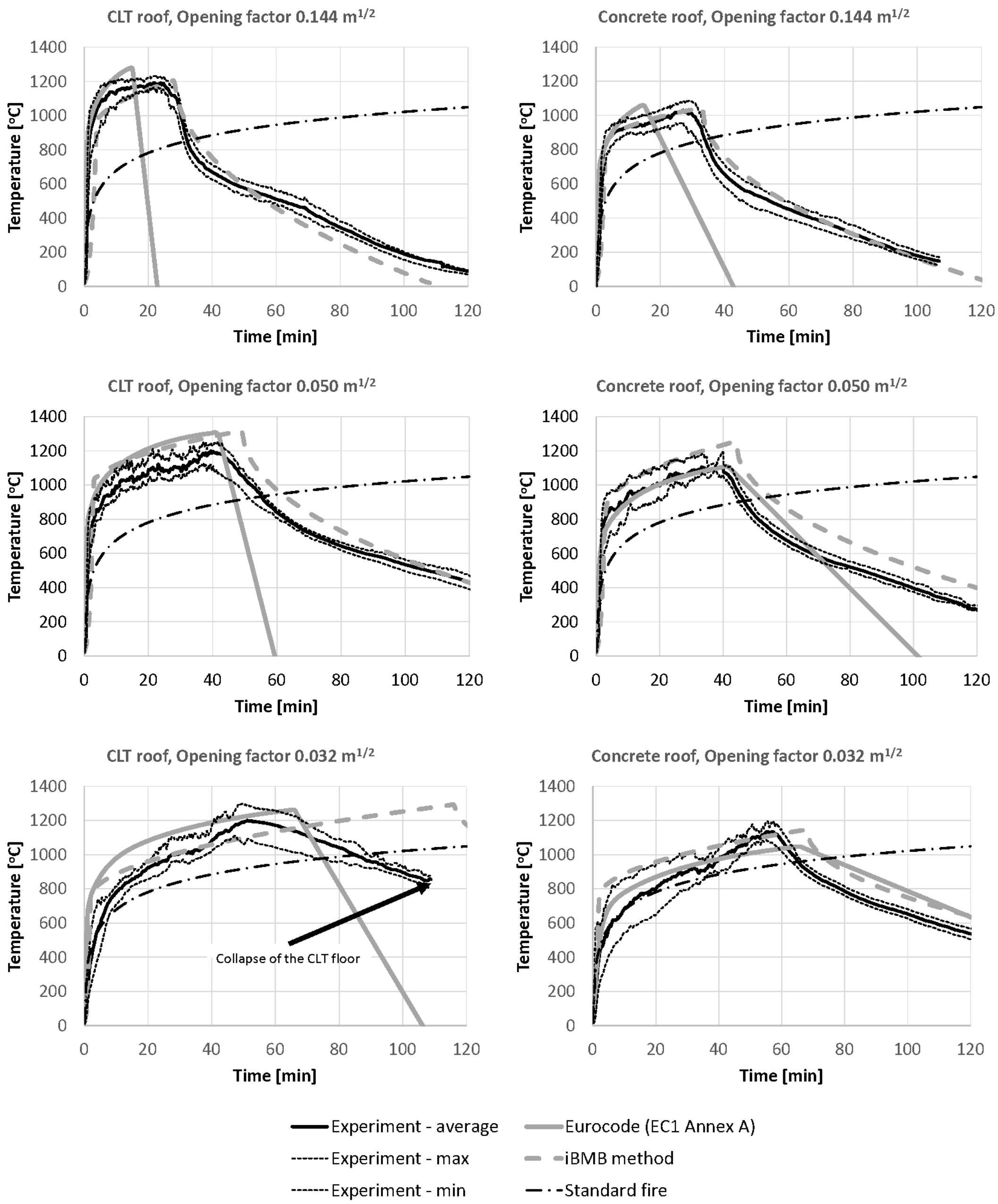


Figure 4. Average, maximum, and minimum temperatures of the 15 plate thermometers mounted 100 mm beneath the slabs' soffits, compared against calculations according to the EN 1991-1-2 and iBMB parametric fire models.

Figure 5 compares the length of the growth phases and maximum temperatures measured during the experiments with the results from calculations. The maximum temperatures recorded in the experiments were considerably higher than suggested by the work of Thomas and Heselden[21] that was used to design the experiments (shown in Figure 3). In the CLT experiments the maximum temperature was 200 to 440 ºC higher than during the concrete experiments, 110 to 280 ºC higher. Also, Scenario 2 was predicted to reach highest temperature based both on the data from Thomas and Heselden[21] and according to the two models used, however this was not the case during the experiments. In the experiments the maximum temperatures for CLT were about 1200 ºC for all three scenarios. The corresponding temperatures in the concrete experiments ranged between 1031, 1108, and 1136 ºC for scenarios 1, 2 and 3. The reasons for this difference in maximum temperatures compared with Thomas and Heselden[21] are not presently known.

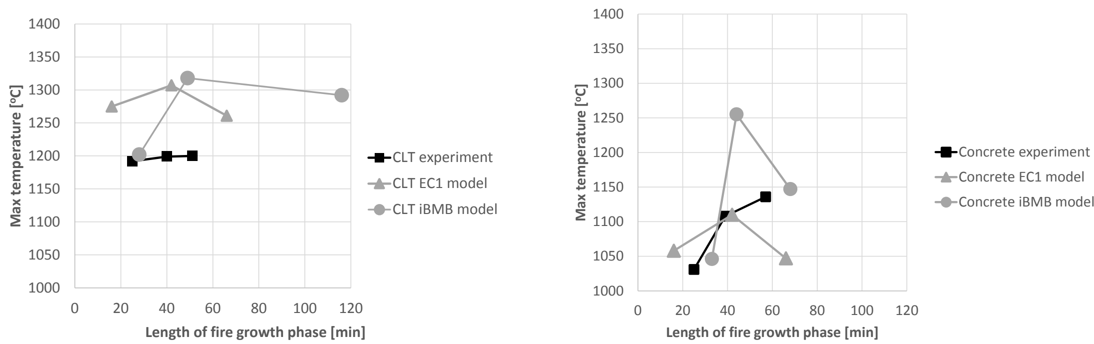


Figure 5. Summary of maximum temperatures and durations of the fire growth phases during experiments and predicted by models. Each series includes from left to right scenarios 1, 2, and 3.

Calculations with the EN 1991-1-2 model

According to the EN 1991-1-2 calculations, the fire with opening factor of 0.144 $m^{1/2}$ was fuel-controlled and the other opening factors, 0.050 and 0.032 $m^{1/2}$, were ventilation-controlled. A summary of the comparison between calculations with the EN 1991-1-2 parametric fire model and the experiments is given in Table 3.

Table 3. Comparison between temperatures calculated with the EN1991-1-2 parametric fire model and average temperatures from measurements.

Opening factor [$m^{1/2}$]	**CLT slab (calculation not including extra energy contribution for burning ceiling)**	**Concrete slab**
0.144	Calculated temperatures higher than the measured temperatures in the fully developed phase. The model underestimates the duration of the growth phase by 36%. The decay phase is too rapid in the model.	Calculated temperature higher than the measured temperatures in the fully developed phase. The model underestimates the duration of the growth phase by 36%. The decay phase is too rapid in the model.
0.050	Calculated temperatures 100-200ºC higher than the measured temperatures in the fully developed phase. Duration of fully developed phase correlates but decay phase is too rapid in the model.	A good correlation between calculated and measured temperatures during the fully developed phase. Minor deviation in shape of the decay phase curve.
0.032	Except in the end of the fully developed phase, temperatures 100-200ºC higher in calculation compared with measurements. In the model the duration of fully developed phase is slightly longer, and the decay phase is more rapid.	A reasonable correlation of temperatures in the fully developed phase although a slight overestimation by the model in the early stages and a slight underestimation in the final stages. A longer fully developed phase in the calculations but a similar decay phase rate.

Calculations with the iBMB model

Generally, the modified iBMB model was able to reproduce the temperature-time development of the experiments reasonably well. But in Scenario 3 (O = 0.032 $m^{1/2}$) the maximum temperature of the CLT calculation was higher and the time of maximum temperature was overestimated. It appears that for the highly under-ventilated fire the simplified approach of adding a linear burning rate of the timber additionally to the moveable fire load leads to an overestimation of the total consumed fire load. For these cases an appropriate approach has to be developed. A summary of the comparison between calculations with the iBMB parametric fire model and the experiments is given in Table 4.

Table 4. Comparison between temperatures calculated with the iBMB model and average temperatures from measurements.

Opening factor [$m^{1/2}$]	**CLT slab (calculation including extra energy contribution for burning ceiling)**	**Concrete slab**
0.144	Calculated temperatures in reasonable agreement with measured temperatures. The model also has a reasonable agreement concerning the duration of the fully developed phase and the decay phase.	Calculated temperatures in reasonable agreement with measured temperatures. The model also has a reasonable agreement concerning the duration of the fully developed phase. The model over-predicts the rate of decay.
0.050	Temperatures 100-200ºC higher in calculations. Duration of fully developed phase longer in calculations and decay phase is in reasonable agreement.	Temperatures 50-100ºC higher in calculations. Duration of fully developed phase correlates. The rate of decay in reasonable agreement.
0.032	A reasonable correlation of temperatures in the fully developed phase although a slight overestimation by the model in the early stages and a slight underestimation in the final stages. The model over-estimates the duration of the fully developed phase and the decay phase.	Except in the end of the fully developed phase, temperatures 100-200ºC higher in calculation compared with measurements. The model slightly over-predicts the length of the fully developed phase, rate of decay in reasonable agreement.

ANALYSIS

As expected, the presence of a combustible ceiling with different thermal inertia influences the temperature development in a compartment fire. In Figure 6 the average temperatures measured by plate thermometers from the experiments with either a combustible CLT ceiling or a non-combustible concrete ceiling are compared. The largest difference is seen in the experiment with the largest opening factor where the difference is around 200 ºC during the fire growth phase. Measurements with ordinary shielded thermocouples placed in parallel with the plate thermometers are also included. During the heating phase the temperature difference was highest for the fuel-controlled fire, Scenario 1. This is likely because the heat release rate in the enclosure was higher due to burning of the ceiling in this case, and because a wooden ceiling absorbs/transfers less energy than a concrete ceiling. During the ventilation-controlled experiments, i.e. Scenarios 2 and 3, the differences in temperatures are less dependent on differences in the ceilings' thermal properties. During these experiments the extra energy added from the CLT appears to have resulted mainly in more severe external flaming[20]. Also, the measurements made with shielded thermocouples (that are not directionally dependent as the plate thermometers) corroborates this hypothesis. In general, the temperatures measured with plate thermometers and ordinary shielded thermocouples were very similar in the fire growth phase, the only significant difference being the first few minutes when the plate thermometers are slower to react, as expected. In the decay phase, differences between the two ways of measuring temperature are highest for the concrete slab experiment with the largest opening factor, again as expected.

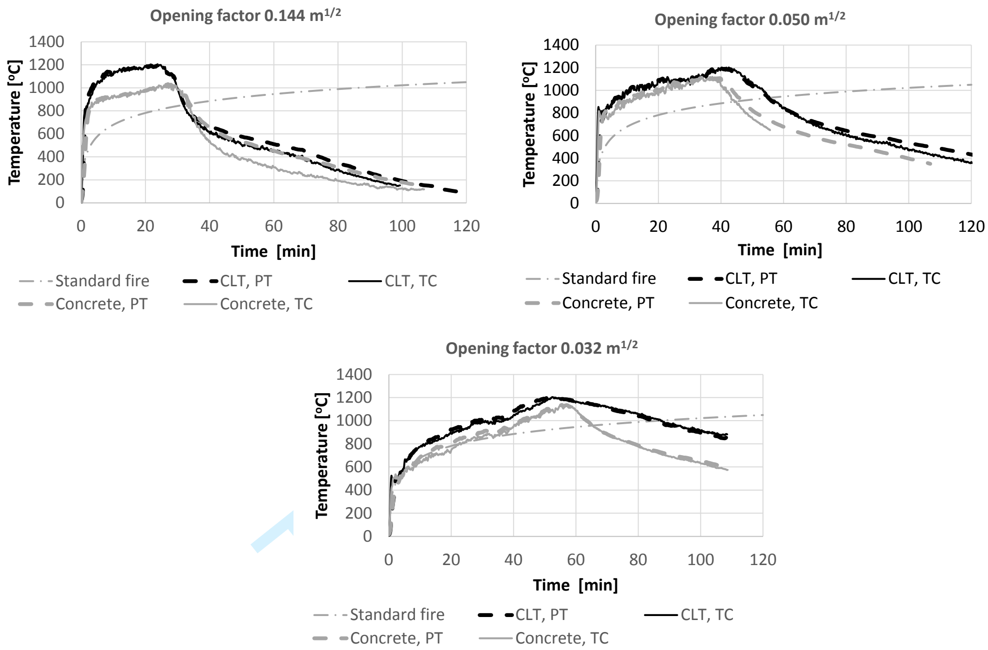
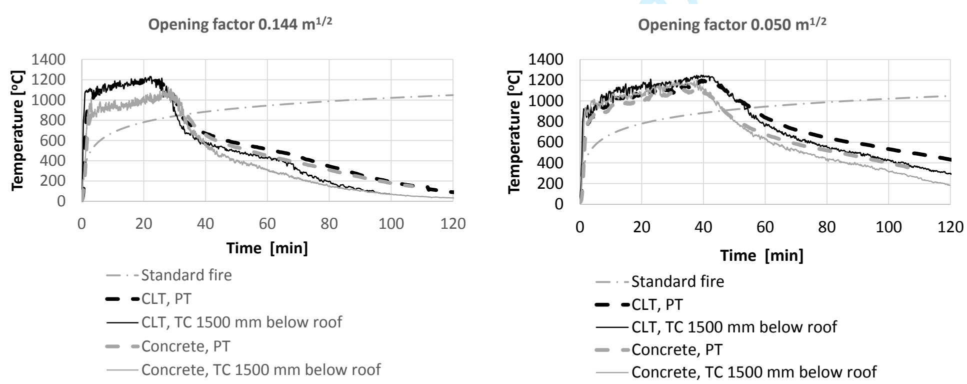


Figure 6. Average temperatures recorded by plate thermometers (PTs, looking *down*) and shielded thermocouples (TC) placed 100 mm below the surface of the ceiling.

The main focus of the comparisons shown in Figure 6 is the temperatures to which the ceilings i.e. load bearing structure were exposed. Figure 7 compares the temperatures measured with plate thermometers 100 mm below the ceiling against those measured in the middle of the room at 1500 m below the soffit. The difference between these two measures in the growth phase are in general small and the temperatures measured in the middle of the room are inside the span of temperatures that was measured with plate thermometers under the ceiling (compare with Figure 4). The only exceptions in the growth phase are between 10 and 33 minutes of the experiment on concrete with the smallest opening factor, where the temperature in the middle of the room was about 200 degrees higher than as measured by the PTs.



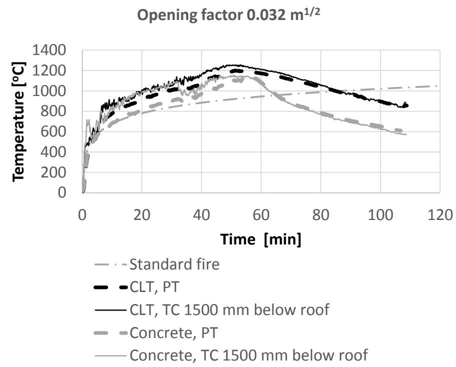


Figure 7. Average of plate thermometers (PT) and shielded thermocouples (TC) placed in the centre of the compartments at 1500 mm from the slabs' soffits.

When comparing the temperature development measured in the experiments with calculations based on the Eurocode 1-1-2 model, the model overestimates the temperatures for the CLT experiments. This overestimation of the temperature development is somewhat surprising on the basis of the available literature and validation of the Eurocode parametric fire model. However, in previous work by Hakkarainen[22] with an opening factor of 0.042 $m^{1/2}$, an over-estimation of the temperatures in a compartment with ceilings and walls made of laminated timber was between 300 and 500ºC. During these experiments it was estimated that 50% of the burning took place outside the compartment, which indicates an elevated pyrolysis rate inside the compartment.

The approach of considering the additional fire load of timber by imposing an increased burning rate with the modified iBMB model led to reasonable predictions in terms of maximum temperatures and durations of the fully-developed phases. For the most under-ventilated case the duration of the fully-developed phase was overestimated for the CLT slab. A simplified approach of considering the additional fire load by imposing a linear charring rate therefore requires additional research. A difficulty with this approach is also that the additional fuel generated from pyrolysis of the combustible ceiling appears to have burned outside the compartment, and therefore did not lead to significant extension of the duration of the fully developed phase.

An additional factor that must be estimated during real fires is the combustion efficiency, this being the ratio between the heat of combustion in practice to the heat of combustion with perfect combustion. This depends primarily on the material burning and the availability of oxygen for the combustion reaction – with reduced oxygen (as in a compartment fire) incomplete combustion will occur, and the combustion efficiency decreases. A constant combustion efficiency of 0.8 was assumed for all opening factors for calculations with EN 1991-1-2. This introduces a potential error, since the stoichiometry can be expected to change with different opening factors and throughout a fire. When comparing the length of the fully developed phase for the under-ventilated fires with opening factors of 0.050 and 0.032 $m^{1/2}$ it is evident that the model with a combustion efficiency of 0.8 reasonably predicts the length of the fully developed phase for the 0.050 $m^{1/2}$ fire, 3 minutes difference, but overestimates the length of this phase in the 0.032 $m^{1/2}$ fire. The latter being a difference three times higher, 9 minutes. This might be due to the fact that the 0.032 $m^{1/2}$ fire is more severely under-ventilated, which would be expected to reduce the combustion efficiency. The reasonable fit of the length of the curves for the opening factor 0.050 $m^{1/2}$ suggests that the EN 1991-1-2 model may be calibrated to a combustion efficiency close to 0.8. To illustrate the effect of different values of assumed combustion efficiency on the length of the fully developed phase, calculations with combustion efficiencies of 0.7 to 0.9 are included in Figure 8. A change of combustion efficiency of 0.1 corresponds to a change in fuel load of about 12.5% for the scenarios considered in this paper.

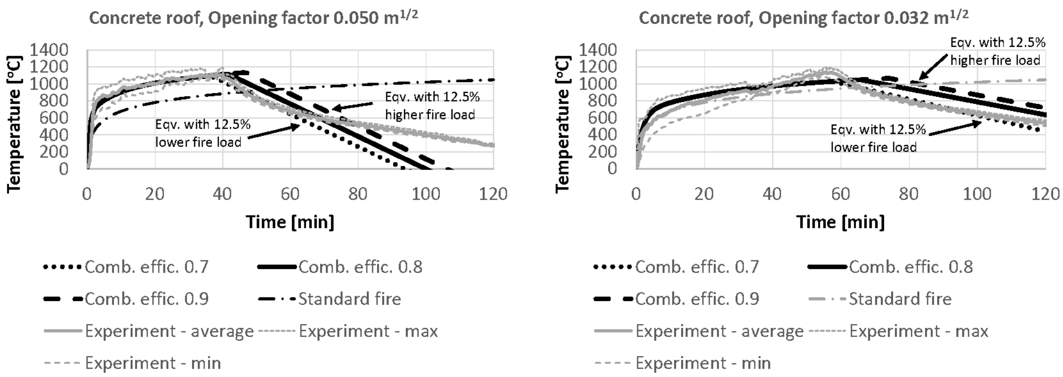


Figure 8. Influence of assumed constant combustion efficiency in the EN 1991-1-2 model.

During the initial calculation of the two fuel-controlled experiments, the opening factor 0.144 shown in Figure 4, fire growth rate "fast", was used as input parameter for the Eurocode model. This assumption was based on the use of 18 litres of heptane as the ignition source, but Table E5 in the Eurocode gives a fire growth rate of medium for dwellings. In Figure 9, calculations with both fast and medium fire growth rate are shown. When using medium fire growth rate the predictions corresponds better to the data in the growth phase, however both assumptions predict fire durations that are too short. This deviation is known from previous studies, and was one of the original reasons for developing the iBMB model[15] which is now required by the German National Annex to the Eurocode[16].

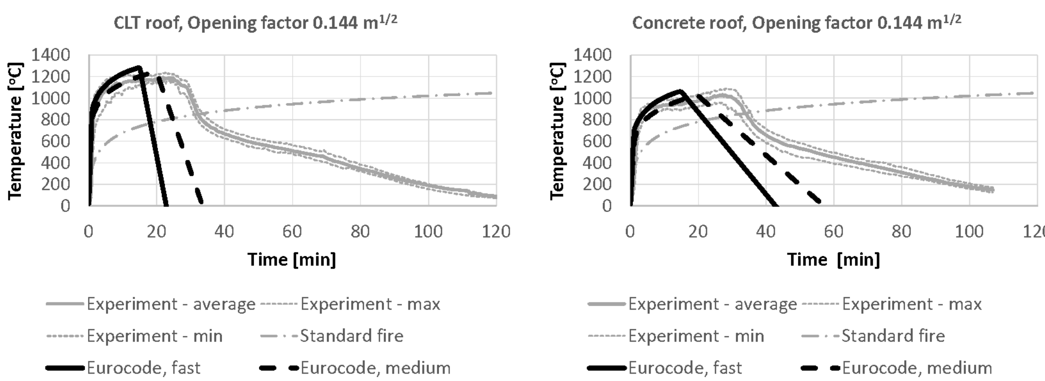


Figure 9. Influence of the choice of fire growth rate on the predictions from the EN 1991-1-2 model.

CONCLUSIONS

A series of compartment fire experiments has been performed with a range of opening factors and either a combustible (CLT) or non-combustible (reinforced concrete) loadbearing ceiling. On the basis of the data and models presented and discussed in this paper, the following conclusions can be drawn:

- The introduction of a combustible CLT ceiling can lead to higher temperatures in a fire compartment than a corresponding fire compartment with a reinforced concrete ceiling. When the compartment fire was fuel-controlled, with opening factor 0.144 $m^{1/2}$, the temperature in the experimental study was around 200 ºC higher in the fire growth phase. In the ventilation-controlled cases, opening factor 0.050 and 0.032 $m^{1/2}$, the difference between CLT and concrete ceilings was largest in the decay phase with a difference of 150-250 ºC.
- During the investigated circumstances the EN 1991-1-2 parametric fire model overpredicted the gas phase temperatures for compartments with combustible ceilings during the growth phase of ventilation-controlled fires. In the decay phases the converse was true, and the EN

1991-1-2 parametric fire model predicted substantially lower temperatures then those measured in the gas phase. As should be expected, the temperature predictions were better for the cases with non-combustible ceilings during both the growth and decay phases.

- The iBMB model, modified in a simplified manner to account for combustion of the ceiling, gave reasonable predictions for both concrete and CLT ceiling cases during the fire growth phase, but overpredicted the duration of the fully developed phase for CLT in the ventilation-controlled cases due to the simplified approach considering the burned timber as additional fire load.
- According to Thomas and Heselden[19] the maximum temperatures measured during the experimental studies were expected to have been measured for Scenario 2, with an opening factor of 0.050 $m^{1/2}$ which, in theory is closer to stochiometric combustion than scenarios 1 and 2 (opening factors of 0.144 and 0.032 $m^{1/2}$). This expectation was not realised during the experiments, since maximum temperatures for all three experiment with CLT ceilings were around 1200 ºC and temperatures for the concrete ceilings were highest for Scenario 3 (opening factor 0.032 $m^{1/2}$).
- Whilst not a novel conclusion, the data presented in this paper confirm that parametric models for compartment fire dynamics in compartments that have exposed mass timber (at any point during the fire) must explicitly consider the contribution made by the combustible compartment linings. Such models are under development in the framework of the Eurocode 5 revision.

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