TRAVELLING FIRES IN COMPARTMENTS WITH EXPOSED CROSS-LAMINATED TIMBER SURFACES

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ABSTRACT: This paper presents results from two large-scale experiments where the fire spread in large open-plan compartments with exposed cross-laminated timber (CLT) was studied. In the first experiment, #FRIC-01, the ceiling was exposed, and in the second, #FRIC-02, both the ceiling and the back wall was exposed. The charring rates of the CLT, the mass loss rates and heat release rates of the CLT and wood crib were measured. In addition, the fire spread was studied visually by recording the development of the fire with several cameras. The experiments provide unique information about how exposed surfaces affects the fire dynamics and fire spread in a modern wooden compartment. Both experiments showed that the presence of exposed CLT surfaces significantly affect the fire spread rate and fire dynamics of a compartment fire.

KEYWORDS: Cross-Laminated Timber, Compartment fire, Fire spread, Travelling fire

1 INTRODUCTION

Cross-laminated timber (CLT) has in recent years become very popular due to its many advantages; possibility of prefabrication, low carbon footprint, easy handling and mounting of wood, it's aesthetic look, and high strength and stiffness properties. With the increased popularity, CLT is now used in large apartment buildings, public buildings and office buildings.

Through a number of experiments, it has been found that the fire dynamics of a compartment is significantly changed when exposed surfaces of CLT are present. Examples of such changes are: higher heat release rate (HRR), increased duration of the fire, higher temperatures, and larger external flames [1, 2].

However, most experiments with CLT have been conducted in small compartments with nearly quadratic floor areas, and with small window openings, resulting mainly in ventilation-controlled fires [3-5]. Modern buildings, on the other hand, have large open-plan spaces and large window openings to allow for natural light. Fire dynamics of large, and sometimes long, open-plan spaces with large window openings is often characterized as travelling fires [6]. Travelling fires are recognized with a clear leading and trailing edge which propagates through the space.

Several full-scale experiments with travelling fires have been conducted over the last years, but mostly in compartments with non-combustible surroundings [7]. However, recently experiments have also been carried out with an exposed CLT ceiling. These experiments have provided new knowledge about how an exposed CLT surface affects the fire dynamic and fire spread rate.

In a small scale test, Nothard et al.[8] studied the effect of exposing CLT in the ceiling, and reported a more rapid fire spread with an exposed ceiling. In the Malveira fire experiments, the fire spread slowly for ~4 hours, until the fire spread to a location of the compartment where the ceiling was combustible. The burning ceiling significantly increased the fire spread in the rest of the compartment.

In the CodeRed-experiments [9, 10], the fire spread across a ~380 m^2 compartment with an exposed CLT-ceiling in 5 and 8 minutes. After ignition of the exposed CLT in the ceiling, the fire spread rapidly across the ceiling. This triggered the spread across the wood crib due to the strong radiation heat flux from the ceiling towards the wood crib. The impact of the exposed ceiling could clearly be demonstrated when compared against the X-ONE [11] and X-TWO [12] fire experiments, which were almost identical to the CodeRed-tests [10], but without exposed CLT in the ceiling. In these tests, the fire spread across the room in 25 and 32 minutes, respectively.

Through the few tests performed with a combustible ceiling, it is evident that there is a need for more knowledge on how different exposed CLT surfaces affects the fire spread and fire safety in large compartments. The rate at which a fire spreads is highly relevant for several aspects within fire safety, for example available time for people in the compartment to evacuate safely or be rescued, and efforts needed to contain and

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suppress the fire, extinguishing tactics, spread to other parts of the building, etc.

To better understand how an exposed CLT-surface affects the fire spread in a large open-plan compartment with large window openings, two large-scale experiments have been conducted. This paper is a short summary of some of the results. Additional results will be published in separate articles.

2 METHOD

Two experiments were conducted. The first, #FRIC-01, had an exposed CLT ceiling, while in the second, #FRIC-02, the CLT was exposed in both the ceiling and the back wall. The compartment is shown in Figure 1-Figure 3.

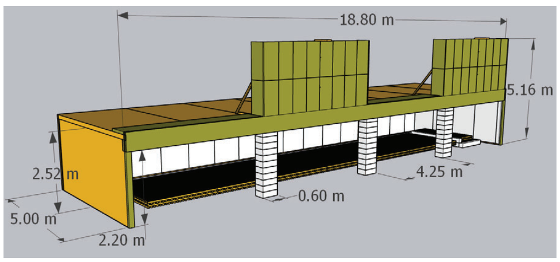

Figure 1 Sketch of compartment with dimensions.

Compartment

The compartment was built of a CLT roof and three CLT walls, while the front wall with large openings was made of a glue-laminated timber beam and three Siporex columns. The CLT in the roof and back wall was 140 mm thick, with 5 layers (40-20-20-20-40 mm), made of Norwegian spruce, and glued together with a regular polyurethane (PUR) adhesive. The CLT in the end walls were 80 mm thick with 3 layers (30-20-30 mm).

The inner geometry of the compartment was 18.8 m x 5.0 m x 2.52 m (l x w x h). The compartment was well ventilated with four large window openings in the front wall, with a total opening of 17.0 m x 2.2 m (l x h). This corresponds to an opening factor of 0.18 $m^{1/2}$. A 2.45 m high inert façade wall was mounted above two of the windows to study the external flame. The beam in the front wall protruded 350 mm below the ceiling.

The unexposed CLT surfaces were protected with 2 layers of 15 mm fire rated gypsum boards (type F) [13] to prevent any contribution from them. The edges of the CLT and the beam in the front wall were protected with a ceramic insulation.

Fuel load

The fuel load density was 373 MJ/m^2 per floor area and was chosen to represent a typical office building. The fuel load was represented by a 2.8 m x 15.5 x 0.2 m continuous wood crib and a 2.8 m x 1.0 m x 0.2 m wood crib positioned on a scale. The wood crib was made of four alternating layers with wood sticks with a 50 mm x 50 mm cross-section. The wood crib is shown in Figure 2 and Figure 3.

Figure 2 Compartment with exposed ceiling and back wall in #FRIC-02.

Figure 3 Inside compartment before ignition in #FRIC-02, with exposed CLT in ceiling and on back wall. Wood crib on the floor, TC-trees hanging from the ceiling. #FRIC-01 was identical except for gypsum boards covering the CLT back wall.

The fire was ignited at one end of the wood crib, the left end. Ten aluminium trays with heptane were evenly distributed under the end of the wood crib. In #FRIC-01 a total of 5.0 litres of heptane was used, and in #FRIC-02 a total of 9.8 litres.

Instrumentation

The compartment was instrumented with thermocouples (TC) and plate thermometers (PT) distributed inside and outside the compartment. The sensors measured the temperature and heat fluxes, and gave valuable data on fire spread rate, temperature distributions, charring rates, and heat flux towards the façade.

Charring rates of the CLT were determined based on temperature measurements. Embedded TCs were installed into the CLT elements from the sides, parallel to the isotherm, at depths 0, 10, 20, 30 and 40 mm into the CLT (Figure 4), at three different locations in the compartment.

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Figure 4 TCs were embedded into the CLT from the rebate joint.

Determination of heat release rate

The determination of the heat release rate (HRR) of the wood crib was inspired by the method of Rackausakaite et al. [11], which determined the HRR per unit (here: 50 mm of crib length) and then integrated over the entire wood crib. In contrast to the method of Rackausakaite et al., the HRR per unit was determined from the mass loss rate (MLR) of the small wood crib positioned on a scale, instead of just an average value between start and end of burning.

The HRR contribution from the CLT was derived based on the charring rates, the density, and the area of the exposed CLT. Charring rates of the CLT were determined based on the development of the 300°C isotherm inside the timber [14].

3 RESULTS AND DISCUSSION

3.1 Fire development

In #FRIC-01, the heptane fire did not cause the ceiling to ignite, and the wood crib fire almost extinguished when the heptane burned out after 4 minutes. After ca. 20 minutes the wood crib fire had developed to cover an area of about 1 m x 2.8 m of the crib. The flame height was 0.5-2.2 m above the floor, i.e. not impinging the ceiling. During the next 13 minutes the flames travelled 0.5 m of the wood crib, but the base area and flame height was almost unchanged as the flames at the left end of the crib were dying out.

After ca. 33 minutes the CLT in the ceiling ignited. This occurred from a combination of radiation and convection, as the flames did not impinge the ceiling After this the fire spread across the entire room in approximately 12 minutes. Within these 12 minutes, the fire travelled back and forth in four distinct waves or cycles (Figure 5). We have chosen to call them *flashing waves* in this article.

The flashing waves were recognized by a rapid flash fire along the ceiling, followed by a spread along the top layer of the wood crib, triggered by the radiation from the ceiling. Each wave caused external flaming from the window openings. After a short intense fire of 30-60 seconds, the flames gradually reduced in the ceiling, and the radiation-controlled fire in the top layer of the wood crib was reduced or even extinguished. The wood crib fire grew in size after each wave, and spread to the right end of the compartment in the the 3rd and 4th wave, in which the full flashover occurred at the end of the 4th wave at 45:30 (mm:ss).

Figure 5 #FRIC-01: Fire spread and retraction of 3rd flashing wave. Time (hh:mm:ss).

Figure 6 #FRIC-01: Most intense phase of burning shortly after flashover.

After the flashover, the fire burned intensely for about a minute (Figure 6), and then gradually decreased in intensity. From 49 minutes, the fire was clearly most intense at the far end from ignition, and external flames were only present from the far end window. Self-extinguishment of flames in the CLT ceiling started at around 50 minutes, from the left end of the compartment towards the right end over the next 10 minutes. The wood crib fire was continuous until about 60 minutes into the fire. From 60 to 95 minutes, the wood crib fire became increasingly discontinuous, starting from the left end of the compartment and moving towards the right end. Visible flames in the wood crib self-extinguished at 95 minutes. The compartment was observed for a total of 4 hours. At this point, very little of the wood crib was left. A few lamellae of the outer layer of the CLT in the centre of the compartment were hanging down from the ceiling. Hot spots were present around these loose lamellae. Manual extinguishing was then conducted. No reignition occurred after the manual extinguishment.

In #FRIC-02, the amount of heptane used to ignite the wood crib was increased to avoid the risk of self-extinguishment, based on the experience from #FRIC-01. The extra heptane caused both the ceiling and the wall to ignite at 2 minutes. From this point on, the fire spread extremely fast, and flashover occurred at 3 minutes and 15 seconds (Figure 7).

After flashover, the fire burned intensely with large external flames for about 8 minutes. The flames in the CLT wall and ceiling gradually extinguished from the left end of the compartment after ca. 14 minutes. At around 16 minutes all flames in the wall and ceiling had self-extinguished, and only the wood crib was still burning.

From around 25 minutes, the crib was burning with discontinuous flames, and the last flames extinguished after 40 minutes. However, after 75 minutes a 2nd flashover was seen with flames on the entire back wall and the ceiling (Figure 8). The fire continued until 175 minutes (Figure 9), when it was manually extinguished.

3.2 Mass loss rate and heat release rate

#FRIC-01

The HRR of the CLT was estimated to be 21 MW at maximum, while the estimated HRR of the wood crib was 20 MW. Combined the total HRR was estimated to 41 MW, see Figure 10.

#FRIC-02

The HRR of the CLT was at maximum 24.5 MW for the ceiling, and 13 MW for the wall. The estimated HRR of the wood crib was 35 MW at maximum. The total HRR was at maximum approximately 73 MW. This is 32 MW (78 %) higher than in #FRIC-01.

However, the contribution from the CLT wall was only 13 MW. The additional 19 MW, compared to #FRIC-01, is due to an increased HRR from the wood crib, which was 15 MW higher than in #FRIC-01, and from the CLT ceiling, which was ca. 4 MW higher.

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Figure 7 #FRIC-02: Most intense phase of burning shortly after flashover. Time (hh:mm:ss).

Figure 8 #FRIC-02: A 2nd flashover developed about an hour after the flames in the CLT had self-extinguished. Time (hh:mm:ss).

Figure 9 #FRIC-02: The fire was still burning strongly just before it was manually extinguished.

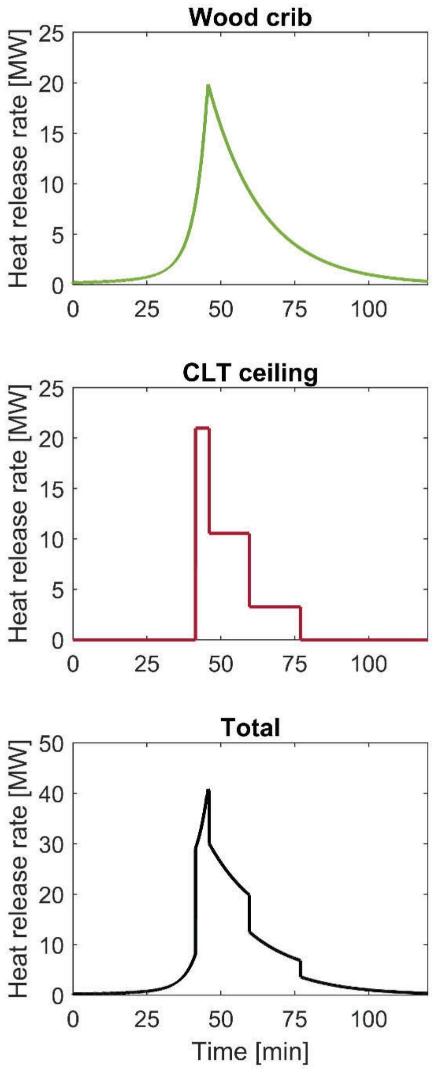

Figure 10 #FRIC-01: Estimated heat release rates of the wood crib and the CLT ceiling

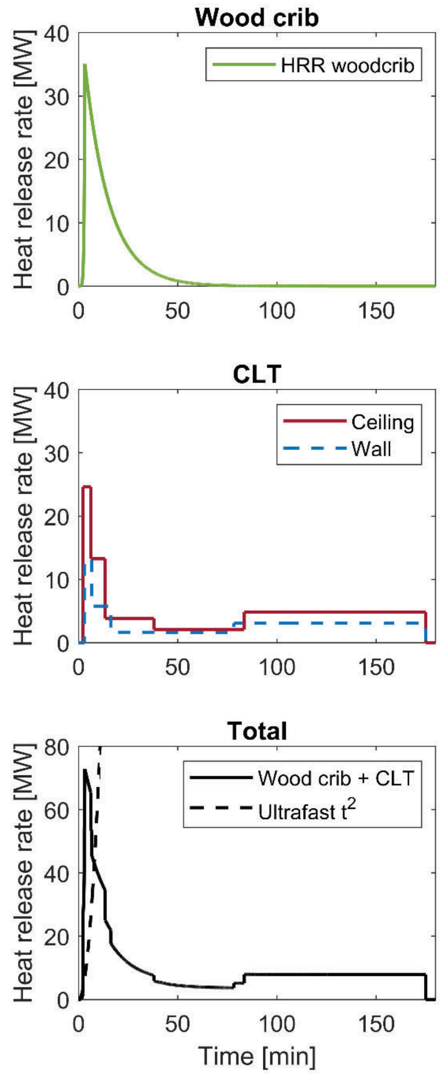

Figure 11 #FRIC-02: Heat release rate of wood crib and CLT in the ceiling and on the back wall

4 CONCLUSIONS

The experiments #FRIC-01 and -02 were conducted to increase the knowledge about fire spread and fire dynamics in large open-plan compartments with large ventilation openings. Both #FRIC-01 and -02 showed, in line with previous experiments, that the presence of exposed CLT surfaces significantly affect the fire spread rate and fire dynamics of a compartment fire.

In #FRIC-01, however, the time until ignition of the CLT ceiling occurred later than in previous experiments. This can be explained by the flame height of the wood crib fire, which were not impinging the ceiling.

In #FRIC-02 the ignition of the ceiling occurred earlier due to the increased amount of heptane in the start fire. However, the flame spread after ignition of the ceiling was much faster in #FRIC-01, which can be explained by the additional exposed surfaces on the CLT wall.

Both tests, but in particular #FRIC-02, show clearly that the presence of exposed CLT could cause a rapid fire development. A rapid fire development affects fire safety in several ways, for example available time for safe evacuation and rescue, and the size of the fire when the fire brigade enters the building.

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