Practical method to determine the contribution of structural timber to the rate of heat release and fire temperature of post-flashover compartment fires

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Abstract

The lack of a method to quantify the contribution of exposed timber to a fire was identified as one of the main gaps of knowledge concerning the challenges of building high-rise timber buildings, in a recent gap analysis performed by the NFPA. Recent experimental studies successfully quantified the contribution of large surfaces of exposed timber, in terms of rate of heat release. However, a method to predict these quantities has not been found in the literature.

This report proposes a model that includes the contribution of exposed or protected timber to post-flashover fires in compartments with a floor area up to $100m^2$. The model consists of a one-zone model and a wood combustion model. Using the one-zone model, the temperatures in the room are estimated from the heat release rate. Using the wood combustion model, the heat release rate coming from exposed or protected timber is estimated. The influence of delamination of lamellas or fall-off of claddings can be estimated with some restrictions regarding accuracy.

Comparative studies showed that predictions of the model correspond well with previous full scale compartment fire tests.

Key words:
Compartment fire, Timber, CLT, natural fire, charring rate, heat release rate, delamination, cladding failure

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Preface

The model presented in this report was developed at SP Sustainable Built Environment and is named *SP-TimFire*.

1 Scope

The model presented in this report is giving estimations of the contributions of exposed and protected timber surfaces in a compartment fire. This contribution is expressed in terms of heat release rate, fire temperature, and duration of the fire. The model aims to assess the contribution of timber in post-flashover fires. The pre-flashover fire is simplified by using an assumed fire growth rate.

The influence of delamination of engineered wood products and gypsum board fall-off is included in the model. The accuracy of the model is evaluated using results of previous compartment tests.

Assessment of complete self-extinguishment or continuous smouldering combustion at the end of the decay phase is not within the scope of this work.

2 Background

The maximum height of timber buildings has been regulated in many countries, due to the combustible nature of timber. However, recently, more and more countries within Europe started to allow high rise buildings with a main structure made of timber.
A recent gap analysis Gerard *et al.* (2013) showed that exposed timber surfaces contribute to a potential fire. However, they showed that methods able to quantify the contribution of exposed structural timber in a compartment fire were lacking. It has also been shown that potential cladding failure and delamination of engineered timber products significantly influence the contribution of timber to a compartment fire (Brandon and Östman, 2016). Therefore, future models that predict the contribution of timber structures in compartment fires should be able to account for potential delamination.

2.1 Compartment fire tests

Overviews and discussions of previous compartment fire tests of timber structures have recently been published by the NFPA (Brandon and Östman, 2016). Six studies have been found that included compartment fire tests in which the timber surfaces were unprotected against fire before the fire started (Hakkarainen, 2002; Frangi and Fontana, 2005; McGregor, 2013; Medina Hevia, 2014; Hox, 2015). Two of those studies involved measurements of the heat release rate of the fire (McGregor, 2013; Medina Hevia, 2014), which can be used to quantify the contribution of exposed structural timber elements.

From the work of Frangi and Fontana (2005) it was concluded that the temperatures inside the compartment do not significantly differ between compartments with exposed timber surfaces and without exposed timber surfaces. However, it was convincingly shown that there can be significantly more combustion outside of openings of the compartments. A similar conclusion was drawn earlier from the study by Hakkarainen (2002). Frangi et al. (2008) reported an increase of external combustion which occurred simultaneously with a sharp increase of temperatures behind the gypsum board protections, indicating that a sudden exposure of cool timber surfaces results in an increased combustion outside of the compartment.

In a number of tests it was shown that the duration of the fully developed phase of a fire can be influenced by the presence of exposed timber. Medina Hevia (2014) showed that fires in compartments can decay if only one of the compartment walls consist of fully exposed cross laminated timber and all other walls are fully protected by gypsum plaster boards for the duration of the fire. Tests of compartments with two exposed CLT walls showed a second flashover during the decay phase as a result of delamination of the polyurethane bond line between the CLT lamellas. Fires in compartments with more than two exposed walls did not show a decay phase before the fire was manually extinguished at the end of the test (Hakkarainen, 2002; McGregor, 2013; Hox, 2015).

3 Model (SP-TimFire)

The model proposed in this report combines a one-zone model with a wood combustion model. This model is named *SP-TimFire*. The algorithm of the model for the estimation of the contribution of CLT to a compartment fire is shown in Figure 3-1.

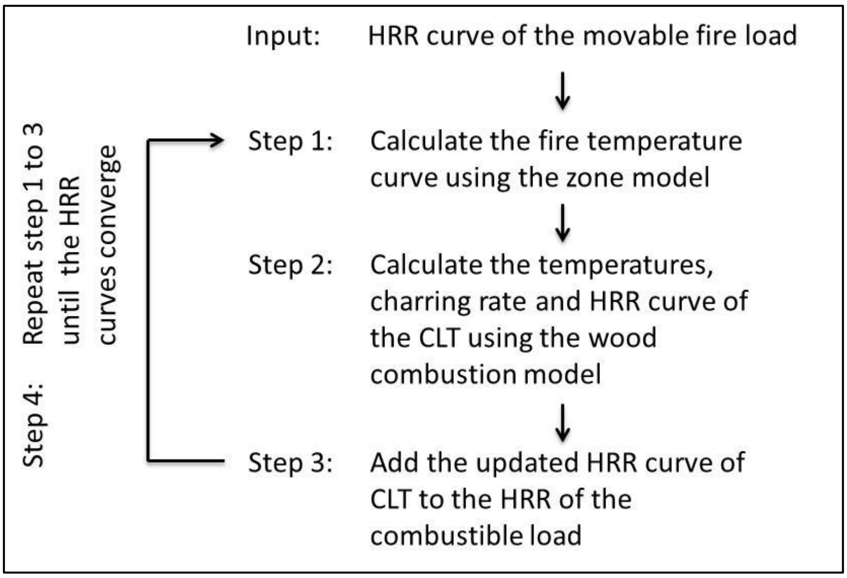

Figure 3-1: Algorithm of SP-TimFire

In step 1. (see Figure 3-1) a one-zone model is used to determine the fire temperature based on heat release rates (HRR) of the CLT and the movable fire load. The predicted temperatures are based on an assumed airflow through compartment openings. The one-zone model is further discussed in section 3.1.

In step 2. a wood combustion model, which is further discussed in section 3.2, calculates the heat release rate corresponding to the CLT ceiling and walls from the fire temperature. The temperatures within the CLT are calculated based on the fire temperatures only. For simplification, differences of oxygen content and velocity of the surrounding air are assumed to have no influence on the charring rate. Measurements of charring depths after previous compartment fire tests (McGregor, 2013) have not shown an increased charring depth near openings, where higher oxygen levels were expected. Instead, the highest charring depths were located where a deficiency of oxygen can be expected during the fully developed phase, far away from an opening and close to high fuel sources.

Based on the charring temperature of wood (300°C) and an experimentally determined heat release per charring depth of 5.39 MJ/m^2mm (Schmid *et al.*, 2016), the charring rate and the heat release rate per unit area of CLT can be estimated.

In step 3. the HRR curves are updated in order to be used in the subsequent iteration of the algorithm. Step 3 involves the principle assumption of the model:

The heat release rate of the fire is assumed to be equal to the heat release rate of the CLT plus the heat release rate of the movable fire load. Therefore, 100% of the CLT contribution to the heat release is allowed to take place outside of the compartment.

The assumption can be tested using the studies found in the literature that involved compartment tests of exposed CLT and calorimetry to determine the heat release rate. These studies were reported by McGregor (2013) and Medina Hevia (2014). In Figure 3-2 and Figure 3-3 curve 2 is obtained by multiplying the reported charring rates by 5.39 MJ/m^2mm and the surface area of the exposed CLT. The following should hold if the assumption is correct:

Curve 1 + Curve 2 = Curve 3 ≈ Curve 4

It can be seen that there is good agreement with curve 3 and curve 4 in both figures. This supports the assumption used in step 3. However, it should be stated that the assumption can only be valid in case curve 1 corresponds to a post-flash over fire with a fully developed phase that eventually completely burns out.

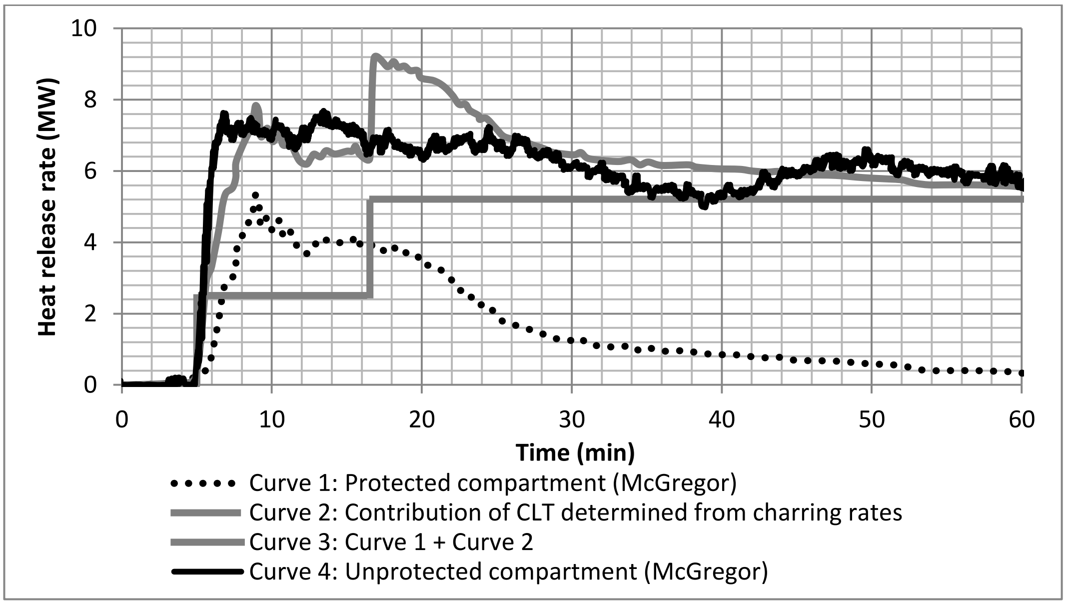

Figure 3-2: Experimentally determined and predicted heat release rates in accordance with assumptions

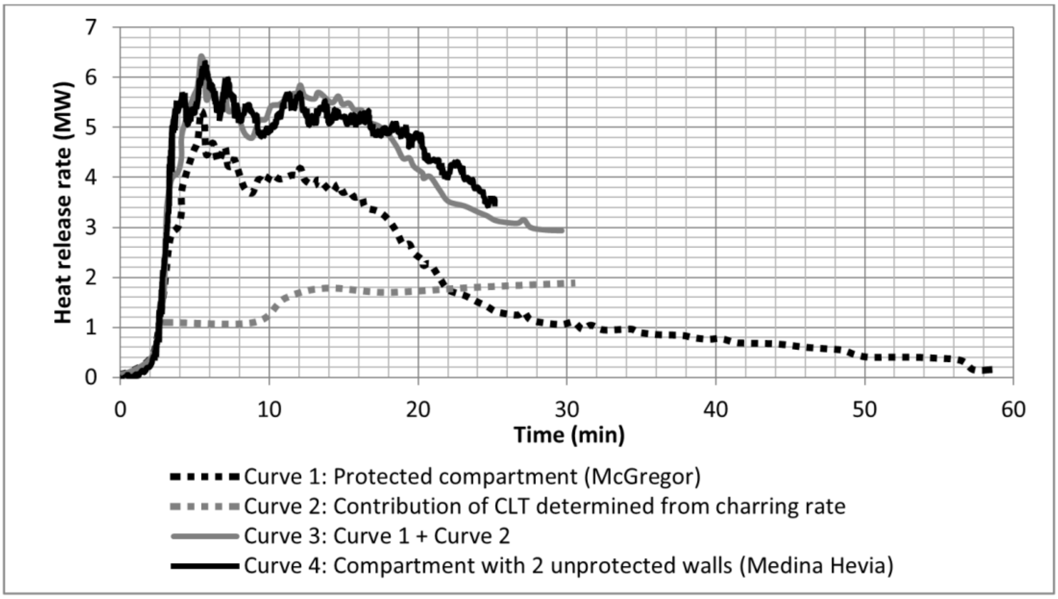

Figure 3-3: Experimentally determined and predicted heat release rates in accordance with assumptions

3.1 One-zone model

A one-zone model was used to determine the fire temperatures from the heat release rate curves. Using a one-zone model, a single gas temperature within the compartment is assumed. Magnusson and Thelanderson (1970) published the first model for predicting compartment fire temperatures. Their model was based on the conservation of mass and energy and it was later revised by Wickström (1986) to develop the parametric fire curves of Eurocode 1.

In SP-TimFire, a distinction is made between the heat release rate corresponding to the movable combustible load, $\dot{Q}_C$, 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.

In an under-ventilated fire, the heat release rate inside the compartment is limited by the amount of oxygen that can flow into the room:

$$\min\left(\dot{Q}_C + \dot{Q}_{C;CLT};\ \dot{Q}_{C;max}\right) = \dot{Q}_W + \dot{Q}_R + \dot{Q}_L \qquad (3.1)$$

Where:
$\dot{Q}_C$ *is the heat release rate corresponding to the movable fire 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*
$\dot{Q}_{C;max}$ *is the maximum heat release rate inside the compartment*
$\dot{Q}_{C;CLT}$ *is the heat release rate of the combustible linings*

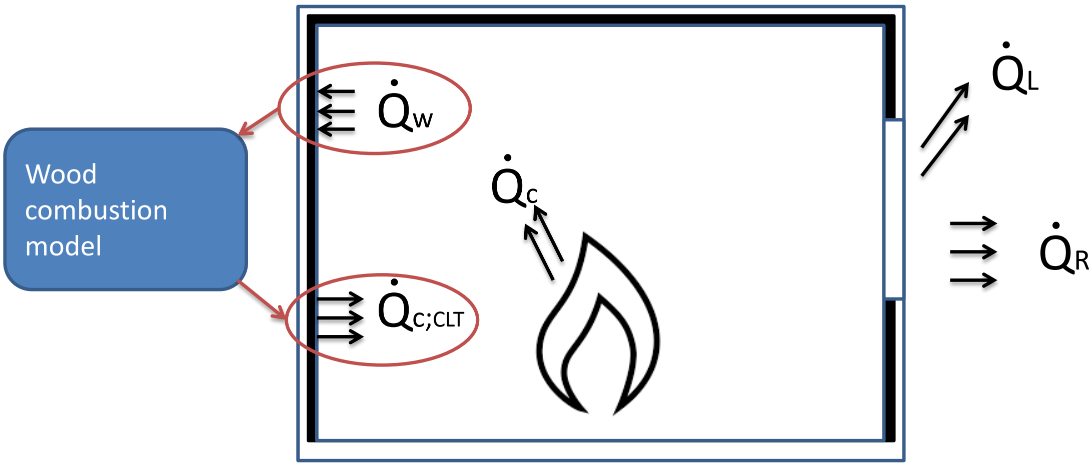

Figure 3-4: Schematic representation of SP-TimFire

The maximum heat release rate inside the compartment, $\dot{Q}_{C;max}$, was determined according to Wickström (1986), assuming a theoretical maximum temperature rise of 1325°C.

$$\dot{Q}_{C;max} = \alpha_1 T_{max} c A\sqrt{h} \qquad (3.2)$$

Where:
α_1 is a flow constant
T_{max} is an assumed maximum temperature rise (1325K by Wickström, 1986) (K)
c is the specific heat of air
A is the opening area
h is the opening height

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

$$\dot{Q}_L = \alpha_1 (T_f - T_\infty) c A\sqrt{h} \qquad (3.3)$$

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

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

$$\dot{Q}_R = A\left(T_f^4 - T_\infty^4\right)\sigma \qquad (3.4)$$

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 previous section.

SP-TimFire uses an algorithm to solve the fire temperatures. The fire temperature is determined by substituting eq. (3.3) into eq. (3.1) and solving to determine T_f:

$$T_f = \frac{\min(\dot{Q}_C + \dot{Q}_{C;CLT}; \dot{Q}_{C;max}) - \dot{Q}_W - \dot{Q}_R}{c\alpha_1 A\sqrt{h}} + T_\infty \qquad (3.5)$$

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. $\dot{Q}_C$ is the input parameter and $\dot{Q}_{C;CLT}$ is determined iteratively according to the algorithm shown in Figure 3-1.

3.2 Wood combustion model

In the wood combustion model, the fire temperature is used to estimate the temperatures inside the timber using a heat transfer model. Using this, the influence of the oxygen concentration on the charring rate is ignored.

The charring temperature of wood is 300°C (Buchanan, 2002; EN1995-1-2:2004). Using this the charring rate is determined from the results of the heat transfer model. The wood combustion model determines the contribution of the timber using a constant heat release rate per millimeter of charring of 5.39 MJ/m^{2}mm, for a char layer thicker than 10mm (Schmid *et al.*, 2016), which was based on a series of cone calorimeter tests by Crielaard (2015). In the cone calorimeter tests, during a period of a few minutes after ignition, the charring rate as well as the measured heat release rates peaked. The reported average charring rate for the first 10mm (approximately 6 minutes) was more than double the average charring rates deeper in the specimens. An increasing slope of heat release per charring depth (see Figure 3-5) corresponded well with the cone calorimeter test results of Crielaard. Therefore, for the model it is assumed that the for first 10 mm of char, the heat release rate is 2.70 MJ/m^{2}mm at the start of charring and linearly increases to 5.39 MJ/m^{2}mm until the charring rate is 10mm.

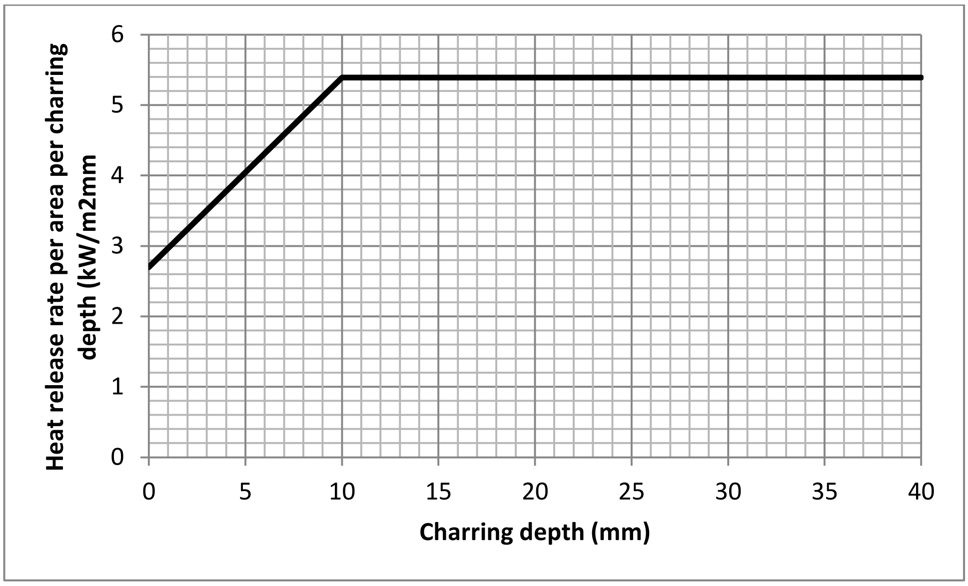

Figure 3-5: Heat release rate per unit area per charring depth

Thermal properties used in the model were published by König and Walleij (2000) and are shown in Figure 3-5 to 3-7. The properties were included in the Eurocode 5 for standard fires only (EN 1995-1-2:2004). However, König and Walleij showed that the use of these properties also leads to a reasonable accuracy for predictions of wood temperatures in parametric fires (see Figure 3-9). Effective thermal properties of gypsum plaster board as a function of temperature are taken from the European design guide for timber engineering (Östman *et al.* 2010). Fall-off of gypsum boards is simulated by removing the gypsum layer from the model at a specified time. Similarly, delamination of CLT is simulated by removing the exposed lamella from the model when temperatures in the bond line reach a specified temperature.

SP TimFire was used in combination with finite element software, SAFIR2007, to calculate the temperatures in the CLT. The temperatures are determined for every millimeter throughout the depth of the CLT. The thermal properties of every element are adapted to the predicted temperature of the element in accordance with Figure 3-6, Figure 3-7 and Figure 3-8. As the charring temperature can be taken as 300°C (Buchanan, 2002), the charring rate can be determined from the movement of the 300°C iso-line.

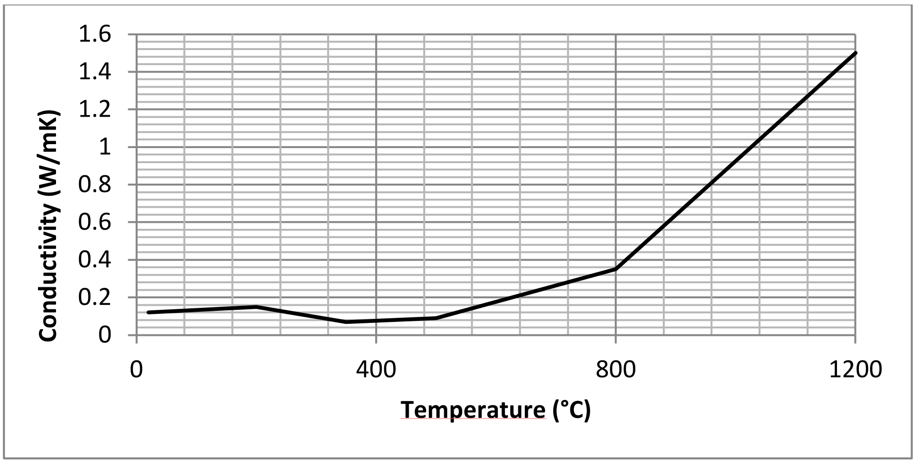

Figure 3-6: Effective properties for conductivity according to König and Walleij (2000)

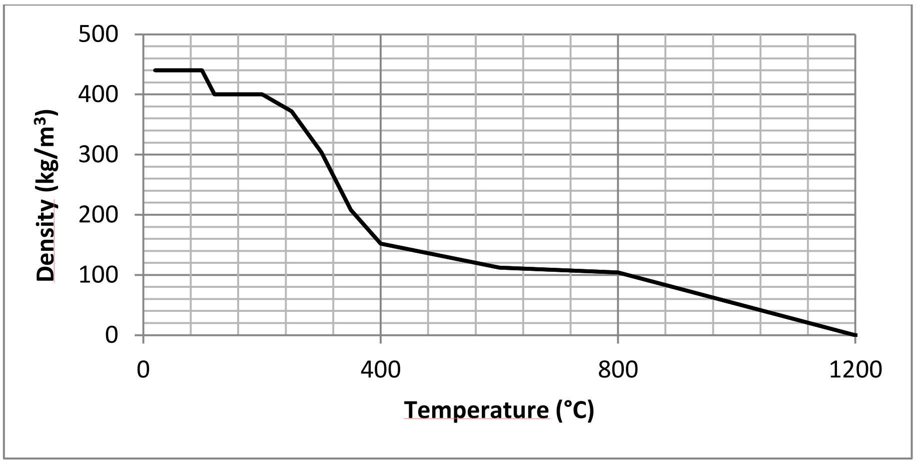

Figure 3-7: Effective properties for density according to König and Walleij (2000)

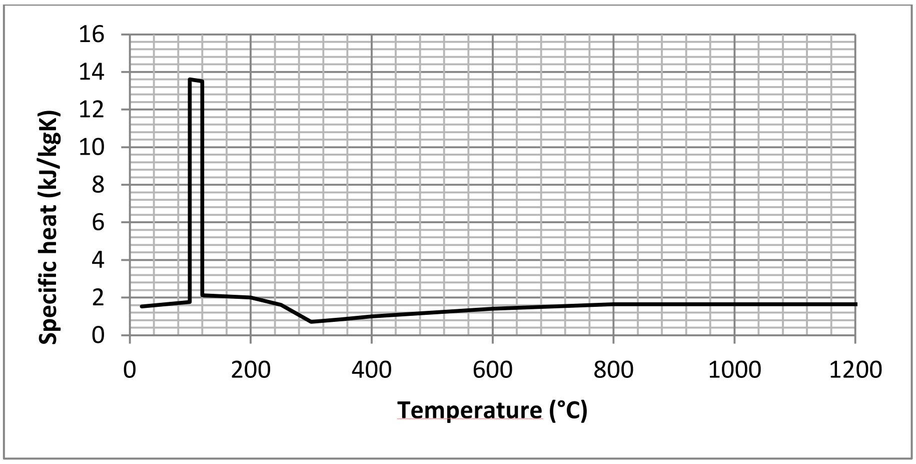

Figure 3-8: Effective properties for specific heat according to König and Walleij (2000)

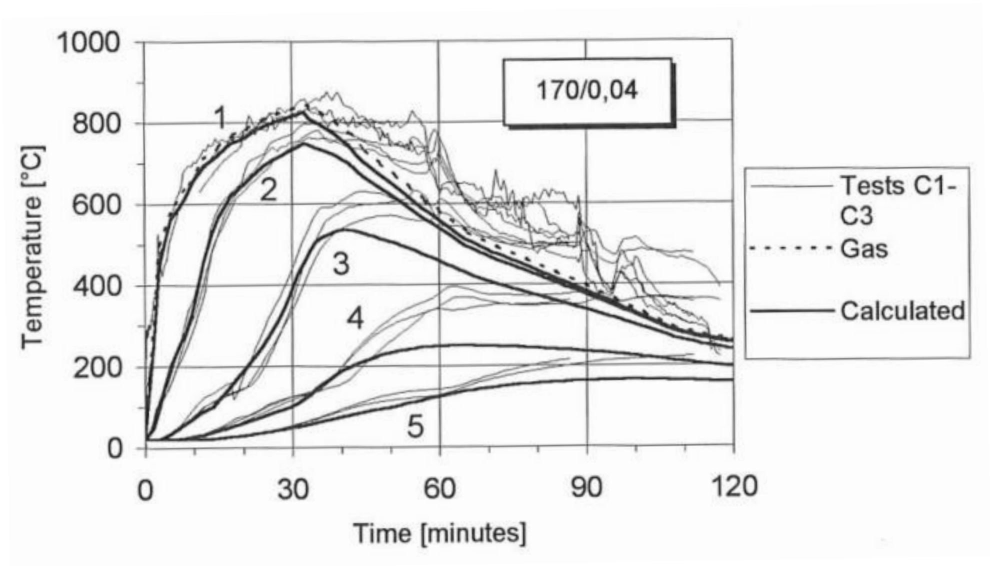

Figure 3-9: Comparisons of experimental and numerical results (from König and Walleij, 2000)

4 Verification

Previous full scale compartment test results corresponding to compartments with exposed CLT or heavy timber walls are modelled. A comparative study between the experimental results and the model predictions is performed in order to assess the model accuracy and identify potential limitations.

4.1 The input parameters for the verification

The main input of the model is the heat release rate curve corresponding to the movable fire load. A series of assumptions were made to describe a heat release rate curve corresponding to the movable fire load. These assumptions were taken so that the resulting heat release curve corresponds well with the fire test results of the fully protected compartment by McGregor (2013) and Su and Lougheed (2014), as can be seen in Figure 4-1. The set of assumptions were used to generate an input for the model, based on a comparable test. Instead of the assumptions below, an alternative would be to use rules given for design fires by ISO 16733-1 (2015). The assumptions were as follows:

- For the pre-flashover fire, it was assumed that the fire grows with a fire growth rate of 0.047 kW/s^2.
- It was assumed that the combustion of the movable fire load that can take place outside of the compartment is 30% of the combustion that can take place inside the compartment. This is comparable to the fuel-excess percentage of 37% published for wood cribs (Babrauskas, 2008). The combustion inside the compartment is assumed to be limited by the amount of oxygen that flows into the room following eq. 3.2.
- The heat release rate per floor area during the decay phase corresponding to the movable fire load was assumed to be similar to the heat release rate per floor area found for compartment tests involving fully protected CLT elements McGregor (2013).

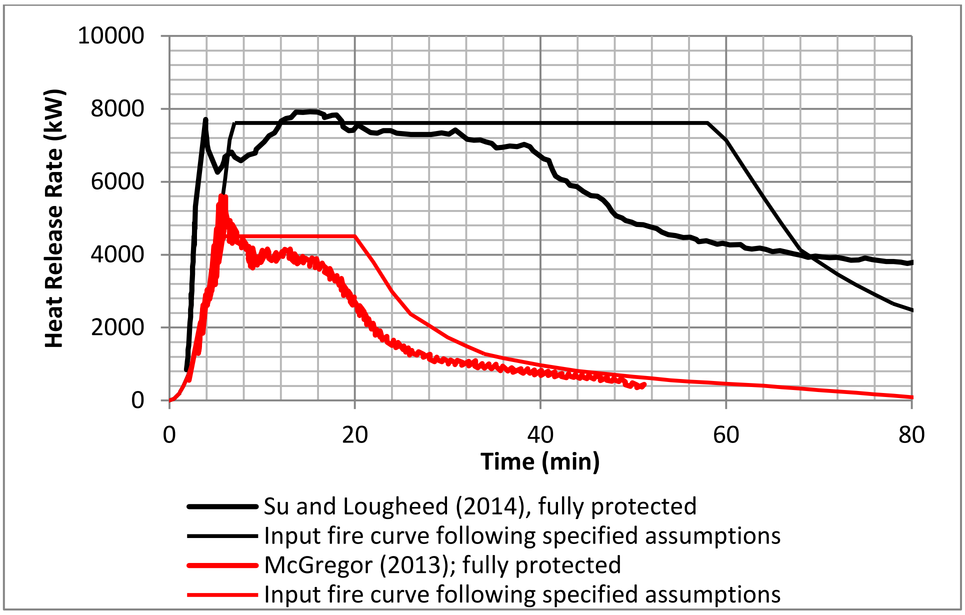

Figure 4-1: Heat release rate corresponding to the movable fire load

For the one-zone model, a small time step of 2 seconds was used in order to minimize the temperature increments. The flow constant α_1 is taken as 0.6, which is in within the range given by Rockett (1976). For the heat transfer model, the effective emissivity, ε_{eff}, is assumed to be 0.8 and the convection coefficient h_c is assumed to be 25W/m^{2}K in agreement with Buchanan (2002).

The temperature at which delamination occurs is very much dependent of the adhesive used. Medina Hevia (2014) reported that the adhesives used in the tested CLT was poly-urethane based with a melting point of 200°C, which indicates that delamination occurs at temperatures below 200°C. The temperatures were not measured in the bond line during the fire tests. However, using a rough extrapolation of other temperature measurements, the temperature in the bond line at the start of delamination is estimated to be 140°C. The modelled lamella thickness is 35mm, which is similar to the lamellas of the CLT tested by McGregor (2013) and Medina Hevia (2014).

4.2 Experiments versus predictions

McGregor (2013) performed compartment fire tests with fully exposed CLT walls and ceiling. Figure 4-2 shows the corresponding temperature measurements and predictions by SP-TimFire. If delamination is not included in the analysis SP-TimFire predicts a start of decay within the test duration, while this is not observed in the tests. In case delamination is included, the decay phase is not expected to occur within the test time. As a result of this the temperatures are expected to increase slowly.

The predicted heat release rate corresponding to McGregor’s test is shown in Figure 4-3. It can be seen that the predicted heat release rate is higher than the measured heat release rate directly after flashover and directly after delamination. The overestimation of the heat release rate after delamination is caused by the assumption that all CLT in the entire room delaminates at the same instant. Instead of a single heat transfer model for all CLT, a series of heat transfer models could be implemented of which each represents an area of CLT that delaminates at different points in time. This is recommended for future research. The overestimation of the heat release rate after initial flashover could be caused by lack of accuracy of the heat transfer model used. However, it should be noted that the peak heat release rate during tests can be missed if the extraction is not sufficient to clear all the smoke from the laboratory.

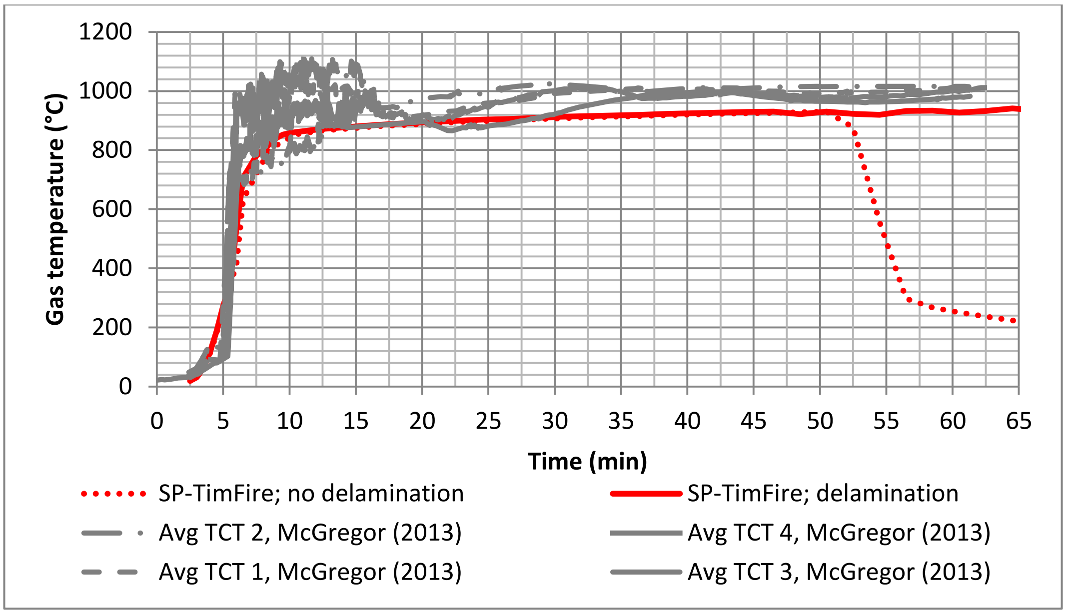

Figure 4-2: Experimentally determined and predicted temperatures for a compartment with exposed CLT walls and ceiling according to SP-TimFire

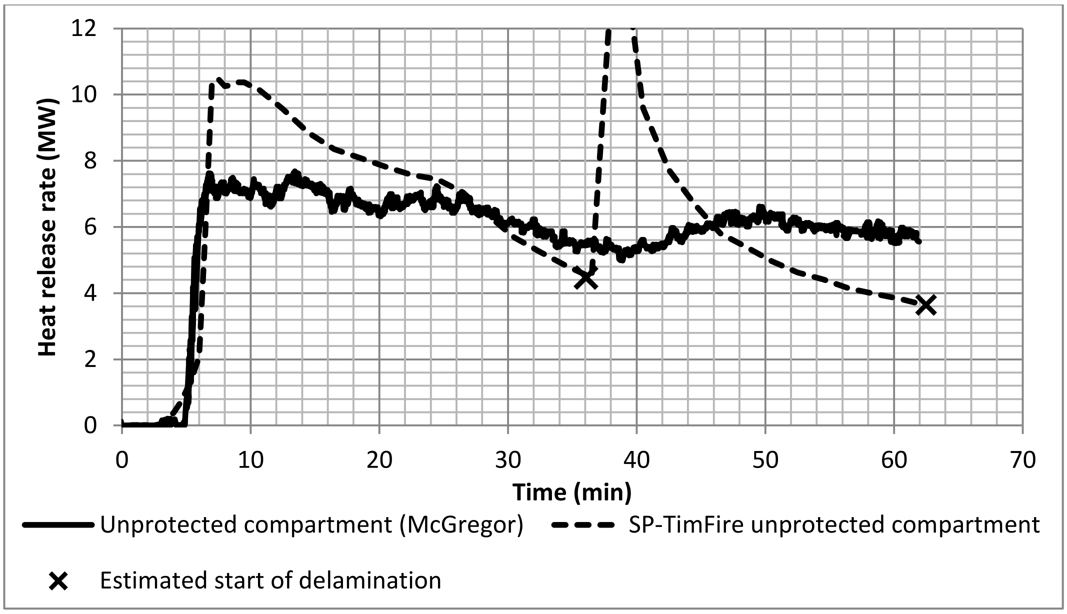

Figure 4-3: Experimentally determined and predicted temperatures for a compartment with exposed CLT walls and ceiling according to SP-TimFire

Delamination was clearly observed during a fire test of a compartment with two exposed walls and other surfaces protected (Medina Hevia, 2014). Figure 4-4 shows temperatures of a compartment fire involving two exposed walls that face each other, together with corresponding predictions. The predicted temperatures are generally lower than the measured temperatures. However, the start of the decay phase is estimated accurately. Due to delamination, the temperatures increased after 40 min. The time at which delamination occurs corresponds well with the model results. However, the predicted increase of temperatures is too steep. This is related to the simplifying assumption that delamination occurs at one instant in all CLT walls.

The heat release rate corresponding to the test is shown in Figure 4-5. For comparative purposes the measured heat release rate of a compartment with fully protected CLT is included in the figure. The heat release rate of both fires seems to be overestimated. However, the contribution of CLT, which is the difference between the black and the red curve, is predicted with a reasonable accuracy.

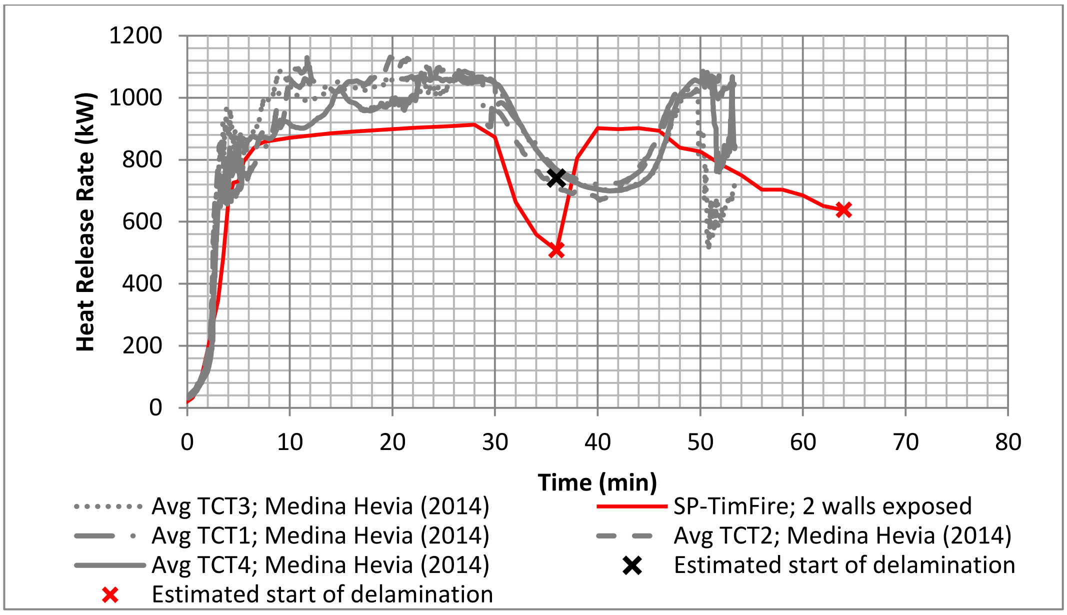

Figure 4-4: Experimental results and predictions using SP-TimFire for a compartment with two exposed walls

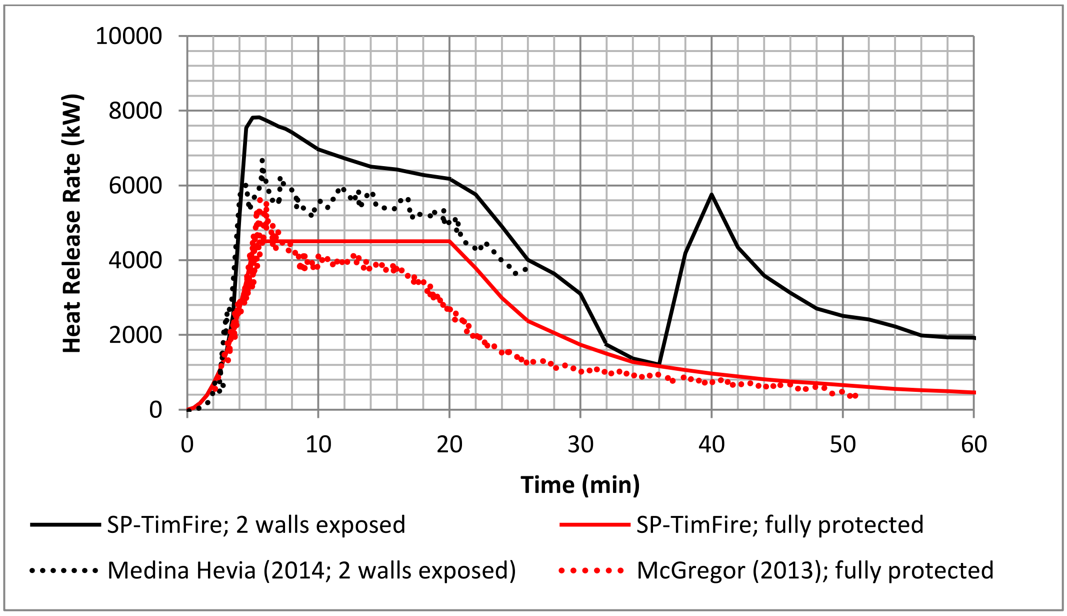

Figure 4-5: Experimental results and predictions using SP-TimFire for a fully protected compartment and a compartment with two exposed walls

Medina Hevia (2014) performed a fire test of a compartment with one wall exposed and all other surfaces protected, which did not lead to delamination. In accordance with SP-TimFire delamination does not occur in this fire, which is in agreement with the test results. After the fire temperature has dropped below 300°C, delamination could still occur. However, it will not result in an increase of predicted temperatures or heat release rates as the timber is not considered to char below 300°C by the model.

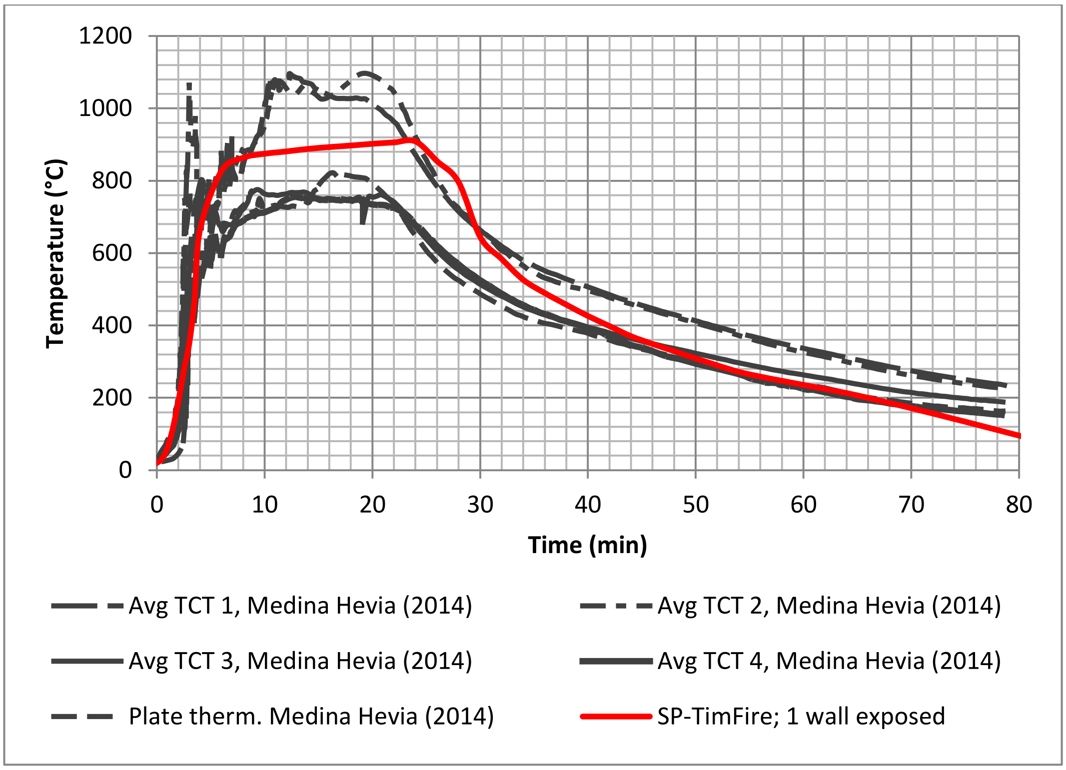

Figure 4-6: Experimentally determined and predicted temperatures for a compartment with one exposed CLT wall using SP-TimFire

5 Conclusions

SP-TimFire, a model to predict temperatures and heat release rates of fires in compartments with exposed timber was developed. The model includes a method to predict delamination and its influence on the heat release and the fire temperature. Comparisons with existing test results were used to evaluate the model.

The following was concluded from the comparative study between the numerical results and the test results:

- The predicted temperatures were generally underestimated for the fully developed phase by approximately 100°C. However, the accuracy of the temperature predictions is considered to be reasonable.
- The predicted peak heat release rates were higher than the peak heat release rates measured during the tests.
- The time to start of the decay phase was predicted with a good accuracy.
- The predicted time at which delamination occurs corresponds well with the experimental results.

- The increase of fire temperature and the increase of heat release rate due to delamination were overestimated by the model, because of the assumption that delamination of a large CLT surface takes place at one instant.

6 Future research

In the present study, a relationship between charring rate and heat release rate was used as a basis for calculations of the contribution of CLT in a compartment fire. It is possible to have a comparable approach using the mass loss and heat of combustion of the wood to calculate the heat release rate.

The following improvements are planned:
- Improvement of the heat transfer model for calculations of the wood temperature in the decay phase. Existing heat transfer models for the calculation of temperatures in wood will be considered.
- Improvement of the delamination model to implement delamination occurring in a time period instead of delamination occurring in a single moment in time for the entire room.

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