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SAFETY

Wind effect on internal and external compartment fire exposure

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Abstract

Wind effect on compartment fires

Changes of buildings regulations regarding the allowable height of mass timber structures in North America have been proposed. The proposed changes are to a significant extent based on real scale fire experiments of compartments that have been performed in laboratories in which the influence of wind is negligible. It has, however, been questioned whether the proposed regulations are relevant for realistic scenarios with external wind loads acting on the building during a compartment fire.

The study discussed in this report involves a review of previous literature, analysis of available test results and single zone modeling to study potential effects of external wind on the internal and external exposure of fires in compartments with exposed CLT.

Key words: CLT, wind, fire, mass timber, tall timber buildings

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Content

Preface

The study discussed in this report was performed in assignment of the American Wood Council and the Canadian Wood Council. The research is performed at RISE in Sweden.

1 Introduction

The development of cross laminated timber (CLT) has resulted in an increase of multi-storey timber buildings in multiple countries. Recently, changes of buildings regulations regarding tall mass timber structures in North America have been proposed. The proposed changes are to a significant extent based on real scale fire experiments of compartments that have been performed in laboratories in which the influence of wind is negligible. It has, however, been questioned whether the proposed regulations are relevant for realistic scenarios with external wind loads acting on the building during a compartment fire.

The effect of wind on fires in tall mass timber buildings with exposed timber surfaces inside the compartment was studied, as is discussed in this report.

This report includes a review of relevant studies, analysis of available experimental data and single zone modeling to indicate the effect of external wind on the external and internal exposures of a compartment fire.

2 Background

An experimental study of fires in compartments made of CLT was performed recently (Zelinka et al. 2018). The study included five fire tests (denoted A1-A5) of compartments with inner dimensions of 30 ft x 30 ft x 9 ft (9.1 x 9.1 x 2.7m). The fire compartments were part of a larger structure, as can be seen in Figure 1. The fire load comprised of typical apartment furniture with an average fuel load density of 550 MJ/m^2. Three of the five compartments, A1 to A3, had two (window) openings of $17.8m^2$ or 182 ft^2. The other two compartments, A4 and A5, had closed windows of the same dimensions and had sprinklers installed. The compartments had different quantities of exposed CLT, as indicated in Table 1. The opening factor given in the table was calculated using:

$$O = A_o \sqrt{H_o} / A_t$$

Where, A_o and H_o are the area and height of the opening and A_t is the total area of the boundary surfaces.

175mm thick CLT consisting of five 35mm thick plies were used for all load-bearing members. It should be noted that the CLT adhesive used in these tests complies with the 2016 version of ANSI/APA PRG 320, but does not comply with the stricter fire-performance requirements of the most recent (2018) version of the ANSI/APA PRG320. The fires in the sprinklered compartments (A4 and A5) extinguished the fire and avoided flashover, despite the intended delay of sprinkler activation in test A5. The fires in compartments without sprinklers involved flashover, but the fire decayed and finally the flaming combustion seized.

Figure 1: Compartment fire test after flashover (Hasburgh et al., 2018)

Table 1: Overview of compartment tests by Zelinka et al. (2018)

Test	Floor area of ignited comp.	Ventilation opening area of ignited comp.	Opening factor ($m^{1/2}$)	Thickness and type of gypsum board protection (exposed layer last)	Sprinklers	Movable fire load density (MJ/m^2)	Extinguishment
A1	82.8m^2 or 900 ft^2	17.8 m^2 or 192 ft^2	0.105	All surfaces: 2 layers of 15.9mm Type X	Not installed	550 (MJ/m^2) Furniture	Self-extinction
A2				30% of the ceiling exposed; Other surfaces: 2 layers of 15.9mm Type X	Not installed		
A3				66% of two walls exposed; Other surfaces: 2 layers of 15.9mm Type X	Not installed		
A4		17.8 m^2 or 192 ft^2 window closed	0.105 window closed	None	Auto-activation		Extinguishment by sprinkler
A5				None	Manually activated after 20 minutes		

Changes of regulations regarding the maximum surface area of CLT exposed and the amount of gypsum board protection and requirements for adhesive performance have been based on this study and other studies. It has, however, been questioned whether these results are valid for scenarios in which wind acts on the compartment externally.

3 Scope

This study aims to assess the influence of wind on fire conditions inside the compartment and exterior flames from openings in compartment fires. Post-flashover fires in compartments with openings on one side have been considered. The effect of wind from one direction and wind from changing directions on the external fire plume are of interest for this study (Figure 2). This study does not consider combustible façade systems. The effect of wind on combustible façade systems is recommended for further research.

The effect of an increased or reduced air flow into and out of a compartment after flashover (Figure 2), as a potential result of wind, is studied using a single zone model. A prediction of the damage caused by the fire is made using the single zone model. Additionally, previous tests and CFD simulations are reviewed.

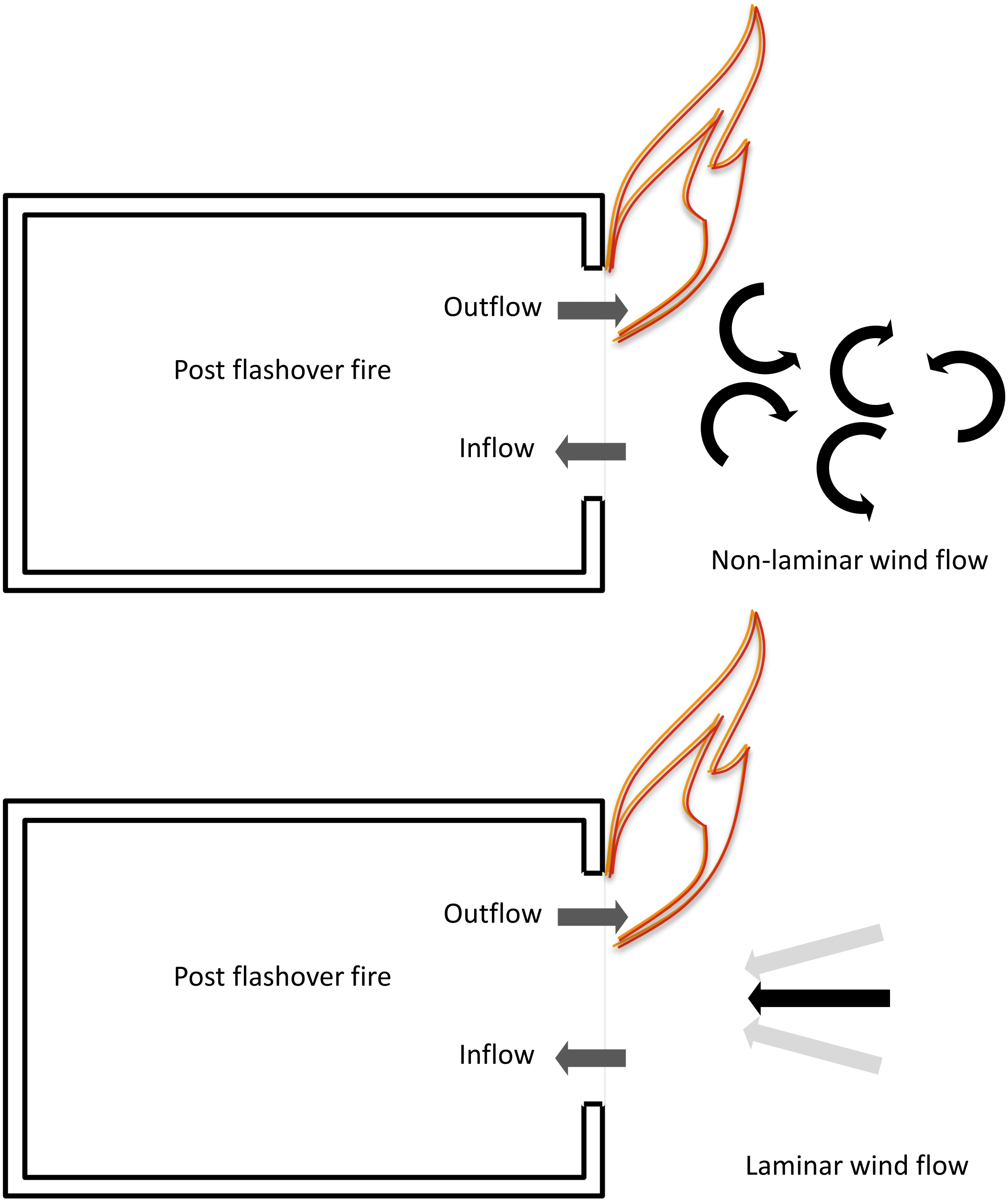


Figure 2: Wind exposure on compartment fires

4 Influence of wind on the external fire plume

This report includes a review of literature and analysis of outdoor fire tests to study the influence of wind on the fire plume exposure on façades. Combustible façade systems are not within the scope of this report.

4.1 Literature review

The number of studies found regarding wind-effect on compartment fires and corresponding external fire plumes is limited to mostly CFD studies and small-scale compartment tests in an environment with controlled air velocity. The studies all considered ventilation-controlled fires in compartments with one ventilation opening and wind exposed to the façade with the opening. The conclusions of these studies are in line with each other:

- The height of external flaming reduces as the wind increases (while the neutral plane lowers and the flames spread wider either side of the opening).
- For the same heat release rate an increased wind speed seems to reduce the gas temperatures both internally and externally.
- The addition of external wind load reduces the maximum temperature gas temperatures of a compartment fire if the heat release rate stays the same.

The reduction of the flame height out of ventilation opening was visualized by Hu et al. (2017) and Zhao (2017). Hu et al. (2017a) performed CFD analyses of compartments with external wind load and performed compartment fire tests in environments with a controlled air velocity and direction. Zhao performed CFD analyses of compartments with external wind from angles parallel and perpendicular to the plane of the opening. The studies both indicated that external wind reduces the height of the external fire plume if the wind was perpendicular to the plane of the opening. According to Zhao (2017) the outflow of unburned combustible gasses is increasingly hindered with increasingly high velocities, leading to a reduced flame height (Figure 3). This is not the case if the wind is parallel to the plane of the opening and he mentions that sideways wind velocities increases the risk of sideways fire spread. It was, however, seen that the footprint of elevated temperatures exposed on the façade reduced with increasing wind speed (Figure 4) for a wind direction parallel to the façade with the opening.

Experimental studies of compartment tests exposed to velocity-controlled external wind were published by Ren et al (2018). Ren et al. performed small-scale compartment fire tests in airflows controlled using a wind tunnel. A matrix of thermocouples was used to determine numerous temperatures at different heights above the compartment opening and at different distances from the façade. It was shown that the maximum temperatures decreased with an increasing wind velocity from 0 m/s to 2.0 m/s (or 0 mph to 4.5 mph). Additionally, the height at which elevated temperatures were measured, reduced with increasing wind velocities.

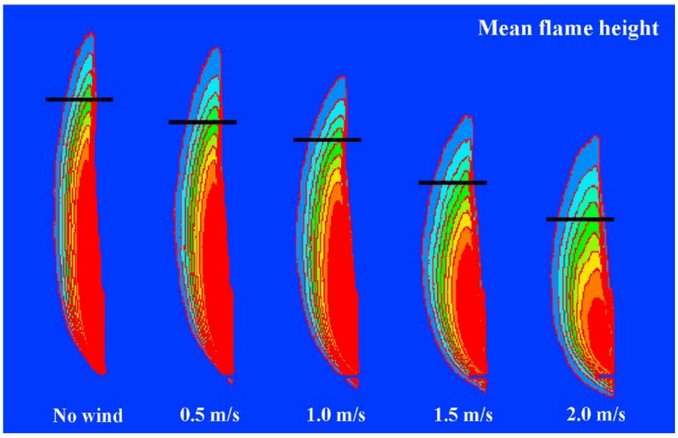


Figure 3: Mean external flame height depending on wind perpendicular to the façade opening. From Hu et al. (2017a)

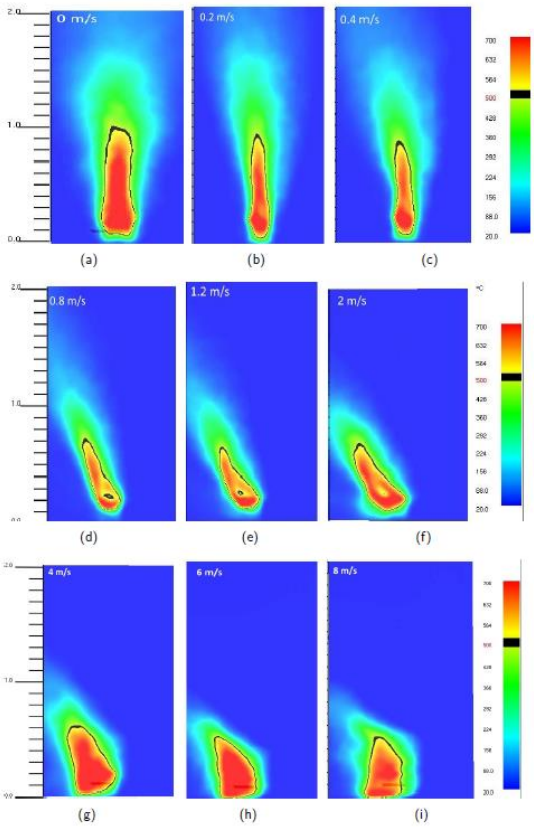


Figure 4: Time averaged temperature contour plots with wind parallel to the façade and wind velocities varying from 0 to 8 m/s (or 0 to 17.7 mph). From Zhao (2017). Figures (a) to (i) correspond to increasing wind velocities.

Previous studies considered constant wind velocities. However, in reality, the wind velocity and even the direction of the wind can fluctuate significantly. In order to evaluate the relevance of previous findings in real scenarios, available data of 2 outdoor façade fire tests are compared with similar indoor façade fire tests.

4.2 Analysis of recent façade fire tests in outdoor environment

A standardized British façade fire test BS 8414 (2015) can be performed indoors and outdoors. For the test results to be valid, the wind velocity should be less than 2 m/s (or 4.5 mph). However, during two demonstration tests (Anderson et al. 2017) the wind velocity was significant. For this study, façade temperatures of the tests reported by Anderson et al. (2017) were compared to temperatures of similar tests without wind. Additionally, the behavior of the external fire plume is studied visually.

BS 8414 uses a compartment with a 400 kg crib of conditioned wood as fuel. During the test, external flaming of the compartment leads to fire exposure on the facade. In order to give an indication of the exposure on the façade for indoor fire tests, the maximum temperatures measured using 8 thermocouples at the façade in a horizontal line 2.5m or 8 ft 2 in above the compartment opening (see Figure 5) were determined for 13 published BS 8414 façade tests (Clark, 2005; Howard, 2015; McIntosh, 2015; Clark, 2015; Clark, 2016; Farrington, 2017; Lalu, 2017; BRE, 2017; Farrington, 2018a; Farrington, 2018b; Lalu 2018; Abukar, 2018). All 13 tested facades were sufficient to meet the approval criteria of BS 8414 and were performed inside fire testing laboratories with negligible wind exposure. Figure 6 shows the range of the temperatures measured in this horizontal line (shown in grey). It can be seen that the temperatures in this line increase comparably for approximately the first 20 minutes of the fire tests. In all 13 indoor fire tests, the highest temperatures were measured in the thermocouple at the center line above the opening or a thermocouple directly next to it.

Results of outdoor BS 8414 tests have been published by Anderson et al. (2017). It should be noted that the external wind load of one of the two tests was not within the acceptable margins set by the British standard BS 8414. The wind velocity of *Test 1* varied between 2 and 5 m/s (4.5 and 11 mph), coming from the N-E direction and the wind velocity of *Test 2* was between 0 and 2 m/s (0 – 4.5 mph), coming from N, N-W direction (see Figure 7). In *Test 2* the wind came from behind the façade, which may have caused turbulence or at least varying wind directions in front of the façade, as evidenced by frequent changes of fire plume direction. Also, in these outdoor fire tests temperatures were measured in a horizontal line 2.5m or 8 ft 2 in above the ventilation opening. The maximum temperatures measured at this line are included in Figure 6. In contrast with the indoor fire tests, the location of the highest temperatures at a horizontal line 2.5 meters above the façade changed regularly, indicating that the direction of the fire plume changed recurrently. The temperatures fluctuated much more significantly as in the 13 indoor BS 8414 fire tests (plotted in grey), indicating a variable height of the fire plumes.

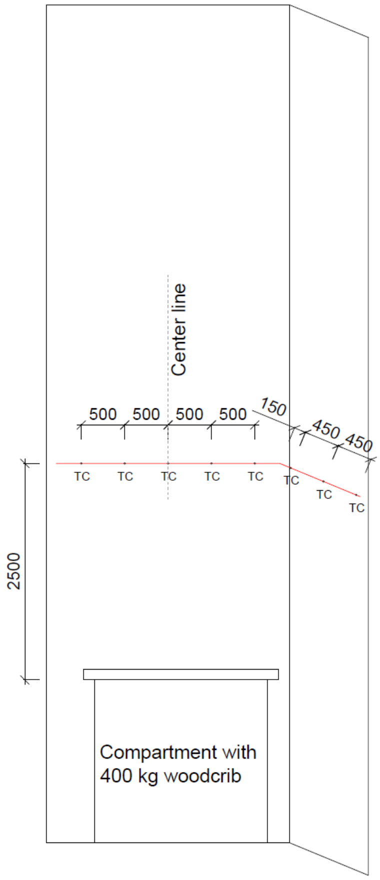


Figure 5: Setup of the BS 8414 test with location of thermocouples (TC) at a level 2.5m or above the opening (Dimensions in mm)

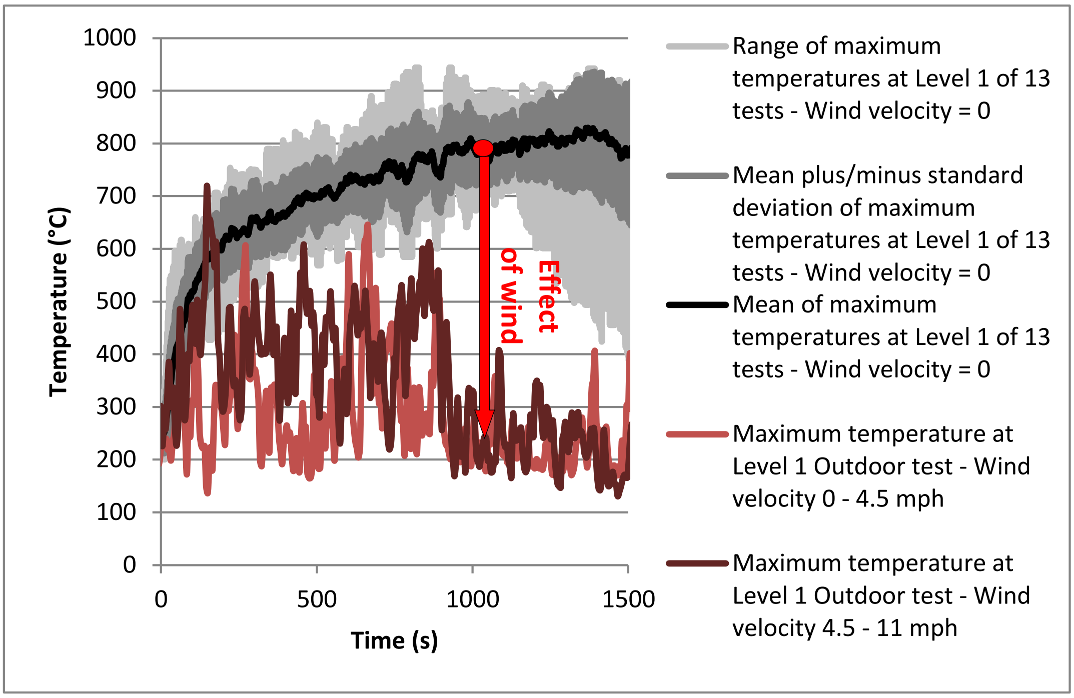


Figure 6: Maximum temperatures of each test measured at a horizontal line 2.5 m or 8ft 2 in above the opening.

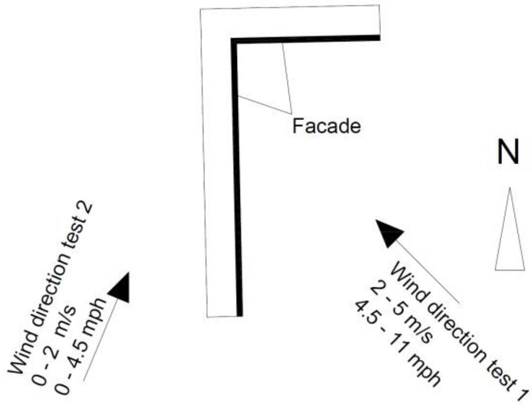


Figure 7: Direction of the wind with respect to the façade (determined from raw data).

In Figure 6 it can be seen that the maximum temperatures measured at the horizontal line 2.5m above the opening were significantly lower throughout the fire tests performed outdoors. This difference is increasingly significant for the first 20 minutes of the fire tests. At 20 minutes the maximum temperatures measured at the line for fire tests with external winds were 400 to 700°C lower than the temperatures measured at the same line during 13 similar indoor fire tests. This indicates that the wind reduced the height of the fire plume. It should be noted that the tests show only two scenarios of wind exposure. Due to the countless combinations of possible wind velocities, wind directions and fluctuations of wind velocities and wind directions, it is not possible to conclude that external wind load cannot increase the height of the fire plume from experimental studies alone. However, the observed reduced height of the fire plumes caused by wind is in line with conclusions of previous research with numerous CFD analyses and compartment fire tests performed in controlled wind conditions.

The effect of wind on external fire plumes of compartments can be studied visually. Fire plumes of indoor BS 8414 fire tests are generally approximately symmetrical and have a peak height approximately above the center of the opening as can be seen in Figure 8. Fire plumes of tests exposed to wind, can change direction frequently if the air flow is not laminar (see Figure 9) and can lower the height of the fire plume. From video evidence it was also seen that the fire plume occasionally in a horizontal direction away from the façade, temporarily missing the façade. There were also brief moments in which the external fire plume completely disappeared. These findings seem to be in line with previous findings by Zhao (2017), Hu et al. (2017a) and Ren et al. (2018).

Figure 8: Typical fire plume during an indoor BS 8414 façade fire test.

Figure 9: Changing directions of the fire plume during an outdoor BS 8414 façade fire test (*Test 2*, Anderson et al. 2017)

Video evidence gives a strong indication of the possible variability of the fire plume size as a result of wind. To give an indication of this variability in this report the shape of the fire plume of *Test 2* is determined graphically for a number of video frames. For a period of 5 seconds, 20 minutes after ignition the size of the fire plume is determined from video frames. The fire plume in each video frame was identified using software (WebPlotDigitizer) that located all pixels within a range of colors that correspond to the fire plume. The same range of colors was used to identify the shape of the fire plume for each video frame. Figure 10 shows the shape of the fire plume with intervals of 1 second. Within the analyzed 5 seconds the fire plume reduced and increased twice, resulting in a difference of fire plume height (measured from the top of the opening) of 400 to 500%.

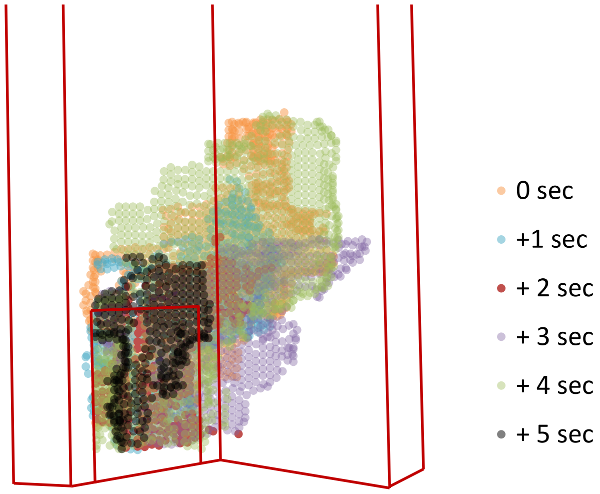


Figure 10: Shape of the fire plume every second for five seconds, 20 minutes after ignition in *Test 2*

4.3 Influence of exposed wood on the external fire plume

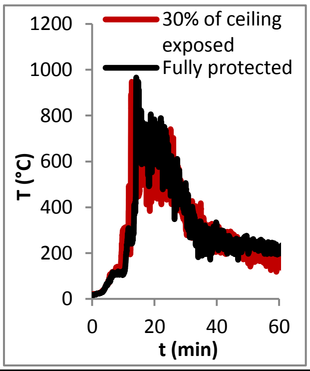
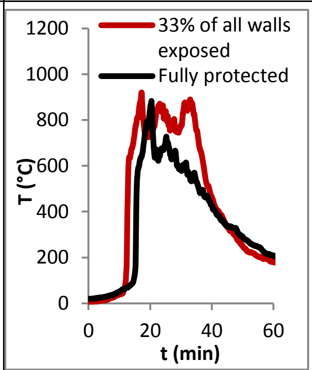
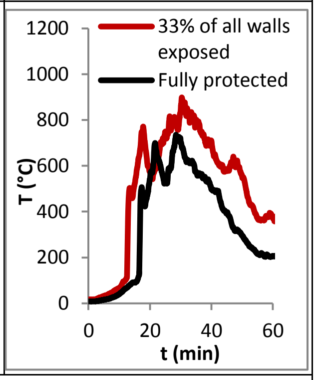
It was previously shown that exposing wood linings or CLT can increase the height of the external fire plume. This was especially apparent in fire tests in which 100% of the wall and ceiling surfaces were exposed and with relatively small window openings and heavily ventilation-controlled fires (Hakkarainen, 2002; Frangi and Fontana 2005; Su et al. 2018). However, the proposed regulations only allow exposing a relatively small percentage of the total CLT surface. In this chapter the temperatures above the opening and the height of the external plumes of relevant fire tests are compared.

Fires in compartments with smaller openings require lower heat release rates in order to achieve a fully developed phase (i.e. the most severe phase of a flashover fire with the highest possible combustion rate inside the compartment) than fires in compartments with larger openings. During the fully developed phase, practically all oxygen that flows into the compartment is consumed. Combustible gasses that do not react inside the compartment due to lack of oxygen can react outside of the compartment. Therefore, the height of the fire plume is dependent on the dimensions of the ventilation openings of a compartment.

In order to assess the effect of relevant amounts of exposed surface areas of CLT on the external exposure, pictures (video frames) of external fire plumes during the fully developed phase are compared in Table 2. Three comparisons of compartments (A, B and C) were included because they involved compartments with surface areas of exposed CLT, which are in line with the proposed regulations. The comparisons A, B and C correspond to significantly different opening factors. The smallest openings (of comparison C) correspond approximately with the minimum allowable window dimensions of 8% of the floor area for a habitable space. Therefore, comparison C corresponds to the most extreme, but unlikely scenario. Differences in flame height are not clearly visible from the photos in Table 2 for comparisons A and B. During a meeting of the International Code Council, the majority of the audience was not able to identify the compartment fire with exposed CLT, based on simultaneously played videos of the external flame of the compartment fire tests of comparison A. The temperatures measured at the façade above the opening for, both, the fully protected and partially exposed compartments, seemed similar as well. Although, the fire plumes of comparison B were similar in height, the intensity of the fire seems higher at the side of the exposed wall of the partially exposed compartment. The temperatures at the façade at a height of 3.5 m were about 100 to 200 °C higher for approximately 15 to 20 minutes. In the extreme case of a small opening (comparison C) a difference can be seen of fire plume height. The measured temperatures at the façade above the opening were increased during most of the fully developed phase, due to the presence of exposed wood.

The comparisons of this section indicate that the presence of the proposed amount of exposed wood does not lead to an increased external fire plume if the opening of a compartment is sufficiently large. For openings corresponding to the smallest allowable windows in habitable space (ICC, 2013) the contribution of timber can lead to an increased fire exposure on the façade.

Table 2: Overview of external exposure data during the fully developed phase of compartment fires with and without relevant exposed CLT surface areas.

	Comparison A: Fully protected versus 30% of ceiling exposed	**Comparison B: Fully protected versus longest 33% of walls exposed**	**Comparison C: Fully protected versus longest 33% of walls exposed**
Reference	Zelinka et al. (2018)	Su et al. (2018a)	Su et al. (2018a)
Compartment dimensions (L x W x H)	9.1 m x 9.1 m x 2.7m Or 30 ft x 30 ft x 9 ft	9.1 m x 4.6 m x 2.7m Or 30 ft x 15 ft x 9 ft	9.1 m x 4.6 m x 2.7m Or 30 ft x 15 ft x 9 ft
Opening dimensions (W x H)	3.7 m x 2.4 m (x 2 openings) Or 12 ft x 8 ft (x 2 openings)	3.6 m x 2.0 m Or 11 ft10 in x 6 ft 7 in	1.8 m x 2.0 m Or 5 ft11 in x 6 ft 7 in
Opening factor	0.105	0.065	0.032
Fully protected compartment (fully developed phase)			
Compartment with exposed CLT (fully developed phase)			
Time of photo after ignition	21 (min)	28 (min)	28 (min)
Temperatures at the facade at 3.5m or 11 ft6in height from the floor			
Note		Delamination of CLT occurred during the tests. As it is currently required to use non-delaminating CLT in North America, the comparisons between temperatures after delamination are irrelevant and are not included in the comparison above.	

5 Influence of wind on the internal exposure

Only a few studies were found that focused on the influence that external wind load has on the fire conditions inside the compartment. This chapter discusses a review of previous research and an analysis using a single zone model to assess the influence of changed ventilation conditions of compartment fires.

5.1 Review of previous research

Hu et al. (2017b) concluded from an experimental study that less heat release rate is required to achieve a (well-mixed) fully developed phase with external wind perpendicular to the plane of the opening. The maximum temperatures inside the compartment are also lower. The results furthermore indicated that, for the same total heat release rate, increasing wind velocity corresponds to a reduction of indoor temperatures.

Klopovic and Turan (2001) performed a series of compartment fire tests in different outdoor wind conditions. The setup of two tests was identical. However, in both tests there was a significant difference in wind velocity and wind direction. Despite this difference, the temperatures and the mass loss rate inside the compartment were nearly identical.

5.2 Single zone model with changed air velocity

Single zone models allow the calculation of fire temperatures based on an equilibrium of mass and energy. The first single zone models have been developed multiple decennia ago (Magnussen and Thelandersson, 1970). The single zone model as presented in Appendix A has previously been used to predict the indoor exposure corresponding to tests *A1*, *A2* and *A3* (Table 1). The predictions were made prior to the tests (Brandon 2017a, and Brandon 2017b) and comparisons after the test indicated the accuracy of the predictions (Brandon, 2017c). Figure 11 shows comparisons between the predicted temperatures and heat release rates of compartment fire *Test A2* and the measured temperatures and heat release rate during *Test A2*. The accuracy of the previous predictions is considered sufficient for the current study. The single zone model is based on equilibrium of energy and it is assumed that the temperatures throughout the compartment are homogeneous. Use of the model requires an estimation of the heat release rate corresponding to the combustible content of the compartment. This heat release rate is taken as proposed by Hopkin et al. (2017). As there is an equilibrium of energy flows, the (homogeneous) fire temperatures can be calculated using the single zone model. In order to include the combustion energy corresponding to exposed CLT an iterative calculation was performed of the following calculations: (1) the charring rate as a consequence of the temperature exposure; (2) it's corresponding combustion energy and; (3) a recalculation of the temperature exposure using the single zone model. The principles of the single zone model are summarized in Annex A and used empirical expressions for the heat release rate corresponding to combustible content of the compartment are discussed in Annex B.

For the current study the same model is used as was done for predictions of the tests by Zelinka et al. (2018), but air flow parameters are adjusted to study the influence of a reduced or increased air flow on the indoor conditions of compartment fires.

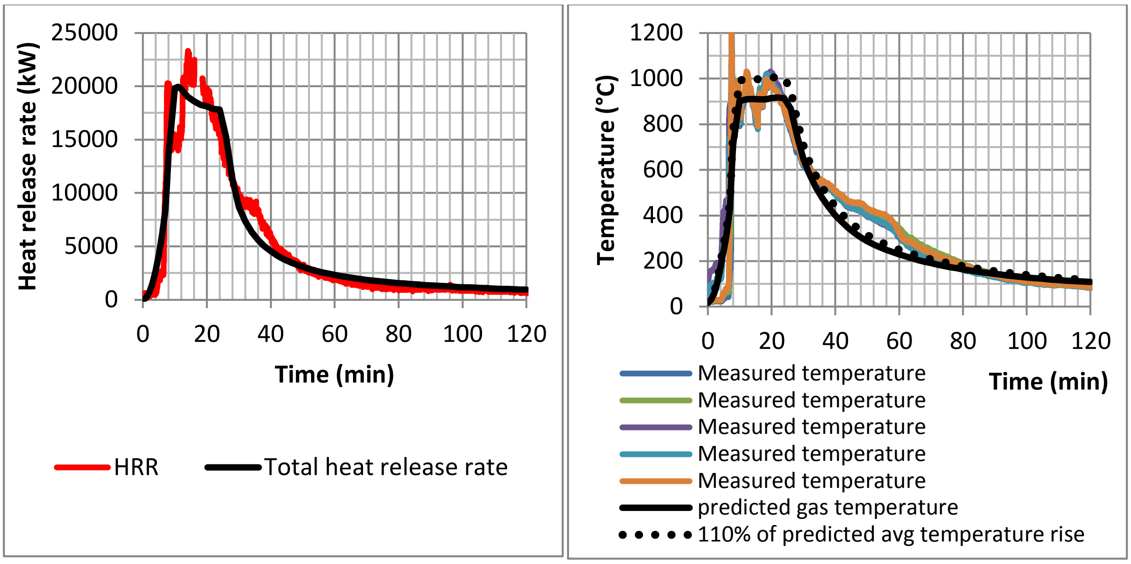


Figure 11: Predicted and measured heat release rate and gas temperatures (Brandon, 2017b) of test A2 (Zelinka et al. 2018)

5.2.1 Modelled compartments

Two different compartments are considered. *Compartment 1* has the same properties and dimensions as *Test A2* (Table 1), including the surface area of exposed CLT. *Compartment 2* is similar, except for the dimensions of the opening (see Figure 12). The dimensions of the openings in *Compartment 2* correspond to the minimum allowable window size for habitable spaces according to Section 402 of the International Property Maintenance Code (ICC, 2013). Small ventilation openings result an increased fire duration and increased damage in comparison with large ventilation openings. Therefore, choosing an opening equal to the minimum allowable window size, should lead to very conservative results. The opening of *Compartment 2* corresponds to an opening factor of 0.048, which is significantly lower than the smallest opening factor of 0.078 found in habitable compartments of a few modern CLT buildings in Europe (Brandon et al. 2018), whereby it was assumed that the windows break during the development of the fire. This indicates the conservativeness of assuming the openings of *Compartment 2*.

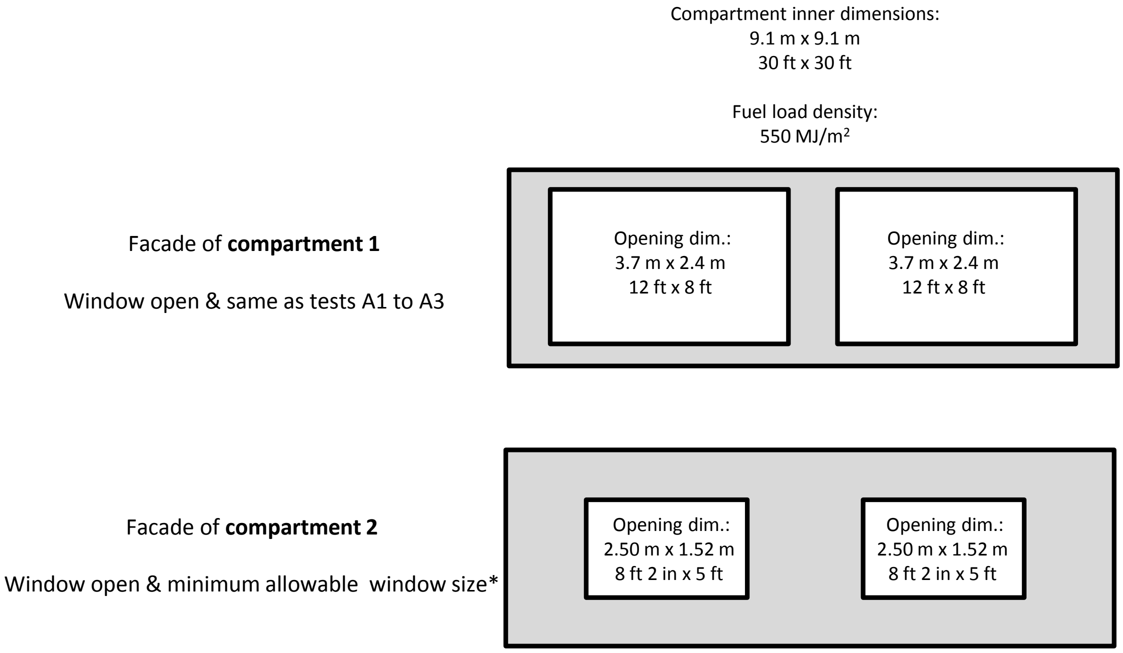


Figure 12: Openings in the façade of *Compartment 1* and *Compartment 2*.

** the opening is approximately equal to the minimum window size in habitable spaces (ICC, 2013)*

5.2.2 Fuel parameters

The same parameters that were used in previous predictions (Brandon 2017a and Brandon 2017b) are used for the current predictions. The fuel load density is 550 MJ/m^2, which is similar to that of the test series by Zelinka et al. (2018), Table 1. The maximum assumed combustion energy of the fuel per surface area (maximum heat release rate density) is assumed to be 190 kW/m^2 which corresponds to the total heat release rate measured in (non-combustible) compartment *Test A1*.

5.2.3 Gypsum board fall-off and CLT delamination

Fall-off of the base layer of gypsum boards and CLT delamination during the hot stages of the fire should be avoided. A recent study by Su et al. (2018b), showed that this can be done for compartments with a small (severe) opening factor, which approximately corresponds to *Compartment 2* of this analysis. This was achieved by using a suitable adhesive and 2 layers of 16 mm gypsum boards and fastening methods specified in the report (Su et al. 2018b). The effect of wind on the falling behavior of gypsum boards is not considered in this study. The effect of possible charring CLT behind the gypsum board is also not considered.

5.2.4 Considered effects of external wind

Only a few studies have previously looked at the internal conditions of a compartment that is exposed to external wind during a fire. The studies are limited to the effect of wind perpendicular and parallel to the façade and a comparison between two random wind conditions of compartments with openings on one side.

CFD simulations by Zhao (2017) indicate that wind can hinder or block the outflow of combustible gasses in a compartment with a ventilation opening on one side and wind perpendicular to the plane of the opening. The reduced maximum temperatures and corresponding heat release rates of compartment fires with external wind according to Hu et al. (2017b) also correspond to a reduced in and outflow of air. Zhao (2017) concluded that this did not occur if the wind was in the direction parallel to the façade. Klopovic and Turan (2000) have performed to similar outdoor compartment fire tests with significantly different wind conditions. They have indicated that the exposure of the external fire plume to the façade was significantly different in both tests. However, the measured mass loss rates and temperatures were almost identical. These findings indicate that wind does not necessarily have an effect on the conditions of a compartment fire.

Hu et al. (2017b) performed fire experiments of small compartments exposed to wind perpendicular to the façade and determined an empirical expression of the heat release rate required to reach a well-mixed state (a state in which the compartment temperatures are approximately similar). Although the well- mixed state is not a synonym of the fully developed state (in which internal combustion cannot be increased due to lack of oxygen), the well-mixed state is regularly used to describe fully developed fires. In order to get a rough indication of the relationship between the external wind velocity (in the direction perpendicular to the façade) and a change of volume flow, the expression by Hu et al. is used.

$$\frac{\dot{Q}_{well-mixed}}{1500A\sqrt{H}} = -0.47U_W/\sqrt{gH} + 1.7$$

Where is the $\dot{Q}^*_{well-mixed}$ heat release rate required for a well-mixed state (kW)

U_W is the external wind velocity

g is the gravitational acceleration (9.8 m/s^2)

A is the area of the opening (m^2)

H is the height of the opening (m)

According to the expression, a wind velocity of 5 m/s or 11 mph perpendicular to the plane of the façade opening leads to a reduction of heat release rate required to reach a well-mixed state of 28% for *Compartment 1* and 36% for *Compartment 2*. In order to get a rough indication of the relationship between external wind velocity (in the direction perpendicular to the façade) and the inflow of air, it is assumed that the reduction of heat release rate required to get a fully developed stage is also 28 and 36%.

It should be noted that previous findings found in the literature are all based on compartments with openings on one side. It is considered possible that the wind increases the air volume flow of a compartment fire if there is a draft, for example in compartments with two opposing openings. Therefore, the effect of both a decrease and an increase of air flow into the compartment is studied.

In the case that the air flow is increased as a result of wind, additional effects could potentially play a role. From tunnel fire tests it is known that an increased air flow can increase the growth rate of fires by a factor of up to 10 (Ingason and Lönnermark, 2010). In compartments it is less likely that the wind has an influence on the fire growth phase than in tunnels, as windows and doors in the façade are commonly closed. However, to study the effect of increased fire growth, scenarios with a fire growth rate of 0.047 kW/s^2 (which was assumed for previous predictions) and 0.47 kW/s^2 were considered for predictions.

In a fuel-controlled fire, the change of air flow does not affect the heat release rate of most synthetic (melting) fuels. It was however seen in tunnel tests that wind can increase the heat release rate of charring fuels such as timber. Ingasson and Lönnermark showed that the heat release rate of porous wood cribs increased up to 70% in wind tunnel tests. It should be noted that the increase of wind in wood cribs can cause flames to spread horizontally, increasing the exposure on the wood and eventually resulting in higher heat release rates. This phenomenon would have less effect if the exposure would be coming from multiple heat sources, which is the case in most compartment fires. In order to get an indication of the effect of an increased maximum heat release rate on the fire damage, scenarios of an unchanged heat release rate and an increased heat release by 70% are considered.

5.2.5 Results and discussion

The predicted char depth after the fire is compared as it can be used as a measure of fire damage. The effects of an increased and reduced airflow into the compartment on the predicted char depth at the end of the fire are plotted in Figure 13. For an increased air flow, additional predictions assuming an increased fire growth rate and an increased heat release rate density of the combustible content (moveable fuel load) were included. The results indicate that the effect of accelerated fire growth and increased heat release rate density on the total char depth after the fire is negligible. Therefore, these effects are not discussed any further.

For *Compartment 1* (with the large opening), the effect of reducing the air flow in the compartment by 40% results in an increase of charring depth of approximately 5 mm. Using an expression by Hu et al. (2017b) and the assumption *that a percentile reduction of the required heat release to achieve a well-mixed compartment fire as a consequence of external wind, is the same as the percentile reduction of the heat release rate needed to achieve a fully developed fire*, it is roughly estimated that an airflow reduction of 30% corresponds to a wind velocity of 5 m/s or 11 mph in the direction perpendicular to the façade/opening. Winds of the same velocity coming from other directions are expected to have less impact on the final char depth.

For *Compartment 2*, which has the minimum allowable window (opening) dimensions, the increase of the char depth is more significant and is approximately 14 mm for a reduction of 40%. It should be noted that the opening factor of the compartment is at the lower (worst case) limit and that this opening factor is significantly smaller than those found in a brief study of modern CLT buildings (Brandon et al. 2018). To get an indication of the structural damage imposed by the fire in this unlikely scenario, the char depth after the fire is compared with an estimated char depth after exposure of a 2 hour standard fire resistance furnace test. In North America tall buildings generally require a 2 hour fire resistance rating. As the char depth gives an indication of the structural capacity, the results indicate that the predicted structural damage is lower than the structural damage imposed in regulatory (2 hour) standard fire resistance tests for tall buildings.

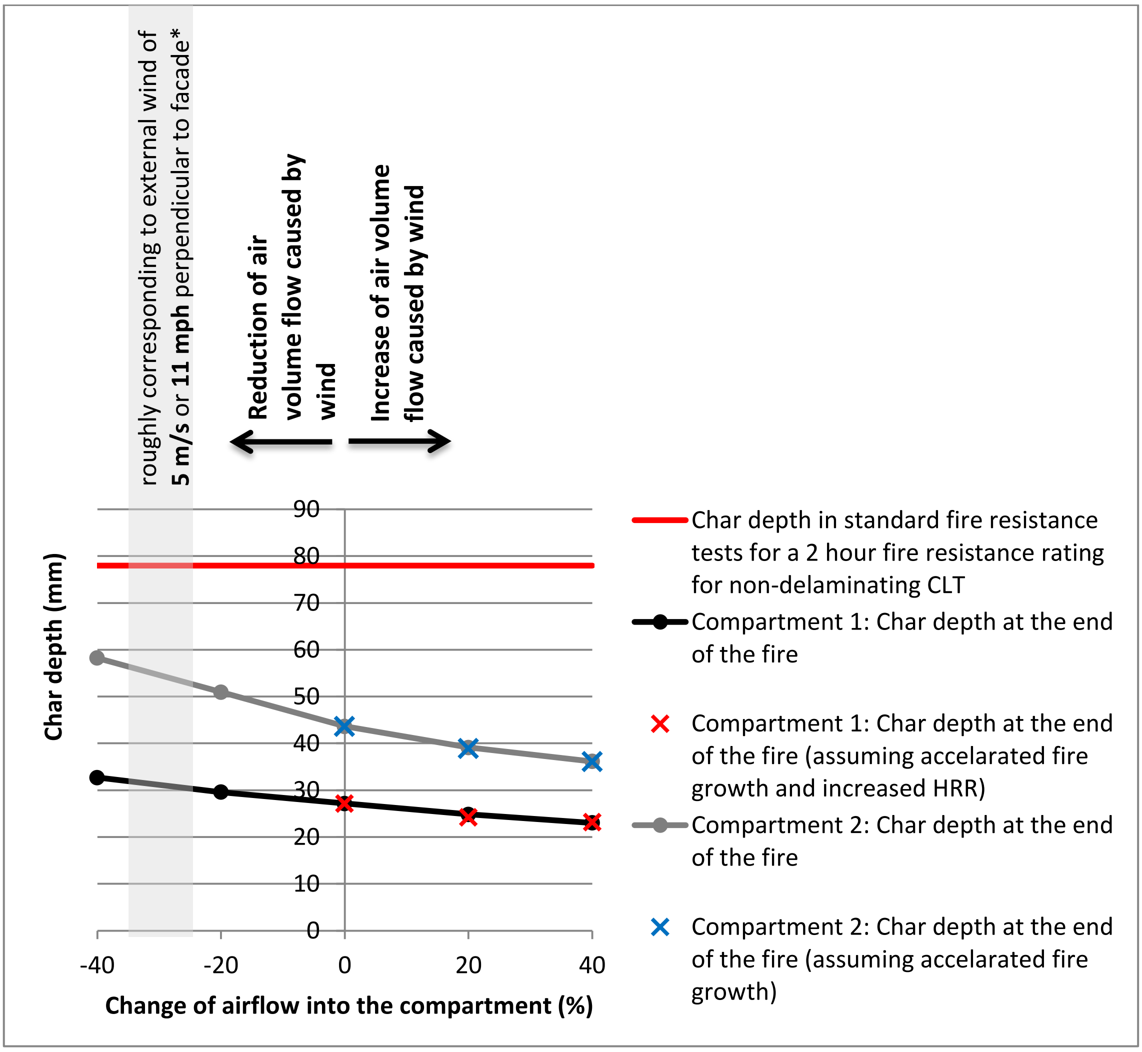


Figure 13: Predicted char depths corresponding to an increase or reduction of air flow into the compartment.

** using an expression by Hu et al. 2017b (corresponding to a compartment with one opening and a wind direction perpendicular to the opening) and the assumption that a percentile reduction of the required heat release to achieve a well-mixed compartment fire as a consequence of external wind, is the same as the percentile reduction of the heat release rate needed to achieve a fully developed fire.*

The change of airflow has a different impact on the temperatures of the two compartments. Due to the small opening, the fire in *Compartment 2* is ventilation controlled after flashover according to the model. In this case an increase of airflow increases the available oxygen in the oxygen-poor environment, which increases the potential combustion energy (heat release rate) inside the compartment. At the same time the convective losses of the compartment increase. However, according to the model the increase of the heat release rate appears to be more significant than the increase of convective heat losses and the predicted temperatures increase for an increasing air flow (Figure 14). Due to the increase of heat release rate, the fuel burns out more quickly and the fire becomes shorter (Figure 16). This explains the lower predicted char depths for increased air flows.

According to the model the heat release rate of the movable content of *Compartment 1* is not enough to consume all incoming oxygen. An increase of airflow into and out of the compartment results in an increase of convective heat losses. Therefore, the increase of airflow resulted in a reduction of temperatures in the compartment (see Figure 14and Figure 15).

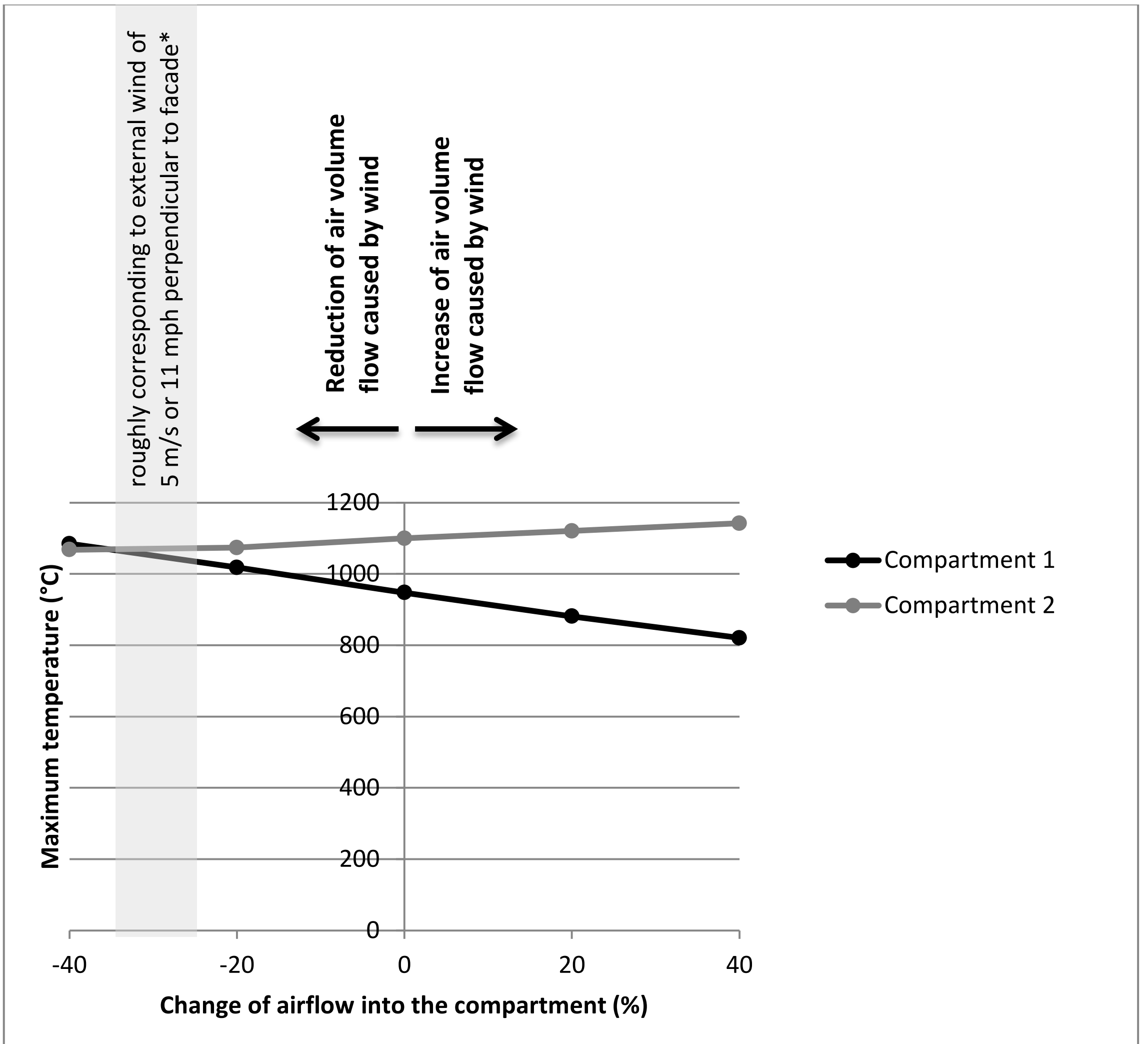


Figure 14: Predicted maximum temperatures corresponding to an increase or reduction of air flow into the compartment.

** using an expression by Hu et al. 2017b (corresponding to a compartment with one opening and a wind direction perpendicular to the opening) and the assumption that a percentile reduction of the required heat release to achieve a well-mixed compartment fire as a consequence of external wind, is the same as the percentile reduction of the heat release rate needed to achieve a fully developed fire.*

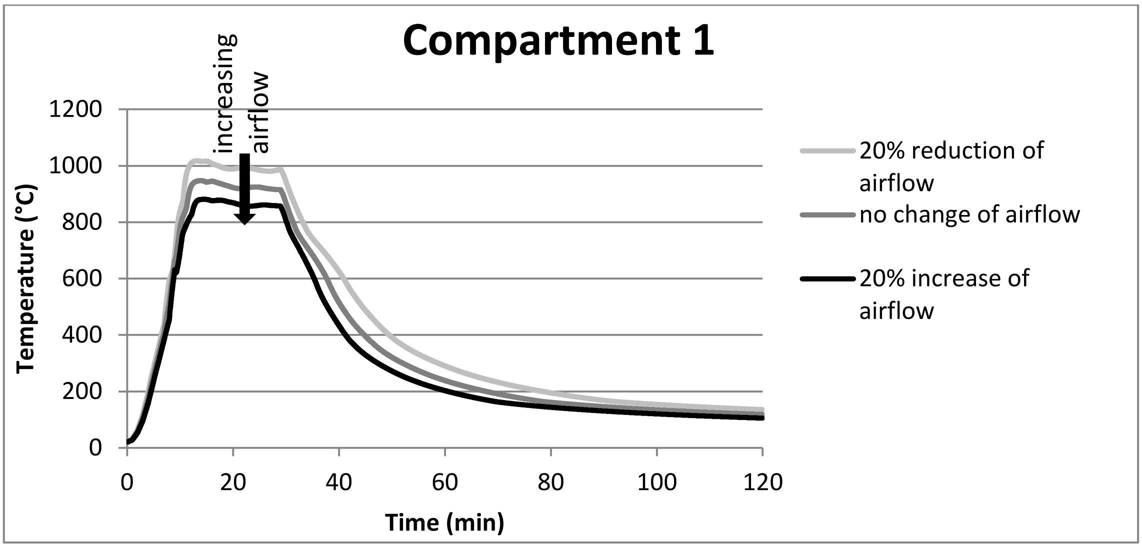


Figure 15: Predicted temperatures corresponding to an increase or reduction of air flow into *compartment 1*.

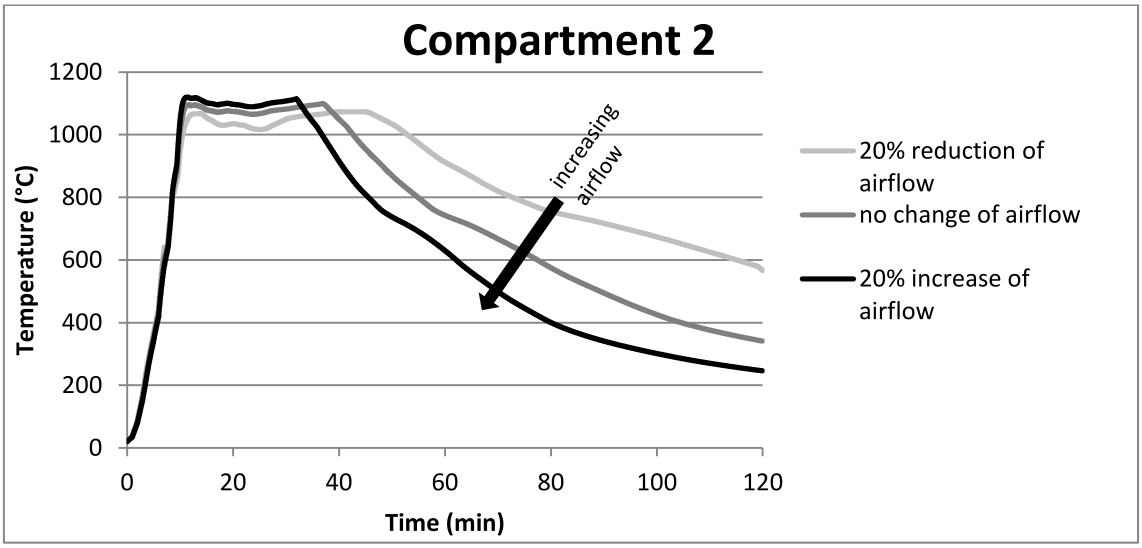


Figure 16: Predicted temperatures corresponding to an increase or reduction of air flow into *compartment 2*.

6 Conclusions

This report summarizes a study that involved a review of relevant literature, analysis of available façade test data and calculations using a single zone model. The study considered a compartment with ventilation openings on one side (in the same external wall) and different external wind conditions. These studies resulted in the following findings regarding external exposure on the façade:

- Previous studies indicate that the height of external fire plumes of ventilation-controlled compartment fires reduce if external wind is exposed on the opening.
- Results of outdoor fire tests performed in different wind conditions indicate a significantly reduced fire plume height in comparison with tests performed without wind.
- Results of outdoor fire tests performed in different wind conditions indicate significant fluctuations of exposure and directions of external fire plumes that are subjected to wind.

Regarding the effect of wind on the exposure inside the compartment, this study resulted in the following findings:

- Previous experiments involving under-ventilated fires in compartments with one ventilation opening and wind exposure in the direction perpendicular to the façade opening has shown a reduction of maximum temperatures inside a compartment as well as a reduction of corresponding heat release rates with increasing wind velocity.
- Previous CFD simulations and experiments indicated a reduction of air flow into and out of the fire compartment as a consequence of wind. It is, however, considered possible that the wind increases the airflow in some compartments if they have openings on more than one side.
- A single zone model that includes the contribution of exposed wood in the calculation of compartment temperatures indicated that the char depth after a complete fire increases for a reduction of airflow into the compartment. The model included the assumption that delamination of CLT and fall-off of the base layer of gypsum board are prevented. The predicted char depths corresponding to a compartment with large openings and a compartment with minimum[1] ventilation openings were, however, significantly lower than char depths corresponding to standard fire resistance test exposure of 2 hours which is relevant for most tall building designs. The damage of compartment fires is expected to be significantly higher if CLT delamination is not prevented.

[1]minimum opening dimensions for habitable space according to current building regulations by the ICC, assuming all windows break during the development of the fire.

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Annex A - Single zone model for compartments with exposed wood

A single zone model based on a previous model presented by Brandon (2016) which was later revised by Hopkin et al (2017) is implemented in the study of the main report. The model was developed to function as a design tool for structural assessment of timber members exposed to natural compartment fires.

The model assumes a well-mixed state, in which the temperatures are similar throughout the compartment. This is generally not valid for the pre-flashover phase and fires in large compartments. However, the main report indicated that the pre-flashover phase had negligible influence on the predicted total damage after the full duration of a flashover fire, as it was shown that the predicted structural damage is relatively insensitive to the assumed fire growth rate. For the purpose of the model it is therefore considered reasonable to simply assume a fire growth rate and a well-mixed pre-flashover phase. The use of the model is not recommended for compartments with a floor area exceeding 500 m^2 or 5400 ft^2, which is in line with standardized calculation methods that also assume a well-mixed state (EN 1991-1-2).

The model involves an iterative calculation of the fuel contribution of the timber. Starting with a given heat release rate curve (heat release rate versus time, which is discussed in Annex B) that corresponds to a flashover fire in compartments with non-combustible lining materials, every iteration involves the following calculations in chronological order:

- calculation of the fire temperature curve (fire temperature versus time) inside the compartment from the heat release rate curve, using a single zone model;
- calculation of the temperatures in the <u>exposed</u> timber structure, using a finite element or finite difference transient state heat transfer model;
- calculation of the temperatures in the <u>protected</u> timber structure, using a finite element or finite difference transient state heat transfer model;
- calculation of the char rates of all timber walls ceiling and floor assuming that timber chars at 300°C;
- calculation of the combustion energy release rate (heat release rate) from the charring rate;
- calculation of the new heat release rate curve by the summation of the heat release rate corresponding to a compartment with non-combustible linings and the heat release rate of the timber. The new heat release rate curve is used for the next iteration.

The iterations should be repeated until the difference between the heat release rate curves of two subsequent iterations is negligible.

In addition to the assumptions generally made using single-zone models, the presented method involves the following main additional assumptions:

- the movable fuel (combustible room content) is sufficient to cause a flashover fire on its own, if it were positioned in a similar compartment with non-combustible linings;
- the combustible gasses that come to exist during heating of timber, combust at or near the moment they come to exist. If there is not enough oxygen inside the compartment, this combustion will take place outside of the compartment and increase the external fire plume. If there is oxygen left inside the compartment, this combustion will take place inside the compartment.

A.1 Single zone model

In the single zone model, a distinction is made between the heat release rate corresponding to the movable fuel load, $\dot{Q}_C$ which is discussed in Annex B, and the heat release rate corresponding to CLT, $\dot{Q}_{C;CLT}$. The heat release rate corresponding to CLT is determined from the charring rate, which is predicted using a heat transfer model. The heat transfer model is also used to determine the heat loss through the CLT compartment boundaries, which is needed for the single zone model, as discussed below.

Due to the law of conservation of energy, there should be an equilibrium of energy. The energy released should, therefore, be equal to the energy lost (hereby the heat energy stored in gasses inside the compartment is neglected):

$$\dot{Q}_C + \dot{Q}_{C;CLT} = \dot{Q}_W + \dot{Q}_R + \dot{Q}_L \qquad \text{eq. A1}$$

Where:
$\dot{Q}_C$ *is the heat release rate corresponding to the movable fuel load*
$\dot{Q}_W$ *is the rate of heat loss through compartment boundaries (floor, walls and ceiling)*
$\dot{Q}_L$*is the rate of heat loss through air flow out of openings in the compartment*
$\dot{Q}_R$ *is the rate of heat loss through radiation out of openings*
$\dot{Q}_{C;CLT}$ *is the heat release rate of the CLT calculated using a heat transfer model*

The maximum heat loss rate due to air flow out of the openings is determined using (Wickström 1986):

$$\dot{Q}_L = \alpha_1(T_f - T_\infty)cA\sqrt{h} \qquad \text{eq. A2}$$

Where:
T_f *is the fire temperature (K).*
T_∞ *is the ambient temperature (K)*

The radiant heat loss rate is determined using (Magnusson and Thelandersson, 1970):

$$\dot{Q}_R = A\left(T_f^4 - T_\infty^4\right)\sigma \qquad \text{eq. A3}$$

Where:
σ *is the Stefan Boltzmann constant.*

The heat loss rate through the CLT boundaries, $\dot{Q}_W$, is calculated using the heat transfer model, discussed in the next section (eq. A6).

The single zone model uses a simple algorithm to solve the fire temperatures. The fire temperature is determined by substituting eq. A2 and A3) into eq. A1 and solving to determine T_f (Brandon, 2016):

$$T_f = \frac{\dot{Q}_C + \dot{Q}_{C;CLT} - \dot{Q}_W - \dot{Q}_R}{c\alpha_1 A\sqrt{h}} + T_\infty \qquad \text{eq. A4}$$

In the calculation, the fire temperature is determined for every time step. At each time step, the values of $\dot{Q}_W$ and $\dot{Q}_R$ are determined and used as an input for the subsequent time step.

For the study discussed in the main paper $\dot{Q}_C$ is determined according to Annex B and $\dot{Q}_{C;CLT}$ is determined iteratively as discussed in the next section.

A.2 Heat transfer in walls, floor and ceiling

The calculation of the contribution of CLT (or other exposed timber linings) $\dot{Q}_{C;CLT}$is determined using a 1-dimensional heat transfer model to predict the heat transfer from the exposed side of the wall to the unexposed side. On both sides the following boundary condition is assumed to account for convection and radiation:

$$q_n = h(T_f - T_s) + \sigma\varepsilon(T_f^4 - T_s^4) \qquad \text{eq. A5}$$

Where:

q_n is the net heat flux through the surface,
h is a convection coefficient,
ε is the effective emissivity,
T_s is the surface temperature.

The used convection coefficient and emissivity are *25* W/m²K and *0.8*, respectively, which are in accordance with EN 1991-1-2 (2002) and EN 1994-1-2 (2004).

Heat transfer/ temperature calculations should be performed for all wall and floor assemblies with different built-ups, including those that have gypsum board protection. The heat transfer calculations are performed for two reasons:

1. determine the total heat loss through the compartment walls, floor and ceiling;
2. determine the heat release rate of the CLT from the charring rate, which is determined from the temperature development in the CLT.

The total heat loss through wall, floor and ceiling assemblies is calculated using:

$$\dot{Q}_W = \sum_{i=1}^{m} \dot{q}_{n;i} * A_i \qquad \text{eq. A6}$$

Where:
$\dot{q}_{n;i}$ *is the net heat flux per surface area through assembly i*
A_i *is the surface area of assembly i*
m is the number of assemblies

Using the char temperature of wood, which is approximately 300°C (Buchanan, 2002; EN1995-1-2:2004), the charring rate during the whole fire can be estimated from the calculated timber temperatures. Results of previous studies (Schmid *et al.*, 2016) have shown a constant heat release rate per millimeter of charring of 5.39 MJ/m²mm. This relationship is hereby used to determine the heat release rate from the calculated charring rate:

$$\dot{Q}_{C;CLT} = \sum_{i=1}^{m} 5.39 * \frac{\dot{\beta}_i}{60} * A_i \qquad (MW) \qquad \text{eq. A7}$$

Where:
$\dot{\beta}_i$ *is the charring rate (mm/min)*
A_i *is the surface area of assembly i* (m^2)

The effective thermal properties of timber (CLT) and the gypsum board used for the predictions in the main text are shown in Table A.1 and A.2. The thermal properties for temperatures in-between the temperature values of the table were linearly interpolated.

Table A.1: Effective thermal properties of CLT material implemented for predictions made for the main report

Temperature (°C)	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m3)
20	0.07	1347	494.6
98	0.06	987	494.6
99	0.73	4006	494.6
120	0.75	6075	494.6
121	0.20	2577	494.6
200	0.67	2300	494.6
250	0.82	3671	460
300	0.24	1936	375.9
350	0.12	4305	257.2
400	0.14	3388	187.9
500	0.15	4472	163.2
600	0.53	7799	138.5
800	0.82	9192	128.6
1220	1.37	9192	1

Table A.2: Effective thermal properties of CLT material implemented for predictions made for the main report

Temperature (°C)	Conductivity (W/mK)	Specific Heat (W/mK)	Density (kg/m3)
20	0.40	960	896
70	0.40	960	896
100	0.27	960	896
130	0.13	14900	829.7
140	0.13	25200	808.2
150	0.13	21700	785.8
170	0.13	960	741.9
600	0.13	960	741
720	0.33	4360	740.1
750	0.38	960	695.3
1000	0.80	960	695.3
1200	2.37	960	695.3

A.3 Calculation procedure

The calculation of the fire temperature, T_f, using eq. A4 requires knowledge of the heat release rate corresponding to the CLT, $\dot{Q}_{C;CLT}$. However, $\dot{Q}_{C;CLT}$ is calculated using T_f as was discussed in section A.2. This problem is solved iteratively, starting the first iteration with $\dot{Q}_{C;CLT} = 0$. In the first iteration, the fire temperatures correspond to the heat release rate of the movable fuel load only. The CLT temperatures and charring rates are determined based on those temperatures. The corresponding heat release rate of CLT $\dot{Q}_{C;CLT}$ is used to calculate the fire temperature in the subsequent iteration. This allows the same process and the calculation of $\dot{Q}_{C;CLT}$ for the second and subsequently third calculations and so forth. The iterative procedure is stopped when the change of $\dot{Q}_{C;CLT}$ in subsequent iterations is negligible.

Annex B – Generation of the heat release rate curve corresponding to a flashover fire in a non-combustible compartment.

The heat release rate (HRR) corresponding to solely the movable fire load (combustible content of the compartment) is required as model input for the single-zone model discussed in Annex B. This information should be based on the fuel type, quantity of fuel and the ventilation condition in the compartment. Examples of methods to generate a suitable heat release rate curve are given by Chen (2008) and Staffansson (2010). The method used in the main report was solely based on previous flashover fire tests in non-combustible compartments, with typical apartment furniture as fuel and is discussed here

B.1 Review of Experimental Data

The heat release rate corresponding to solely the variable fire load is needed as input for the model presented herein. Therefore, it is important that the fire tests used for correlation excluded involvement of combustible structures in the fire.

B.2 Maximum heat release rate and external flaming

Numerous correlations exist in the literature describing the maximum heat release rate that can be attained within a small enclosure in ventilation-controlled conditions. Herein, the common correlation noted in textbooks (Wickström, 2016) is adopted, i.e.:

$$\dot{Q}_{C;max;int} = \alpha_1 * \alpha_2 * A_o\sqrt{H_o} \qquad \text{eq. B1}$$

Where α_2 is the energy released per unit mass of inflowing air (3.01 * 10^6 W s/kg, if supply air has an oxygen content of 23%). The factor α_1 is a flow rate coefficient and is often assumed to be 0.50 or 0.45 kg/(s $m^{5/2}$). According to Rockett (1976) the value of this coefficient ranges between 0.40 and 0.61 kg/(s $m^{5/2}$). In this study the value of α_1 is chosen empirically, using the series of post-flashover fire tests of compartments with non-combustible linings shown in Table B.1. As will be shown in B.6, a value of α_1=0.40 corresponds well with experimental results.

During the post-flashover fire, combustion can take place outside the ventilation opening, where outflowing combustibles will enter an oxygen-rich environment. The extend of external flaming is commonly expressed using an excess fuel fraction, α_3. The excess fuel fraction can be defined as the ratio between the interior heat release rate and the exterior heat release rate.

$$\dot{Q}_{C;max;total} = \dot{Q}_{C;max;int} * (1 + \alpha_3) \qquad \text{eq. B2}$$

Where $\dot{Q}_{C;max;total}$ is the maximum heat release rate of internal and external combustion.

B.3 Fire growth rate

The model presented in this paper aims to give a practical solution for the structural assessment of compartments exposed to fires. In the main text of this report it was shown that the predicted damage after the full duration of an uncontrolled flashover fire is practically independent of the fire growth rate. As the pre-flashover fire is not the focus of the model, a fast fire growth rate of 0.047 kW/s^2, which corresponds well with the experimental results of flashover compartment fire tests of Table B.1, is assumed.

B.4 Combustion efficiency

In most fires, not all of the combustibles completely burn out. The combustion efficiency is the ratio between the variable fire load and the total heat released during a fire and can be determined as follows:

$$\alpha_4 = \frac{\int_0^{t_\infty} Q_C(t)dt}{F} \qquad \text{eq. B3}$$

Where $Q_C(t)$ is the heat release rate as a function of time, t;

F is the total variable fire load.

All tests included in Table B.1 were stopped after a significant period of fire decay. However, none of the tests was performed until the heat release rate completely diminished. Therefore, it is not possible to determine the exact combustion efficiency from these results. However, it is determined that the combustion efficiency should be approximately 0.8. Therefore, a combustion efficiency of 0.8 is chosen for this study.

B.5 The decay phase and the start of decay

The start of a decay phase is often assumed to occur after a fraction of the fuel load, α_5, is consumed by the fire. The reduction of the heat release rate is commonly assumed to follow a parabolic or linear function. However, assuming these types of functions generally leads to sudden a stop of the fire, which is too abrupt in comparison with compartment fires. Therefore, this study implements a hyperbolic function for the decay phase, which has the following form:

$$Q_{C;dec}(t) = \frac{1}{x(t-y)} \qquad \text{eq. B4}$$

Where $Q_{C;dec}(t)$ is the heat release rate of the variable fire load during the decay phase as a function of time

t is the time

x and y are determined using the following boundary conditions:

- $\int_{0}^{t_{dec}} Q_C(t)dt = \alpha_4 \alpha_5 F$ as the total area under the heat release rate curve should correspond to the fuel load and the combustion efficiency.
- $Q_C(t_{dec}) = \dot{Q}_{C;\max;total}$ as the heat release declines during the decay phase, from the heat release rate corresponding to the fully developed phase to zero.
- $\int_{t_{dec}}^{\infty} Q_{C;dec}(t)dt = \alpha_4 (1-\alpha_5) F$, as the area under the heat release rate curve of the decay phase should correspond to fuel left at the start of the decay and the combustion efficiency.

B.6 Empirical constants

Values of α_1 to α_5 and the maximum heat release rate per floor area (heat release rate density) of movable fuel (furnishings etc.) are needed for the model. Some, but not all of these can be found in design standards. The values used in the main text of the report are determined empirically from compartment tests as discussed here. Only tests that involved a full or nearly full duration of a flashover fire in compartments with typical apartment furniture were considered.

The experimental heat release rate curves for the purpose of benchmarking herein are those indicated in Table B.1, which were reported by McGregor (2014) and Li *et al.* (2014), Su and Lougheed (2014), Janssens (2015) and Chen (2008). Whilst some charring of the CLT was noted in some of these experiments, the contribution of the CLT to the fire loading was nominal in contrast to that of the variable fire loading. Therefore, the heat release rate measured can be considered representative of the heat release rate of the furniture within the fire enclosure. The design fire input parameters are chosen empirically, so that the predicted heat release rate curves correspond to those of the tests in Table B.1- The resulting parameters are summarised in Table B.2. Figure 17, Figure 18, Figure 19 and Figure 20 contrast the experimental data and the model input time-HRR relationship.

Table B.1: overview of compartment tests with non-combustible linings and no sign of combusted construction

Test	Reference	Name in ref.	Floor area of ignited comp. (m^2)	Ventilation opening area of ignited comp. (m^2)	Height of ventilation opening (m)	Open-ing factor [v]	Main struct. mem-bers [vi]	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load density (MJ/m^2)	First item ignited
B2[ii]	McGregor, 2014	test 2	15.75	2.14	2.00	0.042	CLT	12.7mm fire rated 12.7mm fire rated	furniture	533	bed
B4[ii]		test 4	15.75	2.14	2.00	0.042	CLT	12.7mm fire rated 12.7mm fire rated	furniture	553	bed
C1	Li *et al.*, 2014	test 4	15.75	2.14	2.00	0.042	LTF	12.5mm type C 12.5mm type C	furniture	614	bed
C2		test 5	15.75	2.14	2.00	0.042	LTF	12.5mm type C	furniture	610	bed
C3		test 6	15.75	2.14	2.00	0.042	LSF	12.5mm type C	furniture	601	bed
D1	Chen, 2008	test 1	15.72	2.25	1.50	0.040	LSF	12.7mm cement board 15.7mm type X[i]	furniture	397	bed
D2		test 2	15.72	2.25	1.50	0.040	LSF	12.7mm cement board 15.7mm type X[i]	furniture	366	bed
E1	Su and Lougheed, 2014	LSF	52.54	4.50	1.50	0.031	LSF	12.7mm, 15.9mm type X or standard	furniture	550[iii]	bed
F1	Janssens 2015	test 1	14.80	3.87	2.07	0.084	CLT & NLT	type X type X	furniture	575[iv]	sofa
F2		test 2	14.80	3.87	2.07	0.084	CLT	type X type X	furniture	600[iv]	sofa

[i] two layers of 15.9mm type X gypsum board on the ceiling
[ii] also reported by Li *et al.* [9]
[iii] movable fire load density:

- bedroom 510 MJ/m^2;
- living area 380 MJ/m^2
- kitchen dining area 970 MJ/m^2
- average living/dining/kitchen 575 MJ/m^2
- whole apartment average 550 MJ/m^2

[iv] rough estimation using graph in resource
[v] opening factors can be calculated using $A_o\sqrt{H_o}/A_t$, where A_o and H_o are the area and height of the opening and A_t is the total area of the boundary surfaces.
[vi] The main structural members were either made of cross laminated timber (CLT), nailed laminated timber (NLT) light timber frame assemblies (LTF) or light steel frame assemblies (LSF).

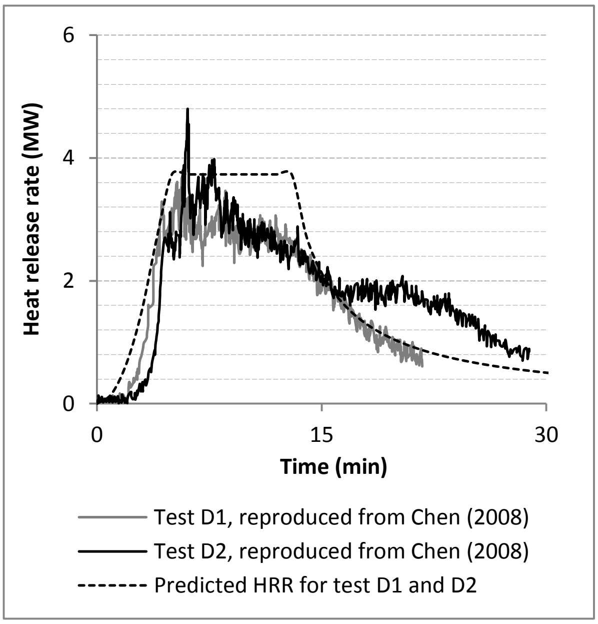

Figure 17 – Experimental and model input heat release rates of test D1 and D2. Experimental results are reproduced from Chen (2018).

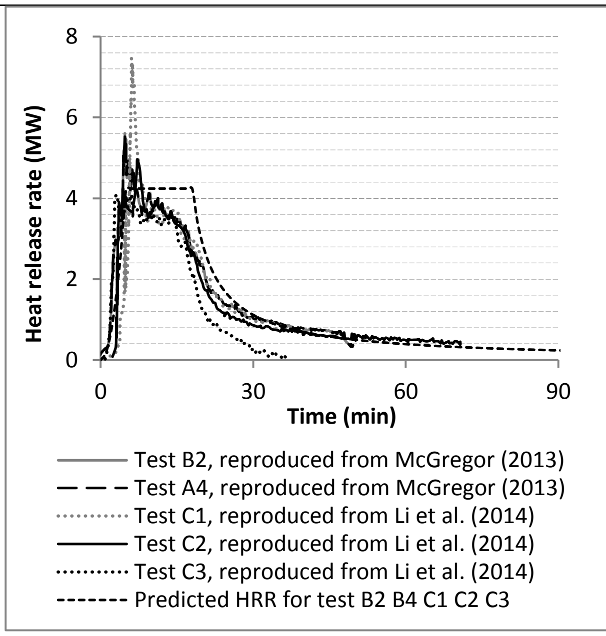

Figure 18 – Experimental and model input heat release rates of Test B2, B4, C1, C2, C3. Experimental results are reproduced from McGregor (2014) and Li et al. (2014).

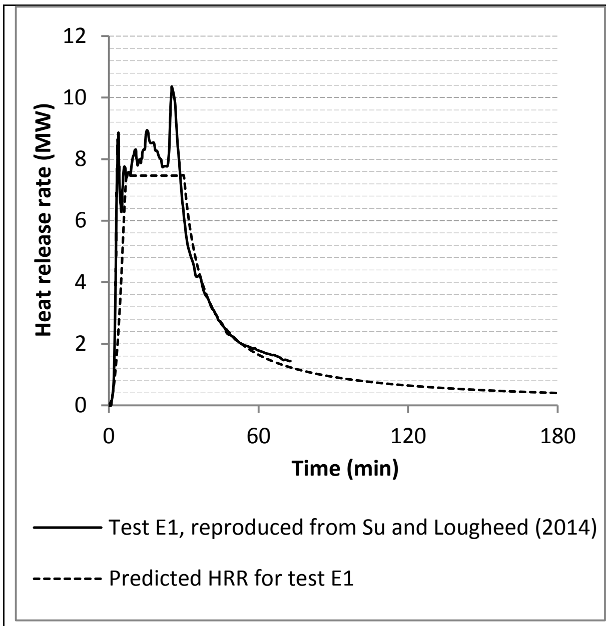

Figure 19 – Experimental and model input heat release rates of test E1. Experimental results are reproduced from Su and Lougheed (2014).

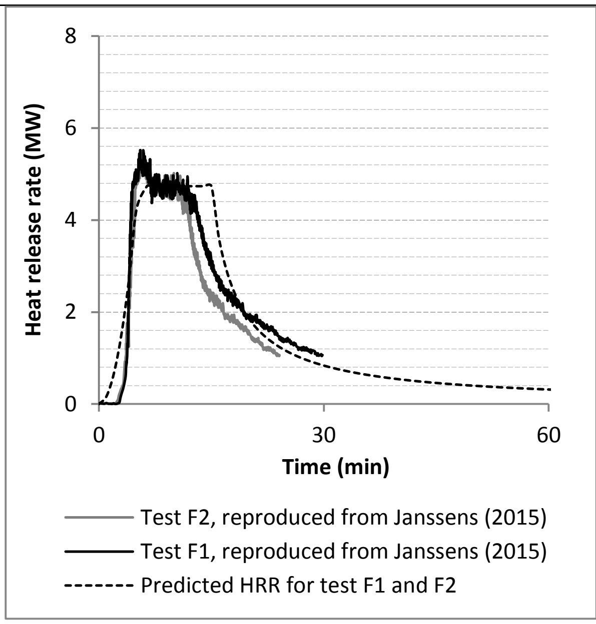

Figure 20 – Experimental and model input heat release rate of test F1 and F2. Experimental results are reproduced from Janssens (2015).

Table B.2: Empirically determined design fire curve parameters for compartments with typical apartment furniture and non-combustible linings

Fire growth rate (kW/s^2)	0.047
Flow rate coefficient, α_1 ($kg/(s\ m^{5/2})$)	0.45
Excess fuel fraction, α_3 (-)	0.1
Combustion efficiency, α_4 (-)	0.8
Fraction of fuel load at start of decay, α_5 (-)	0.5
Maximum heat release rate density of movable fuel (kW/m^2) *Note: Only tests F1 and F2 were fuel controlled according to the equations given in this Annex. The maximum heat release rate density was, therefore, only correlated to 2 tests. The maximum heat release rate density used for predictions in the main text is different as it was directly determined from test A1.*	320