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Large-scale fire experiments in a cross-laminated timber compartment with an adjacent corridor – Partly and fully protected with a water sprinkler system

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ABSTRACT

Two fire experiments have been conducted to study sprinkler system extinguishing performance in a compartment (13 m^2) with an adjacent corridor (12 m^2), both with exposed cross-laminated timber (CLT). Four nozzles were installed in the corridor and two in the compartment. In Experiment 1, the sprinkler system was fully functional and successfully controlled a concealed fire. In Experiment 2, nozzles in the compartment were disconnected, while the corridor nozzles were operative, giving flashover after 5 min with large flames emerging into the corridor, rapidly worsening evacuation conditions. Despite four activated nozzles in the corridor, the temperatures remained high, and flames spread through the corridor along the CLT ceiling and the upper parts of the wall, an area that was not effectively protected by the nozzles. After flashover, the compartment temperatures remained stable at ∼1000 °C until experiment termination at 96 min. This continued fire in the compartment can be explained by water from the corridor sprinklers not reaching this area, extensive radiative feedback by the CLT surfaces and delamination of CLT elements of the 20 mm layers. The charring rate was ≥1.1 mm/min for large parts of the exposed CLT wall and ceiling in the compartment during the fire.

1. Introduction

The ability of wood to sequester carbon, its appealing look, and the possibility to largely prefabricate elements, have increased the interest in using more wood in modern buildings. In particular, the use of cross-laminated timber (CLT) and glue-laminated timber in tall buildings.

Through a range of different fire experiments over the last decade, it is well known that exposed CLT can affect the fire dynamics of a compartment fire. For instance, exposed CLT may cause a more rapid flashover [1,2], cause higher temperatures [3], cause larger external flames [1,2] and cause fires with longer duration [3,4]. Furthermore, an exposed CLT ceiling has in several experiments shown to cause very rapid fire spread rates [5–10]. Summarised, exposed CLT has the propensity to cause a more hazardous fire scenario than if the surfaces were non-combustible.

A common fire safety principle is compartmentation, which means that a fire is not allowed to spread beyond the compartment of origin within a given time, typically 30, 60, 90 or 120 min. For buildings above a certain height or number of floors, or of a certain type of business (hotel, hospital, etc.), it is common and often required to have an automatic fire extinguishing system as an additional fire safety measure.

Worldwide, CLT is now used in a variety of different buildings. However, there is no common agreement on how much exposed CLT that is acceptable for different building types and heights, and the preventive measures that must be added to account for the exposed CLT vary strongly for different countries and regions.

Although it is now well known that exposed CLT has the potential to influence the fire dynamics, the fire safety strategy for a CLT building is not always adapted to this. Where the use of CLT is allowed, the added hazard by CLT is in many cases handled by a similar fire safety strategy as for a building without exposed CLT and is thus heavily reliant on the effect of compartmentation and/or an automatic extinguishing system.

There are two main types of extinguishing systems for buildings, traditional sprinkler systems and water mist systems. They are based on the same overall principle with the use of water to cool down the fire gases and surfaces. However, water mist uses a higher pressure and delivers smaller water droplets which evaporate faster due to the larger surface area to volume ratio [11]. Evaporation of water droplets plays an

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important role in fire extinguishing as a water droplet that is heated from room temperature and evaporates, absorbs six times more energy from the fire compared to if the same water droplet was heated to 100 °C and did not evaporate. In addition, the volume expands by a factor of 1700 when evaporated. This effect contributes to dilute fire gases and induce an inertisation effect, where the water vapour displaces the oxygen and combustible gases. At last, the small droplets contribute with a radiative blocking effect and thus lowering the radiative heat flux to surroundings. While traditional sprinkler systems are well known worldwide, water mist systems are less known and less used despite their good extinguishing qualities and their benefit of using less water.

Sprinkler systems have been used for many decades and there are, therefore, large statistical data and experience generated of successful interactions on a variety of different fires [12]. In the majority of the incidents, fires have been either put out or controlled by one sprinkler nozzle. Hence, the large statistical data can also be used as an indication that an adequately designed and maintained sprinkler system would be able to also handle a room fire with exposed CLT. This indication is supported by a few experiments, described below, where a sprinkler system has been tested in a room fire scenario with wooden surfaces present.

Frangi & Montana [1] performed six fire experiments in a 19 m^2 compartment, in which three of the experiments were performed with a quick-response sprinkler system. In one of the experiments, the wall and ceiling consisted of wooden boards, which could be considered relevant for a CLT-building. In all the experiments, the sprinkler activated within 2–3 min and effectively controlled the fire regardless of the surface material.

Zelinka et al. [13] performed five fire experiments in a 81 m^2 apartment with some exposed CLT. In two of the experiments, a sprinkler system was installed. In one experiment, the nozzles operated normally and activated due to the heat exposure from the growing fire, while in the second experiment, the water was intentionally delayed by 20 min. In both experiments, the sprinkler system effectively cooled down the fire gases and controlled the fire.

In the Code Red test series [5–7], three experiments showed that a fire could develop quickly in a compartment with an exposed CLT ceiling without any extinguishing system installed. In a fourth experiment (Code Red #03) [14], the effect of a water mist system was tested. The system was able to control the fire in the variable fuel and prevented ignition of the CLT ceiling.

Ko & Elsagan [15] compared the effect of two high-pressure water mist systems, one low-pressure water mist system and one sprinkler system, towards a residential fire scenario with exposed CLT walls and ceiling. The experimental setup was inspired by the UL 2167 [16] and BS 8458 [17] corner tests. All the systems successfully maintained the room temperature and gas concentration tenable, when activated with no delay, i.e. activation after 1–2 min. The most effective system was one of the high-pressure water mist systems which used the same water amount as the sprinkler but reduced the temperature and controlled the fire faster. The other high-pressure system had approximately the same cooling effect as the sprinkler system but used only one-fourth of the water content.

Despite the long track record of sprinkler systems with positive experiences on compartment fires, there have also been cases where the sprinkler system has not had the intended effect and has not controlled the fire [12,18,19]. In such cases the system has often fully or partly, intentionally or unintentionally, been closed off, maintenance has been insufficient, too little water has been added to the fire, or the fire intensity has been higher than what the system was designed for. The influence of additional fuel provided by exposed CLT surfaces on the effect of the sprinkler system has not been studied extensively. In all the abovementioned experiments with exposed wood/CLT, the systems have had all nozzles functional, although a few cases have considered a delayed activation. Hence, no publicly available experiments to date have investigated how a sprinkler system in a CLT building would handle a fire where one or several nozzles closest to the origin of the fire fail to activate or where the water droplets for some reason are not hitting the fire (e.g. due to obstacles).

Hence, the experiments presented in this paper give a perspective on how a fire in a CLT building may develop in a rare scenario where the nozzles closest to the fire fail to activate.

2. Method

2.1. Background

Two fire experiments were conducted as part of a risk assessment related to the building of five building blocks with student bedsits, with nine floors made of CLT structures built in 2015, see Fig. 1. The project is called Moholt 50|50.

The aim was to increase the knowledge on whether a functional water sprinkler system would control a fire in one of the student bedsits when some of the surfaces were exposed CLT (Experiment 1), and how a fire would develop in a scenario where the sprinkler nozzles in the fire compartment failed to activate (Experiment 2) and the door to the corridor was open. In both experiments, the visibility of escape route signs in the adjacent corridor was monitored. Another aim of Experiment 2 was to study the fire dynamics, charring rates and delamination related to the use of CLT. Some of the results from these experiments have been published in two Norwegian test reports earlier [20,21]. Compared to the test reports, this paper presents a more comprehensive description of the experimental setup and some additional results and discussions. For clarity, several adjustments were made to the fire safety strategy of the actual buildings after conducting these experiments. Those details are, however, outside of the scope of this paper.

The experimental setup represented one student bedsit (hereafter called "compartment") with part of the adjacent corridor in full size, as illustrated in Fig. 2. The compartment was installed with identical window, door, walls, ceiling, floor and extinguishing system as planned

Fig. 1. Three of the five blocks with student bedsits in the project Moholt 50|50, located in Trondheim, Norway. Photo by FRIC Fire Research and Innovation Centre.

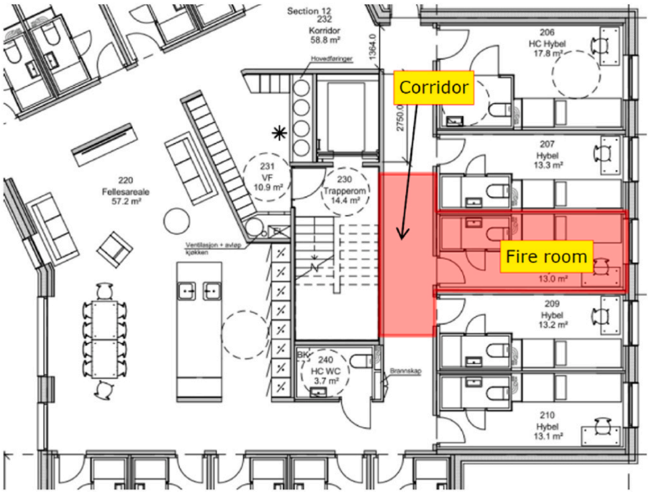

Fig. 2. Sketch of the floor plan of the planned building and background for the configuration of the experimental setup. Note, the fire room was mirrored compared to the sketch. Illustration from Hox [20], reused with permission.

for the actual building and with a fuel load density as expected in such an apartment. Two experiments were conducted:

> **Experiment 1** – Fire in the compartment. Functional sprinkler in both the compartment and the corridor. The door between the compartment and the corridor was open.
>
> **Experiment 2** – Fire in the compartment. Disconnected sprinkler nozzles in the compartment, but functional sprinkler nozzles in the corridor. The door between the compartment and the corridor was open.

The setup of Experiment 2 was inspired by the scenario called “disabled nozzle” in the IMO 265 [22] fire test standard for cabin and corridor onboard ships.

2.2. Geometry

A sketch of the compartment geometry is given in Fig. 3 and images of the compartment seen from the outside and the corridor are shown in Fig. 4. The compartment had a size of 5.75 m × 2.30 m x 2.80 m (l x w x h). Inside the room, there was a small bathroom. The floor area of the room including the bathroom was 13.2 m^2.

The compartment had two ventilation openings, a window (1.20 m × 1.60 m) and a door (0.90 m × 2.00 m). The window was a non-fire rated triple glazed window. In the experiments, the door was forced in a fully open position, while the window was closed. This ventilation configuration was considered a probable case based on experience with other student bedsit apartments. The opening factor was 0.07 $m^{1/2}$ in accordance with the definition in the Eurocode 1 [23], where the opening factor is calculated based on the area and height of the ventilation openings compared to the total surface area including the floor and ventilation openings.

In connection to the room, there was a corridor built of CLT with a width of 1.54 m and a length of 4.80 m. The height was 2.80 m, but had a suspended ceiling positioned at height 2.20 m. The suspended ceiling was a non-combustible system ceiling supported with T-profiles. An extension of the CLT corridor of 0.90 m and 2.40 m on the respective sides was added. The extensions had a timber frame which was protected with two layers of gypsum boards. The extension was made to get a longer corridor and to have equal distances from the door opening to each end of the corridor.

All of the CLT, including walls, floor and ceiling, were built of 100 mm thick CLT elements made up of 5 layers of 20 mm. A regular polyurethane adhesive (PURBOND HB S109) was used, which lacks a demonstrated resistance against glue-line integrity failure also referred to as delamination. The CLT was provided by a European producer and manufactured according to EAD 130005-00-0304 [24].

The build-up of the walls, ceiling and floor is illustrated in Fig. 3. Wall A and B were built up as follows: 100 mm CLT, 50 mm stone wool in a 75 mm steel stud wall, 12 mm gypsum board type A and 15 mm gypsum board type F [25]. The CLT in Wall A was exposed inside the compartment, while the CLT in Wall B was protected. The roof and floor were built up by 100 mm CLT with a 30 mm sound board and a 40 mm substrate layer on top of the CLT. Inside the compartment, the floor had a top layer of linoleum flooring, while the ceiling had exposed CLT. At the beginning of the experiment, 37 % of the enclosure area in the compartment was exposed. In the bathroom, the floor, two walls and ceiling had exposed CLT. The walls between the compartment and the bathroom were made of a light steel frame with stone wool insulation and one layer of gypsum board type A on the compartment side. The door to the bathroom was closed in both experiments. No additional load was added on the roof.

In the corridor, the CLT walls and ceiling were exposed. The suspended ceiling was a non-combustible board fixed with rails along the walls and across the corridor. The floor was similar as in the compartment.

2.2.1. Location of the experiment

The experiments were conducted inside the large fire test hall (12 500 m^3) at RISE Fire Research in Trondheim, Norway. The temperature in the hall was approx. 20 °C during the experiment. Smoke was extracted out from the hall through a fan in the ceiling and the ambient oxygen concentration during the experiment was considered non-affected by the fire.

2.3. Automatic extinguishing system

An automatic extinguishing system was installed in both the compartment and the corridor. The system was installed according to EN 12845 [26], designed as an Ordinary Hazard 1 (OH1) system. Two nozzles were installed in the compartment, and four nozzles were installed in the corridor. Two of the nozzles in the corridor were installed under the suspended ceiling ($z = 2.20$ m), and two nozzles were installed above the suspended ceiling, below the CLT ceiling ($z = 2.65$ m), see Fig. 3. Installation of nozzles above the suspended ceiling is required according to EN 12845 for protection of concealed spaces.

The distance between the nozzles was 3.0 m. The sprinkler nozzles were standard spray nozzles with a k-factor of 79 L/(min $bar^{1/2}$) and a 68 °C quick response glass bulb. The water pressure at the most remote nozzle was set equal to the minimum nozzle pressure of 0.35 bar defined by EN 12845. This pressure and k-factor result in a water flow of 46.7 L/min per nozzle and would have provided a water density of 5.2 mm/min if installed in a uniform grid. However, since the nozzles were not installed in a uniform grid, and nozzles in the corridor were installed in two heights (above and below the suspended ceiling) the actual water density, assuming an equal water flow distribution of the expected discharge area, becomes 9 mm/min in the compartment and 20 mm/min in the corridor. The former is based on a compartment area of 10.2 m^2 when excluding the bathroom. The water density in the corridor is based on a discharge area of 6 m × 1.54 m in the corridor, i.e., 1.5 m outside each end of the nozzle positions. The positions of the nozzles are illustrated in Fig. 3

2.4. Instrumentation

Gas temperatures were measured in the compartment and in the corridor with thermocouples (TC) type K 0.5 mm. The TCs in the compartment were located 100 mm below the ceiling ($z = 2.70$ m). In the corridor, there was one TC 100 mm below the CLT ceiling ($z = 2.70$

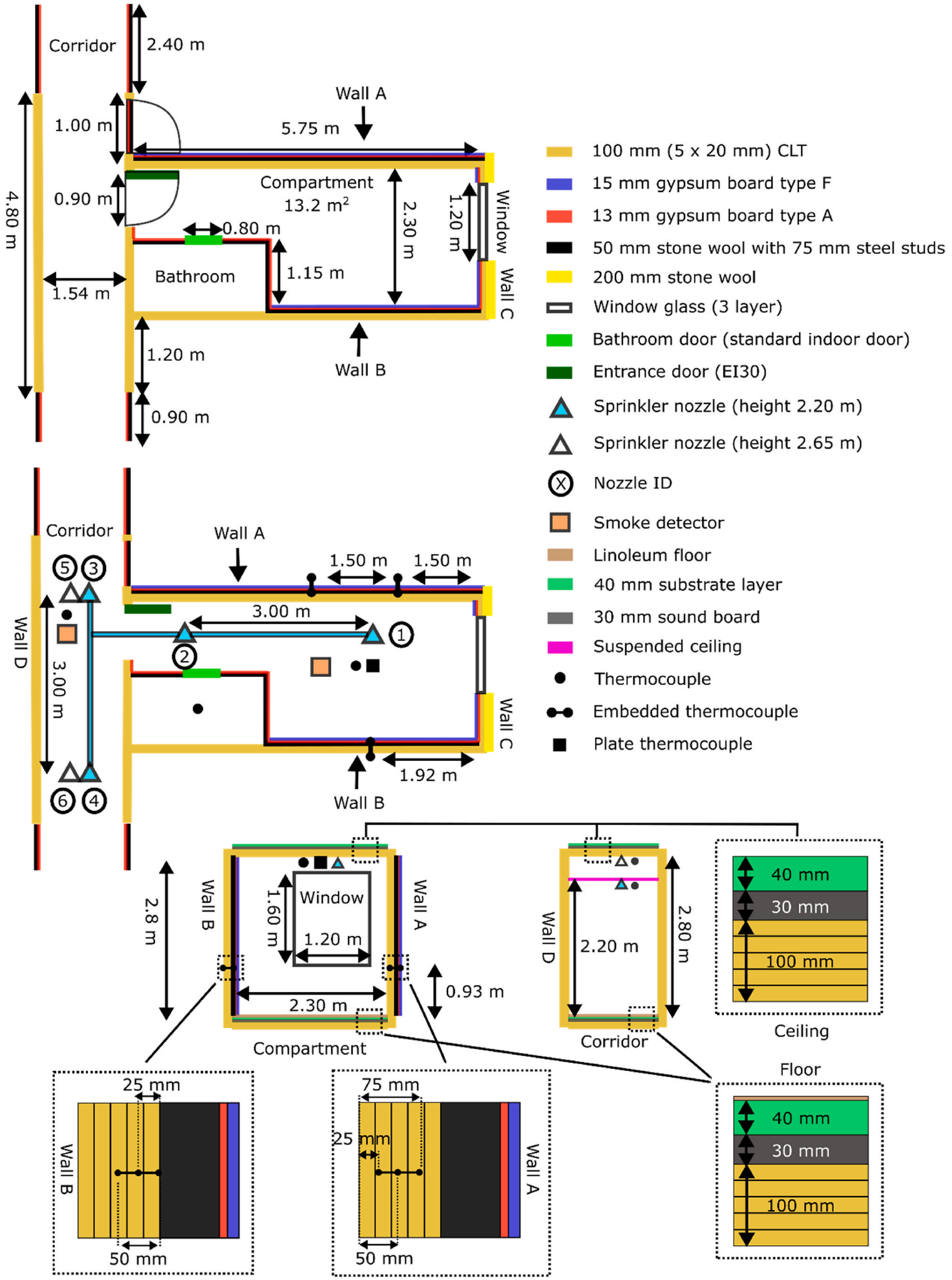

Fig. 3. Overview of geometry and instrumentation of the experimental setup. Horizontal cross-section of the compartment and corridor (above), vertical cross-section of the compartment and corridor (middle), detailed cross-section of Wall A and B, floor and ceiling (below). Illustration by FRIC.

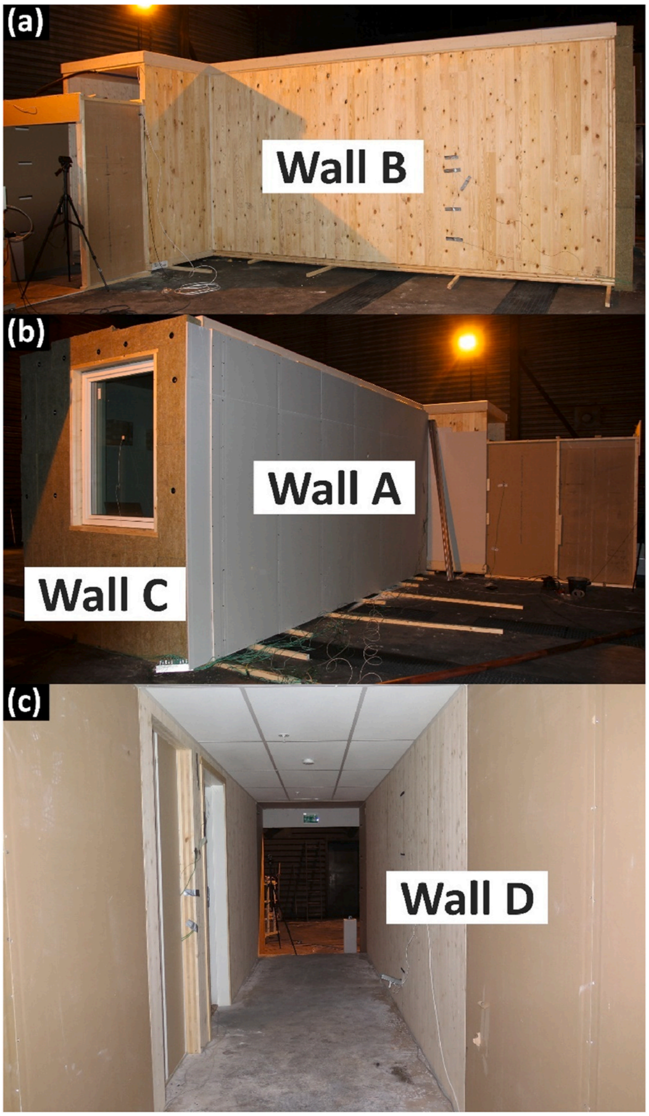

Fig. 4. Images of the compartment from the outside (a, b) and corridor (c). The corridor had exposed CLT on parts of the wall and in the ceiling (above the suspended ceiling). Photos by RISE Fire Research.

m), and one TC 100 mm below the suspended ceiling (z = 2.10 m). A plate thermocouple (PT), as described in EN 1363–1:2020 [27], was also installed in the compartment, 100 mm below the ceiling facing downwards.

In addition, thermocouples type K 1.5 mm were embedded into the CLT walls and ceiling through 1.6 mm diameter holes drilled from the non-exposed side.

Two optical smoke detectors with a heat sensor of type Deltronic PHR-1211 as per EN 14604 [28] were installed, one in the compartment and one in the corridor. An overview of the locations of the instrumentation is illustrated in Fig. 3.

2.5. Fuel load

The fuel was designed to represent the fuel load as in a typical student bedsit. The fuel load of the expected equipment and materials in the student bedsit, including shelves, books, clothes, furniture etc. was calculated to be approx. 8250 MJ, i.e.,625 MJ/m^2 per floor area, and was in the experiment represented by mock-up furniture and wood cribs.

In Experiment 1, the exposed CLT at Wall A was covered by a thin plywood board, and the window on the inside was covered by a gypsum board, see Fig. 5. This was done to protect the window and CLT, so they would be undamaged for Experiment 2. Also, the fuel load farthest away from the ignition point was removed. These changes were made as the involvement of the CLT wall, and the remote fuel load was considered unlikely. The fuel load density of the variable fuel load was reduced to 173 MJ/m^2 in this experiment.

In Experiment 2, the setup was similar as in Experiment 1 but with the addition of wooden pallets and several wood cribs to ensure a variable fuel load density of 625 MJ/m^2, as shown in Fig. 6. A detailed list of the combustibles in the experiment is given in Table 1.

The ignition package was concealed under a table (0.6 m × 0.9 m x 0.9 [w x l x h]) next to the wooden wall and consisted of 1.0 L heptane in a 0.3 m × 0.3 m metal tray with a wood crib positioned on top of the tray. Images of the experimental setup and the ignition package is given in Fig. 5.

2.6. Observation of visibility and measurements of smoke density

Two safety way-guidance signs were located at 2.05 m height, i.e., 0.15 m below the suspended ceiling, at each end of the corridor. One of the signs was a photoluminescent sign that “glows in the dark”, while the other one was illuminated powered by electricity, seeFig. 7.

The visibility of those signs was observed by two people standing at the other end of the corridor, located approx. 8 m from the signs. One type of sign was placed in one end of the corridor, and the other sign type at the other end. The smoke density was measured through the light obscuration of a red laser, in one position in the photoluminescent sign’s corridor side. The light obscuration was measured as a percentage of reduction in the intensity of the laser across the corridor at the same height as the safety way-guidance signs.

3. Results

3.1. Experiment 1

The experiment was started by igniting the heptane in the tray under the table, and the temperatures increased steadily in the compartment and the corridor after ignition, see Fig. 8. At approx. 1 min the smoke detector in both the compartment and the corridor activated. It is unknown whether the detectors were triggered by heat or smoke. At 2 min, one nozzle was activated. At this point, the temperature was 131 °C under the ceiling, in the vicinity of the nozzle. An image of the fire size at this point is given in Fig. 9. The effect of the nozzle was clearly seen half a minute later, in which the temperatures were effectively reduced in both the compartment and the corridor. This reduction prevented additional nozzles from being activated. Due to the table above the ignition source, the fire under the table was not reached by water and the sprinkler system was not able to completely extinguish the fire. However, from 4 to 9 min the temperatures in the room were kept between 20 and 25 °C and the fire was effectively controlled, see Figs. 8 and 10. At 9 min, the sprinkler system was shut down. This caused a minor increase in the temperatures until manual extinguishment was conducted at 9.5 min. A summary of the events of the experiment is given in Table 2.

The water damage after the experiment was not evaluated, but in total approx. 330 L of water was used for the 7 min the one nozzle of the system was operating, which yields a water density of approx. 4.5 mm/min.

3.2. Experiment 2

3.2.1. Fire development

Similarly as in Experiment 1, the experiment was started by igniting the heptane in the tray under the table. Details of the development are listed in Table 3. The first 2 min of the fire developed almost identical to the fire in Experiment 1, as seen in Fig. 11. The similarity was also

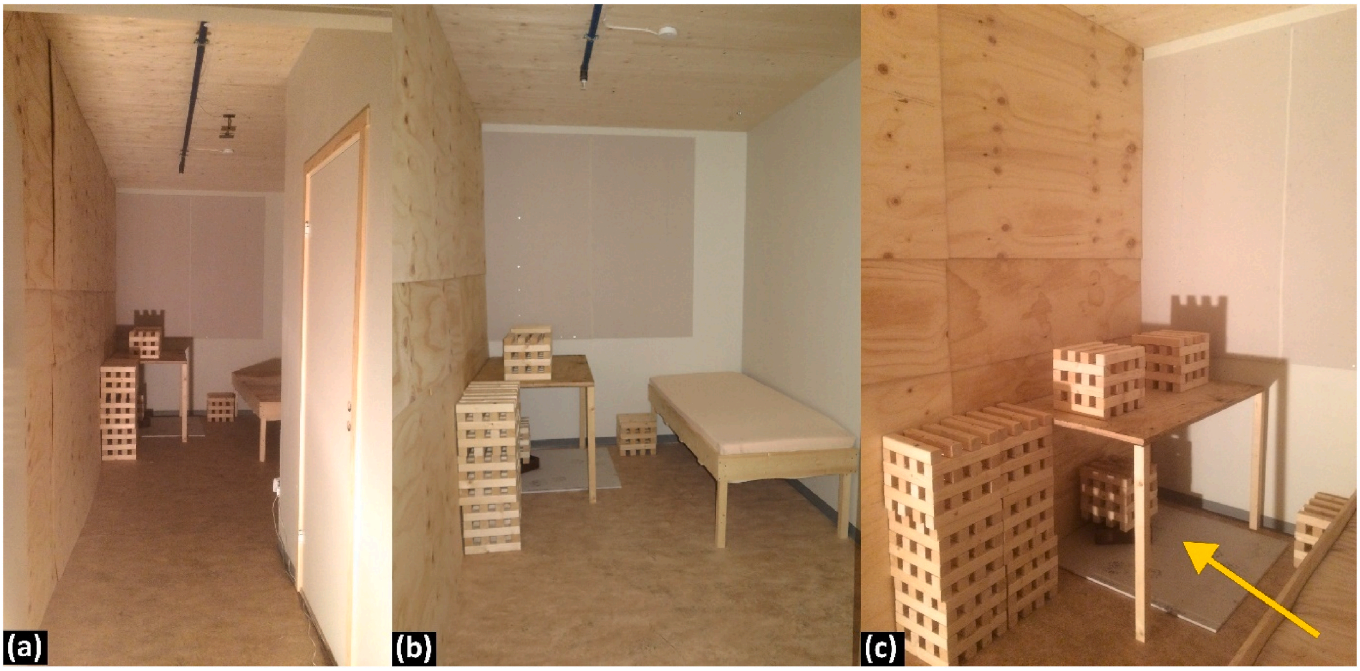

Fig. 5. Compartment in Experiment 1 seen from the corridor (a) and (b) a close-up of the combustibles, and (c) a close-up of the ignition source (yellow arrow) which consisted of a wood crib positioned above a tray of heptane under a table. The exposed CLT on Wall A (on the left side) was here covered by plywood boards and the window was covered by gypsum boards. The door in (a) is leading into the bathroom. This door was closed during both experiments. Photos by RISE Fire Research. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

confirmed through almost identical activation of the smoke detectors (66 vs. 70 s). However, from 2 min, i.e., the activation time of the nozzle in Experiment 1, the similarities ended.

A visual impression of the fire development is given in Fig. 12. The exposed wall, Wall A, contributed to spreading the flames up to the ceiling after approx. 4 min. Thereafter, the flames spread rapidly across the ceiling. Before the ceiling was ignited, the fire was localised to the inner corner where it had been ignited, and combustible items nearby had not been involved in the fire yet. At 04:50, i.e., less than a minute after the ceiling was ignited, the fire had developed to a flashover and ignited all combustible surfaces in the compartment. From this point, the temperatures were almost constant at 1000 °C under the ceiling until the end of the experiment at 96 min, see Fig. 13.

Due to the open door, the temperatures in the corridor increased rapidly as well, and triggered the activation of the nozzles under the suspended ceiling at 02:50 (no. 3) and 04:00 (no. 4). Despite the early activation, the nozzles had little or no impact on the fire development in the compartment as very little water from the sprinkler system reached the fire inside the compartment.

From approx. 5 min, large flames emerged from the door opening and into the corridor and flames spread out from the corridor at 6.5 min, see Fig. 14. Despite four nozzles activated in the corridor, in which two of them were located close to the door opening, the sprinkler system was not able to extinguish the fire, control it, nor keep the temperatures low in the corridor. The high temperatures caused ignition of the CLT ceiling and the upper parts of the walls in the corridor, as seen in Fig. 16. The areas of the CLT that were well protected are also shown here.

Breakage of first, second and third layers of the glass occurred at 04:30, 04:55 and 05:45. At 8.5 min, the suspended ceiling fell down, see Fig. 15. At 12 min, the water pressure was increased from 0.35 bar to 2.0 bar which increased the total water amount delivered from 187 to 440 L/min. This did not have any immediate effect and manual intervention with fire hoses was necessary to control the fire in the corridor. The application of water with fire hoses is recognized through the grey vertical lines in Fig. 17. Despite manual intervention and increased pressure on the nozzles, the temperatures in the corridor quickly increased again after the manual intervention seized. This confirmed that the sprinkler nozzles alone were not capable of controlling the fire in this scenario, despite an increase in the water pressure far above the minimum design pressure. The fire in the compartment burned intensely and showed no signs of cooling down, as seen in Fig. 13. During the fire, many small pieces of wood were seen falling down, which is a clear sign of delamination. At approx. 30 min, the fire had burned completely through the light steel frame wall of the bathroom. This is recognized by similar temperatures measured in the bathroom and the compartment at 30 min. The TCs installed in the compartment gave strongly fluctuating and strange values after 30 min. Thus, the temperatures in the bathroom were from this point considered to represent the whole compartment. The gas temperature was almost constant at around 1000 °C until the ceiling collapsed at 96 min and the experiment was terminated.

3.3. Charring rate

The charring rates of the exposed CLT were calculated at some locations (see Fig. 3) by the propagation of the 300 °C isotherm through the exposed CLT Wall A and the ceiling, and given in Table 4. A clear step pattern was seen for the charring rates, in which the average charring rate was highest for the first 25 mm with 1.45 mm/min and was then reduced to 0.95 mm/min and 0.69 mm/min for the following two 25 mm intervals. Very little of the exposed wall remained after the experiment, as seen in Figs. 18 and 19. However, some of the CLT remained at the locations where the embedded TCs were installed. Thus, the reported charring rates were slower than for the CLT areas that were completely consumed at the end of the experiment.

For the parts of the CLT that were complete consumed during the experiment, the minimum average charring rate was 1.1 mm/min [100 mm/(96–4.8 min)], when assuming that charring of CLT started at flashover, i.e. at 4.8 min, and the duration of the experiment was 96 min.

No pieces of the ceiling were found after the experiment, strongly indicating that the entire CLT ceiling had been burned away before the ceiling (i.e., any remaining CLT + sound board and substrate layer) collapsed. For the initially protected wall, Wall B, most of the wall was

Fig. 6. Experimental setup of the compartment in Experiment 2. In the compartment, the CLT on Wall A (left) and in the ceiling were exposed. The fuel package was similar to Experiment 1 but with additional wood cribs and wood pallets (see Table 1). Photos by RISE Fire Research.

Table 1
List of fuel in the experiments.

Fuel	Heat of combustion	Experiment 1	Experiment 2
Foam mattresses[a]	170 MJ/mattress	2 pcs	2 pcs
Wooden desk	17.5 MJ/kg	28.4 kg	28.4 kg
Wooden bed	17.5 MJ/kg	23.6 kg	23.6 kg
Heptane	30 MJ/L	1.0 L	1.0 L
Wooden pallets[b]	394 MJ/pallet	Not included	12 pcs
Wood cribs[c]	112 MJ/crib	9	20
Energy of fuel		2288 MJ	8248 MJ
Fuel load density		173 MJ/m^2	625 MJ/m^2

[a] The mattresses were similar to the ones used in IMO Res. 265(84) [22].

[b] Based on an average weight of 22.5 kg per pallet and heat of combustion of 17.5 MJ/kg.

[c] The cribs had a weight of 6.4 kg a size of 0.3 m × 0.3 m x 0.3 m, inspired by the ones in IMO 1165 [29] and FM 5560 Appendix G [30].

charred approx. 20 mm, while the maximum char depth was 60 mm.

For the initially protected wall, Wall B, the first observation of burning was after 47 min. This burning was for a smaller area and resulted in a final char depth of 60 mm. From the TC measurements, the interface between the CLT and the stone wool reached 300 °C after 66 min and 463 °C after 96 min, indicating that this part was not directly exposed to flames. The char depth of this location was 20 mm, yielding a charring rate of approx. 0.67 mm/min.

3.4. *Observation of visibility and smoke density measurements of experiment 1 and experiment 2*

A comparison of the results of Experiments 1 and 2 is presented in Fig. 20 and a comparison of the visibility of the safety way-guidance signs during the experiments is given in Fig. 21. The smoke density was approximately the same in both experiments until 4.5 min, but with a slightly faster development in Experiment 2.

In Experiment 1, the photoluminescent sign stopped being visible at approx. 2.5 min into the fire, when the light intensity had been reduced by 90 %. However, at approx. 4 min, the sign became visible again which lasted until the sprinkler system was shut down. The illuminated sign was visible throughout the experiment. The increased visibility after 3 min until 9 min can be explained by the reduction of the fire size due to the sprinkler system controlling the fire, and a correspondingly lower soot production.

In Experiment 2, the smoke filling in the corridor behaved similarly as in Experiment 1 until the first nozzle (no. 3) in the corridor was activated, at 02:50 (mm:ss). The activation of the nozzle caused more disturbance of the smoke which reduced the visibility. The photoluminescent sign was not visible after 2 min, with 85 % light reduction, while the illuminated sign was visible until 4.5 min (98 % light reduction).

It should be noted, that due to ventilation conditions in the test hall during the experiments, some more smoke exited out of one end of the corridor (on the photoluminescent sign side) compared with the other (illuminated sign side), while the smoke density was only measured at the photoluminescent side. When comparing the smoke density at which each sign stopped being visible, some error margin must therefore be taken into account for the illuminated sign.

4. Discussion

4.1. *Experiment 1*

The key result from Experiment 1 was that a functional sprinkler system can be capable of controlling an initially concealed fire in a small compartment with exposed wooden surfaces. This result is in line with several other experiments [1,13–15]. The fire was controlled by one nozzle and could easily be put out by a firefighter after some time.

4.2. *Experiment 2*

Experiment 2 provided new insight into a rare scenario where the sprinkler nozzles in the vicinity of the origin of the fire, for some reason are malfunctioning or do not deliver water to the fire, and where there is an open door from the non-protected area to a sprinklered area. The experiment highlighted that the same initial fire as in Experiment 1 could develop into a severe fire in a few minutes if no automatic extinguishing system is present or activated, which demonstrates how effective a functional automatic extinguishing system can be.

Further details of the experiments are discussed in the following sections.

4.2.1. *Fire dynamics*

A fire with disconnected sprinkler nozzles could be intense regardless of the material choice. However, several observations throughout the experiments and findings in the literature suggest that the presence of the CLT caused a more severe fire than if non-combustible surfaces had been present.

Firstly, it is well known that larger external flames likely would occur for compartments with exposed CLT [2,4,31]. However, it has also been shown that a particular large variable fuel load density (1085 MJ/m^2) can reduce this effect, as the percentage increase of combustible gases from the exposed CLT becomes less [32]. How large this effect was in the presented experiment is not known, but based on available literature,

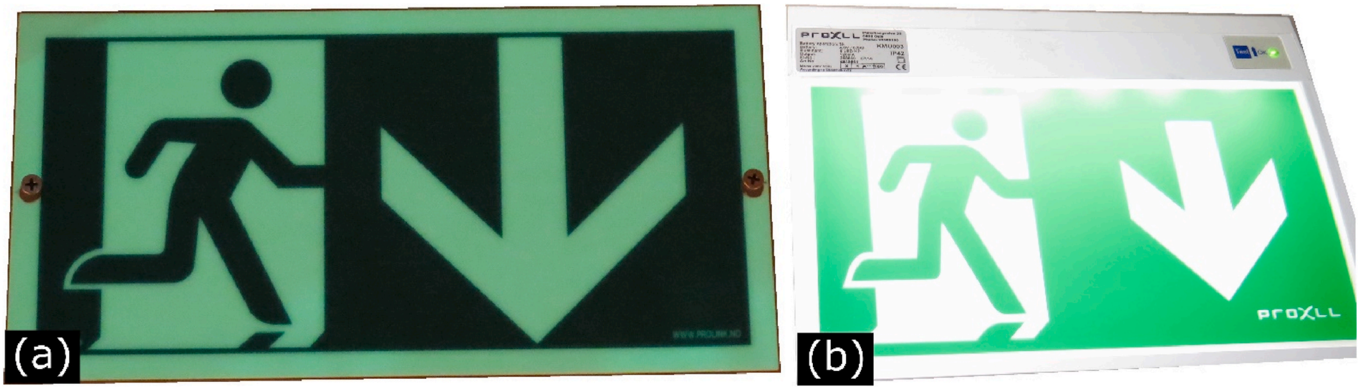

Fig. 7. Pictures of the two types of safety way-guidance signs used, (a) photoluminescent sign and (b) illuminated sign. Photos by RISE Fire Research.

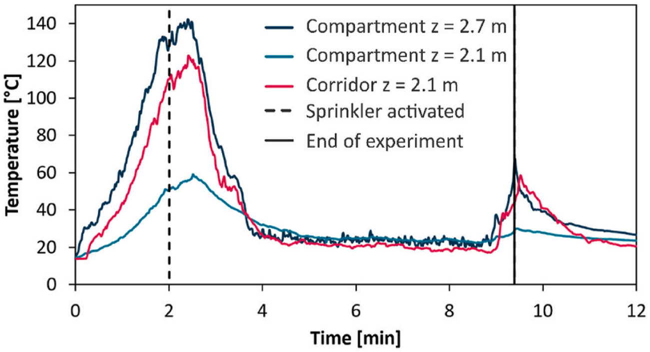

Fig. 8. Temperatures measured by TCs in compartment and corridor during Experiment 1. Location of the measurements are given in Fig. 3.

and the fact that the opening factor was 0.07 $m^{1/2}$, corresponding to a typical ventilation-controlled fire [33], it is assumed that larger external flames were present also in this experiment. It is acknowledged that this phenomenon is not directly related to the use of CLT, and a similar effect could have been obtained with another combustible surface material.

One of the key aspects of a ventilation-controlled fire is that the temperature in the fully developed phase does not increase with increasing fuel load. However, in recent experiments [34] it was observed that the temperature in an underventilated experiment increased slightly (+40 °C) with some exposed CLT (19–26 % of enclosure area), while the temperatures decreased (−50 °C) with more exposed CLT (36–64 %) compared to a reference experiment without exposed CLT. Based on these findings and the large percentage of exposed surfaces in the compartment (37 % at beginning of experiment and 58 % after encapsulation failure of Wall C and burn-through to the bathroom), it is assumed that the temperatures in the compartment were similar to or slightly lower than it would have been in a reference fire.

Compartment fires with exposed CLT have in several experiments [2] reached flashover earlier than in a reference experiment. Although no reference experiment was conducted here, it was observed in Experiment 2 that the fire spread was accelerated by the combustible wall and ceiling (see Fig. 12). This is a strong indication that the fire developed faster than it would have done without the exposed CLT wall and ceiling. Also here, the difference is not solely due to CLT, but due to the combustibility of the surface.

The severe fire in the corridor can be explained by the large flames from the compartment, and the exposed CLT walls and ceiling in the corridor. The flames and the hot smoke gases that emerged from the compartment door induced pyrolysis of the exposed CLT in the corridor, which again released combustible gases into the corridor. Due to the high temperatures below the ceiling of the corridor, those combustible gases burned and contributed to spreading the fire further along the corridor.

A key result of this experiment was the almost constant gas temperatures in the compartment from flashover until the experiment was terminated at 96 min. Such a behaviour has been reported for some experiments [2,4], although it is more frequently reported that the flames of the CLT undergo self-extinguishment when the variable fuel load has started to burn out [5–8,10,38]. Typically, this occurs when the incident heat flux goes below 45 kW/m^2, corresponding to a surface temperature of approx. 700 °C [8,39]. Such flaming self-extinction did not happen in this experiment, and can be explained by the following parameters:

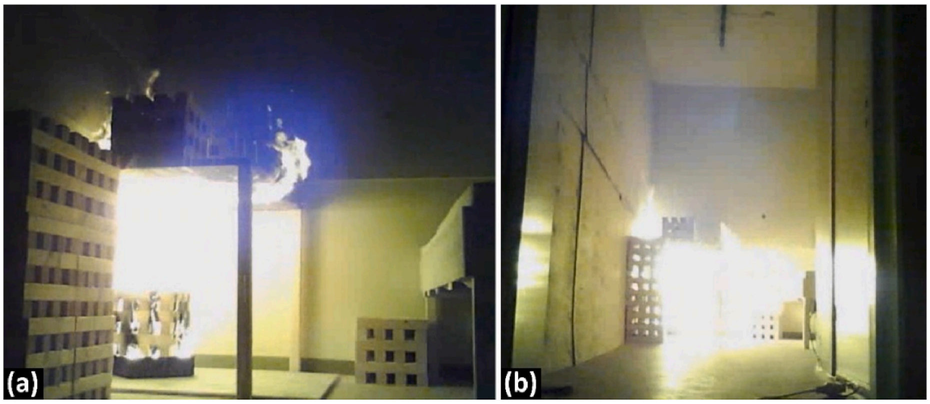

Fig. 9. Image of the fire just before the sprinkler system was activated (01:59 mm:ss). At this point, the wall under the table had ignited, and the fire was spreading upwards the wall. Photos by RISE Fire Research.

Fig. 10. The location of the fire under the table shielded the initial fire from direct water impingement. Hence, the fire was not extinguished, but controlled. Image from 08:10 (mm:ss). At this point the floor was covered by several cm of water. Photo by RISE Fire Research.

Table 2
Fire development Experiment 1.

Time (mm:ss)	Event
00:00	Ignition of 1.0 L heptane under the table under the window.
01:06	Smoke detector in compartment activated.
01:10	Smoke detector in corridor activated.
01:59	Sprinkler nozzle closest to the fire activated (i.e., no. 1).
02:24	Maximum temperature (142 °C) in compartment.
09:00	Sprinkler system shut down.
09:30	Manual extinguishment of the small remaining fire.

- Extensive radiative heat feedback between the wall and the ceiling that were exposed from the beginning, and from CLT that became exposed during the experiment (part of Wall B, Wall C, and surfaces in the bathroom).
- The CLT elements were built up of five 20 mm layers and with an adhesive that lacks a demonstrated resistance against glue-line integrity failure. When the exposed layer delaminated, a new layer was exposed, adding fresh preheated fuel to the fire. With the fresh fuel continuously added to the fire, the temperatures were high still after the variable fuel burned out. In fact, the temperatures and incident heat fluxes were never close to the threshold where CLT typically have experienced self-extinguishment of flames, and it is thus not surprising that self-extinguishment of flames did not happen in this experiment.

Another example of continuous burning when having 20 mm CLT layers and the same type of adhesive is in #FRIC-02 [10] where a second flashover occurred after 76 min and then continued burning with a reduced fire intensity (550–850 °C) until manual extinguishment was conducted almost 2 h later.

It is possible that a different adhesive could have reduced or prevented delamination of the CLT, and thereby have decreased the charring rate and resulted in lower temperatures. However, delamination has been observed also for improved adhesives [40], and it is thus unknown whether self-extinguishment would have occurred with a more heat resistant adhesive.

Table 3
Fire development of Experiment 2.

Time (hh:mm:ss)	Event
00:00:00	Ignition of 1.0 L heptane under the table under the window.
00:01:10	Smoke detector in compartment activated.
00:01:24	Smoke detector in corridor activated.
00:02:50	First sprinkler nozzle (no. 3) in corridor below the suspended ceiling activates.
00:04:00	Second sprinkler nozzle (no. 4) in corridor below the suspended ceiling activates.
00:04:30	First and innermost glass layer of the window breaks.
00:04:50	Flashover in compartment.
00:04:55	Second glass layer of the window breaks.
00:05.45	Third glass layer of the window breaks – external flames emerging out of the window.
00:06:05	First sprinkler nozzle (no. 5) above the suspended ceiling activates.
00:06:05–00:08:30	Second sprinkler nozzle (no. 6) above the suspended ceiling activates (exact time not known).
00:08:30	The suspended ceiling falls down.
00:12:00	The water pressure of the extinguishing system is increased from 0.35 to 2.0 bar, i.e., 110 L/min pr nozzle and a total of 440 L/min.
00:12:30	Manual extinguishing with fire hoses to control the fire in the corridor.
00:25:00	Gypsum boards around the bathroom walls fall down.
00:47:00	First observation that part of the protected CLT wall (Wall B) is burning.
01:00:00	Burn through at the intersection between the CLT and the floor.
01:10:00	First observation of burn-through of the exposed CLT wall (Wall A).
01:25:00	Large parts of the exposed CLT wall (Wall A) are burned through.
01:36:00	The ceiling collapses.
01:36:10	Experiment terminated/manual extinguishment started.

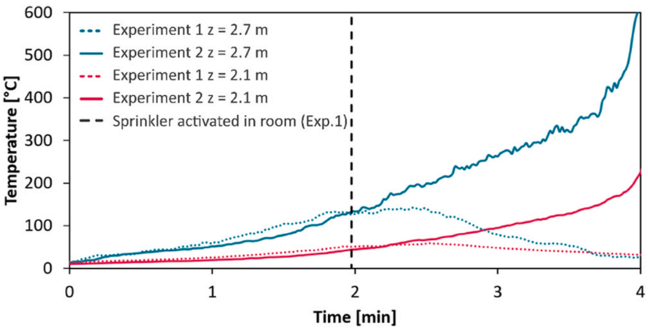

Fig. 11. A comparison of temperatures in Experiment 1 and Experiment 2 shows that the temperature development was similar for the first 2 min, i.e. the time until the sprinkler nozzle activated in Experiment 1.

It is important to note that such a prolonged fire without any decay phase as in this experiment would not have happened for a compartment without CLT or for a compartment with a thin layer of combustible material (wooden cladding etc.). A typical compartment fire with non-combustible linings would reach the decay phase when the variable fuel is burning out.

4.2.2. *Charring rate*

The charring rate was higher the first 25 mm into the CLT than the consecutive 25 mm intervals, with 1.45 mm/min versus 0.95 and 0.69 mm/min. This happened while the gas temperature in the room was approximately constant at 1000 °C, and fits with a typical mass loss rate curve of wood from a cone calorimeter test [35] where there is an initial high peak followed by a stable but lower level.

A similar step-behaviour was observed in the #FRIC-01 and -02 experiments [8,10]. However, in those experiments, the temperature varied a lot, and it is unknown to what extent the difference in temperature influenced the change in the charring rate.

Also from a typical cone calorimeter curve of wood, the mass loss rate typically increases at the end, known as the second peak [35]. This

Fig. 12. Fire development in compartment during Experiment 2. Time in mm:ss after ignition. View from the door opening (left) and close-up of the fire under the table (right). Photos by RISE Fire Research.

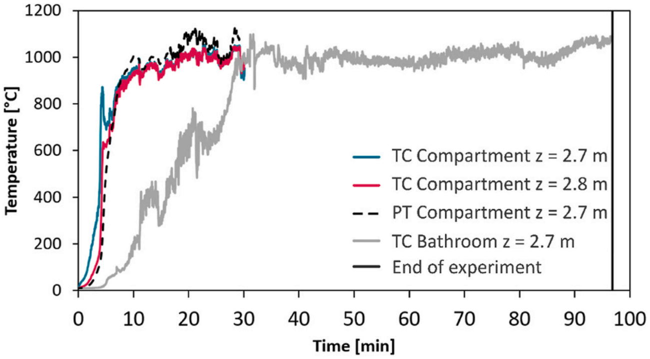

Fig. 13. Temperatures under the ceiling in the compartment. The TCs at 2.7 m and 2.1 m height in the compartment experienced strong fluctuations after 30 min and are thus not included. The PT fell down after approx. 30 min and measurements after this is not included.

Fig. 14. Large flames quickly spread under the ceiling in the corridor. Image at approx. 6.5 min. At this point, the two sprinklers under the suspended ceiling have activated and at least one of the nozzles above the suspended ceiling. Photo by RISE Fire Research.

increase happens as the thermal wave through the wood is affected by the boundary conditions at the insulated non-exposed side. This was not measured directly, but since Wall A was insulated at the non-exposed side (see Fig. 3), it is believed that the charring rate increased before the CLT was close to being burned through. A thicker CLT wall would therefore likely have resulted in a slightly slower average charring rate. How large this effect is, and to what extent this effect will be influenced by delamination is not known.

The charring rates were measured based on temperatures inside the CLT through TCs inserted from the non-exposed side. It is acknowledged that this method may cause an underestimation of the temperatures since the TC wire itself acts as a heat sink due to its higher thermal conductivity than wood [36]. Since several measuring points were installed, it is possible that the heat sink effect affected only the first measuring point, i.e. from 0 mm to 25 mm. For the other intervals (25–50 mm and 50–75 mm) it is likely that the underestimation was equal for those measurement points and thus cancelled each other out.

Since the TCs were located at the few pieces of CLT that were remaining after the fire, it is fair to conclude that the average measured charring rate from 0 to 75 mm of 0.87 and 1.03 mm/min were on the non-conservative side, and faster charring rates must have been present for the CLT areas that were completely consumed by the end of the

Fig. 15. Large flames emerged from the compartment into the corridor and ignited the exposed CLT ceiling and the upper parts of the walls. The suspended ceiling suffered great damage from the flames and fell down after 8.5 min, i.e., approx. 3.5 min after flames emerged into the corridor. Photo by RISE Fire Research.

Fig. 16. (a) The corridor after the experiment. (b) The CLT ceiling and the upper walls of the corridor were heavily charred despite the activation of four sprinkler nozzles. The marks on the wall also show clearly which areas that were effectively protected by the water. Photos by RISE Fire Research.

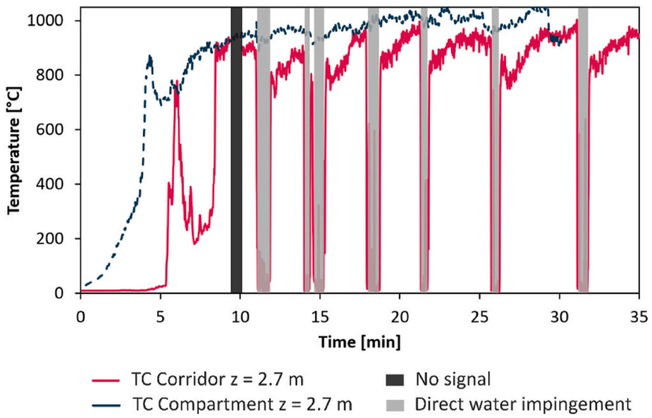

Fig. 17. Comparison of the maximum temperature in the compartment and in the corridor above the suspended ceiling. The low temperatures measured in the corridor are due to direct water impingement by manual extinguishment.

experiment. Since the CLT at several places were completely consumed and no TCs were positioned as deep as 100 mm, it is only possible to suggest a minimum average charring rate for these regions of 1.1 mm/min.

That the CLT was not completely consumed where the TCs were installed, but completely consumed mostly around (see Fig. 19), may have been caused by an anchoring effect of the layers from the embedded TC wires, thus preventing or delaying delamination in these regions. Closer to the door opening, a larger part of Wall A was remaining. This was likely caused by some cooling effect by the supply of colder air into the compartment at this place. Also, some water from the closest nozzle might also have contributed in wetting this part of the wall.

Wall B, that was made up of two layers of gypsum boards (type A + F) and 50 mm stone wool prevented the CLT wall to contribute to the fire for a long time. The low temperatures at the CLT surface (≤463 °C) and the lower charring rate (0.67 mm/min) compared to the exposed CLT (Wall A and ceiling) also indicates that the light steel frame wall with stone wool insulation provided some protection [37] to a large part of the wall throughout the duration of the experiment.

4.2.3. *Effect of the sprinkler system*

The four nozzles in the corridor activated shortly after flashover of the compartment. The water delivered was not able to effectively reduce the fire in the compartment, which can be explained by the short discharge range of the nozzles and the water spray from the closest nozzle being partly blocked by the wall between the compartment and the corridor.

Despite a total water flow of 187 L/min, the temperatures were not reduced significantly under the ceiling in the corridor. The increase of water pressure to 2.0 bar and a total water flow of 440 L/min, i.e., 40 mm/min, did not make any difference. The entire CLT ceiling and upper parts of the walls in the corridor were considerably charred, while the lower parts of the walls were undamaged, see Fig. 16. Manual extinguishment with fire hoses was needed to control the fire.

The reason why the water system was not able to control the fire in the corridor, despite the large water flow used, can be explained as follows:

- Due to the strongly underventilated compartment fire and a fire with no decay phase, a continuous flow of hot (1000 °C) combustible gases were delivered into the corridor.

Fig. 18. Very little of the exposed CLT wall (Wall A) was remaining after the experiment. The light steel frame wall with stone wool insulation that was on the non-exposed side of the wall can be seen lying down to the right. The greyish pieces to the left are parts of the substrate layer from the collapsed ceiling. Photo by RISE Fire Research.

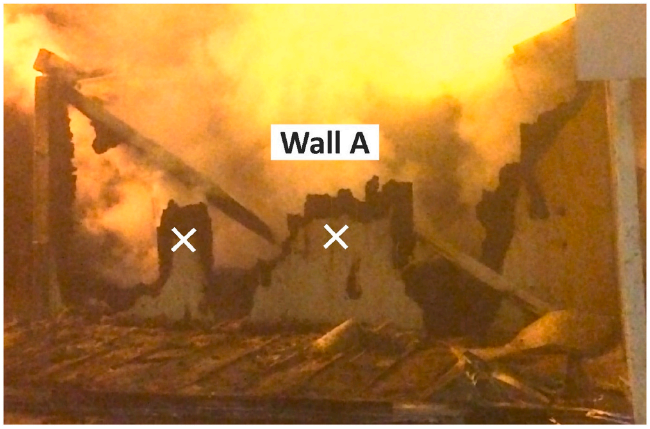

Fig. 19. The remnant of the exposed CLT wall (Wall A). The CLT wall was remaining around the areas where the embedded TCs had been, marked with arrows, and close to the door leading to the corridor (right side). The light steel frame wall that was on the non-exposed side of the CLT is lying down in front of the wall. Photo by RISE Fire Research.

Table 4
Estimated charring rates of exposed CLT based on embedded thermocouples.

	Time to reach 300 °C [min]				Charring rate [mm/min]			
Location	0 mm[a]	25 mm	50 mm	75 mm	0–25 mm	25–50 mm	50–75 mm	0–75 mm
Wall A (1)	4.2	18.8	41.7	76.8	1.71	1.09	0.71	1.03
Wall A (2)	4.2	22.6	52.9	90.8	1.36	0.83	0.66	0.87
Ceiling	4.2	23.9	–	82.9	1.27	–	–	0.95
Average					1.45	0.96	0.69	0.95[b]

[a] Start exposure to the surface was set equal to the time for flashover.

[b] Parts of the wall and ceiling had a larger average charring rate than this value.

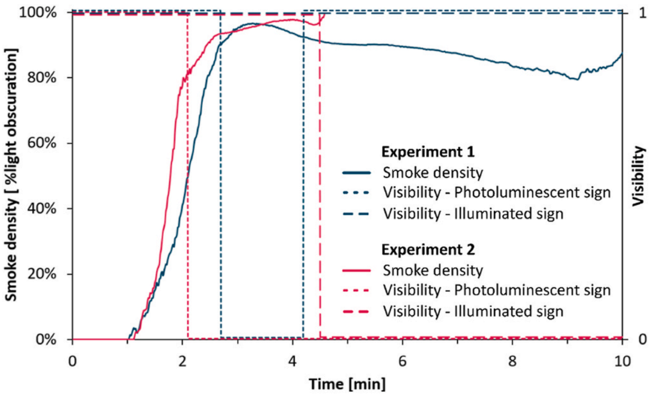

Fig. 20. Smoke density through the corridor measured by the reduction in light obscuration at height 2.05 m for Experiments 1 and 2, and observed visibility of safety way-guidance signs (visible = 1, not visible = 0) by persons located 8 m away at the other end of the corridor.

- An important factor that influenced the outcome was the angle of the nozzles, in which all were pointing downwards. This is, however, the normal orientation of such nozzles. Although two nozzles were installed just 0.15 m below the CLT ceiling, this orientation resulted in an area under the ceiling and the upper parts of the wall that was not cooled by water, as illustrated in Fig. 22.
- With little cooling effect from the sprinkler system to the hot gases emerging out from the compartment, and none, or very little, cooling of the CLT ceiling and the upper parts of the wall, the hot gases from the compartment were sufficiently hot to induce pyrolysis of the upper parts of the CLT walls and ceiling and production of additional combustible gases. The additional combustible gases contributed to feeding the existing flame and thus extended the flame spread along the corridor.

4.2.4. *Realisticness of the experiment*

It is acknowledged that Experiment 2 represented a rare and extraordinarily tough scenario. On the other hand, it is not a completely unrealistic scenario, and the compartment setup and sprinkler configurations were based on a building that was planned and now has been built.

The non-functional nozzles could be caused for instance by a lack of maintenance or that obstacles are positioned in front of the nozzles, and thereby blocking the spray pattern of the nozzles.

Having the door open as in the experiments might not be a likely situation for compartments with self-closing doors. However, based on experience with student bedsit apartments, this is a scenario that is likely to happen as students living together visit each other's rooms.

The setup of Experiment 2 can also represent another case described in EN 12845 [26], which states that there should be a fire wall between a sprinklered and a non-sprinklered area. The setup of Experiment 2 can, therefore, represent a fire in a non-sprinklered area with the fire door leading to the sprinklered area being forced open.

4.3. *Evacuation through the corridor*

The visibility in the corridor gives an indication on whether evacuation could have been possible. In Experiment 1, it seems likely that evacuation through the corridor could have been possible in the entire duration of the experiment. Here, the illuminated sign was visible through the entire duration of the experiment, enabling safe evacuation. The photoluminescent sign was visible during the experiment, except for the time period 2.5–4 min, during which it would not have functioned as a safety way-guidance system. Here it should be noted that also during this time period, the overall visibility along the floor was acceptable, and that photoluminescent signage often is used along the floor as a continuous line or row of spots, rather than as high-mounted point signage as was the case here. During Experiment 1, it is likely that persons evacuating through the corridor shortly would have entered a zone with less smoke where other signage still were visible.

In Experiment 2, it seems likely that escape through the corridor would have been possible for a short time between ignition and flashover (at 5 min), since the smoke, in this period, was mainly localized under the ceiling and the visibility was relatively good. After flashover, the conditions in the corridor became much tougher and would have obstructed evacuation, due to darker, denser and more turbulent fire smoke, and increased temperatures in the upper part of the corridor. Furthermore, the fall-down of the suspended ceiling at 8.5 min, would likely have complicated the movement of firefighters through this corridor. Whether the fall-down was caused by the weight of the water distributed from the nozzles above the suspended ceiling, or whether it was caused by failure of the fixings due to the heat exposure, is not known.

A complete study of the evacuation conditions in the student building would benefit from a larger set-up enabling an evacuation study of the signage's function, that is, how people move through a space, in

Fig. 21. Images of the visibility in the corridor in Experiment 1 during the worst visibility conditions. (a) Reference image of the visibility in the corridor. (b) View towards the photoluminescent sign and (c) view towards the illuminated sign. In Experiment 1 and the first part of Experiment 2, the visibility was only limited for the upper part of the corridor. Photos by RISE Fire Research.

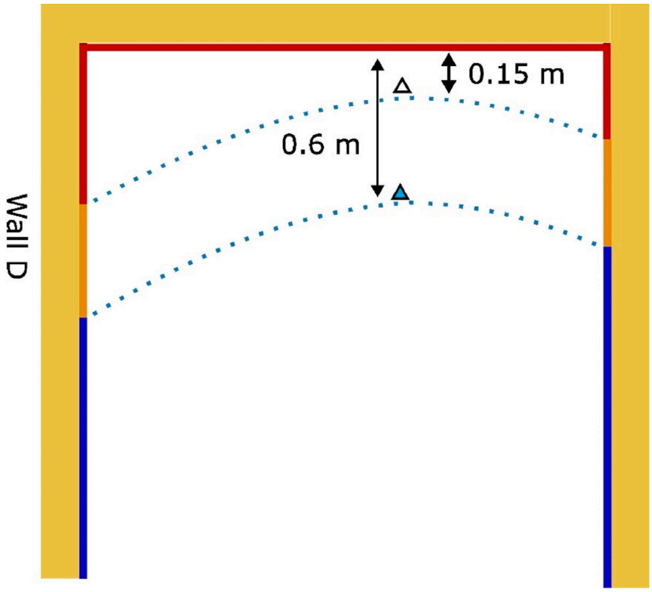

Fig. 22. Illustration of how water from the sprinkler nozzles (triangles) sprayed towards the walls and the ceiling in the corridor. Blue colour indicates a surface that was effectively cooled, orange a surface partly cooled, and red a surface none, or very little, cooled by the sprinkler. The blue dots represent the water spray from the nozzles. It is noted that the sketch is an ideal representation of a water spray in a non-fire scenario, and in a fire, the water spray will be altered due to the impact of the flames and the plume. Illustration by FRIC Fire Research and Innovation Centre. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

addition to knowledge about the visibility. In addition, temperature measurements also at lower heights and gas measurements would be beneficial.

4.4. *Future work*

These experiments have highlighted that a conventional sprinkler system for a given scenario has an operative design that might not be able to control a fire in a building with exposed CLT. The fact that the entire ceiling in the corridor was strongly charred in Experiment 2, is clear evidence that such a setup has some major weaknesses in the disabled-nozzle case. It is acknowledged that this was a tough fire scenario, but it is still valid to question whether this system should be the main system to rely on in exposed CLT compartments. This question is also relevant with the increased awareness of fungal growth and costly water damages for CLT elements exposed to free-water wetting conditions [41,42].

Although there are not many reports on the behaviour of water mist systems on fires in CLT buildings, water mist systems have been thoroughly tested against applications that are relevant for CLT buildings, including IMO 265 for cabin and corridor [22], FM 5560 for protection of non-storage occupancies [30], BS 8458 for residential and domestic occupancies [17], VdS 3883–1 for office spaces and accommodation areas [43], among others.

Hence, we encourage more studies to compare the effects of sprinkler systems to other suppression systems, such as water mist system, to determine the ideal system for a given CLT building regarding extinguishing efficiency and water consumption.

5. Conclusion

Two fire experiments have been conducted in a CLT compartment (13 m^2) with an adjacent CLT corridor (12 m^2). In Experiment 1, the effect of a fully operative sprinkler system was tested against a concealed fire. In Experiment 2, a robustness test of the sprinkler system was conducted, by disconnecting the sprinkler nozzles in the compartment, while the ones in the corridor were operative. The door between the compartment and the corridor was open in both experiments.

The following results are considered the most important:

5.1. *Fire dynamics*

In Experiment 2, the compartment fire was negligibly influenced by the sprinkler system in the corridor and the development can therefore be considered as a freely developing compartment fire.

The temperature in the compartment was stable at approx. 1000 °C from shortly after flashover until manually extinguished at 96 min. The prolonged fire occurred by a combination of an extensive radiative heat feedback between the exposed CLT surfaces, CLT elements built up of relatively thin (20 mm) layers, and the use of an adhesive known to cause delamination. From flashover, large flames emerged from the compartment into the corridor due to the compartment fire being strongly underventilated.

5.2. *Effect of extinguishing system*

The fully functional sprinkler system in Experiment 1 was able to control a concealed fire in the compartment with an exposed combustible wall and ceiling with one activated nozzle. The remaining fire could then easily be put out manually after some time. The maximum temperature measured under the ceiling was 142 °C.

In Experiment 2, with disconnected nozzles in the compartment but functional nozzles in the corridor, the four nozzles in the corridor activated shortly after flashover of the compartment. The activated sprinkler system was able to prevent ignition of the lower parts of the CLT walls in the corridor, whereas the upper part of the walls and the ceiling were strongly charred as water was not effectively delivered to those areas. Also, the fire in the compartment was negligibly affected by the sprinkler system as the water delivered by the nozzle was not effectively reaching the compartment. The latter was partly due to the short discharge range of the water spray and partly as the wall between the compartment and the corridor blocked the delivery of water from the closest corridor nozzle to the inside of the compartment.

With little cooling effect from the sprinkler system to the hot gases emerging out from the compartment, and none, or very little, cooling of the CLT ceiling and the upper parts of the wall, the fire plume from the compartment were sufficiently hot to induce pyrolysis of the upper parts of the CLT walls and ceiling and production of additional combustible gases. The additional combustible gases contributed to feeding the existing flames and thus extended the flame spread along the corridor.

5.3. *Charring rate*

Large parts of the CLT walls and ceiling in the compartment had a minimum charring rate of 1.1 mm/min for the entire duration of the fire. A clear step-behaviour was measured for the charring rate with the fastest charring rate during the first 15–20 min of burning with an average charring rate of 1.45 mm/min ($n = 3$).

5.4. *Evacuation*

The visibility of two types of safety way-guidance signs were demonstrated. The results indicate that they would be visible in a corridor before flashover in an adjacent room with an open door, and visible through most of the time for the case with activated sprinkler in an adjacent room. With no activated sprinkler in the adjacent room, evacuation conditions were rapidly worsened. The results indicate that an illuminated safety way-guidance sign would be visible for a longer time than a photoluminescent sign, for high-mounted point signage.

CRediT authorship contribution statement

Andreas Sæter Bøe: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Kristian Hox:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ragni Fjellgaard Mikalsen:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Kathinka L. Friquin:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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