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Abstract

The aim of this work is to improve the understanding of the fire behaviour of building materials used at the wildland urban interface using laboratory scale experiments. To this end, wood cladding was exposed to a propagating flame front across a decking slab. This slab element was ignited by a radiant panel. Three slab configurations were studied: thermoplastic slabs and wooden slabs with slats oriented parallel or perpendicular to the cladding. The vertical distance between the slabs and the cladding varied from 0 to 20 cm and two types of batten arrangement were used to separate the cladding from the supporting cellular concrete. The experiments first focused on the measurement of the heat fluxes received by a non-combustible wall in place of the cladding, depending on the type of slab used. Radiation was the dominant heat flux measured on the wall and it increased up to 35 $kW.m^{-2}$ as the flame front approached to the cladding. The spreading of the fire from the slab to the cladding was then investigated. Ignition of the cladding occurred in all configurations tested. The slab configuration (material or orientation) has little effect on the combustion of the cladding once it has been ignited. In addition, the distance between the deck slab and the cladding did not have a significant impact on the fire behaviour of the cladding, even at the 20 cm distance recommended by the standards.

Keywords: WUI fire, wood cladding, fire spread, fire reaction

1. Introduction

Wildland-Urban Interface (WUI) fires are responsible for an increasing number of destroyed structures. The issue of these fires has become a recurring topic around the world [1, 2]. As a result, many studies have been conducted to identify the causes of house fires due to a forest fire [3] and many guidelines [4] have been established such as the minimum water supply, or the vegetation clearing distances around dwellings [5]. On the other hand, regulations on the vulnerability of building materials to forest fires remain weak. In fact, the most detailed standards exist mainly in the United States

and Australia, but less so in Europe, where the Mediterranean region is prone to many fires [6, 7]. In this region, the probability of building components igniting in a WUI fire is high, but there are no common guidelines for the regulation and layout of the materials involved. Among the materials that can be affected by a forest fire at the Wildland Urban Interface (WUI) (roofing, gutters, windows, doors, terrace,... [8, 9]), the cladding is a key element because it may spread a surface fire to the most vulnerable points of a building such as openings or vents. Many combustible materials are used now in commercial wall assemblies. Moreover, with the enthusiasm for bio-sourced materials, wooden cladding is increasingly present on constructions and can be found on houses located in the WUI.

Studies of the fire behaviour of cladding vary from the material scale, with cone calorimeter tests [10, 11], to the large scale with a fire escaping from a window of a compartment [12]. Following the Grenfell disaster in 2017, the fire behaviour of facades has become a topic of great interest [13, 14, 15, 16]. However, the fire scenarios often consider a flame exiting from a window hitting the facade. Various standards exist worldwide for testing the fire performance of facades (LEPIR 2, ISO 13785-1 [17], DIN 4102-20 [18], BS 8414 series [19], NFPA 285, FM 4880, CAN/ILC-S134). Tests use single walls, corners or walls with windows. Fire can be created either by gas burners or by wood cribs. Nevertheless, whatever the tests, they are far from the conditions that can be encountered during in a WUI fire: the ignition of cladding by direct contact with flames from burning forest fuels, nearby building elements or secondary structures [20, 21], by the radiation [22], or by the projection of firebrands [3, 23].

To our knowledge, the only study on wooden walls subjected to an ignition representative of a fire at a WUI is the work of Cohen et al. [24], who studied the ignition of a wooden wall by a crown fire propagating in a jack pine and black spruce forest. The wooden wall of 1.2 m $\times$ 1.2 m with a roof was placed at 10, 20 and 30 m from the burning area. Heat fluxmeters and thermocouples were placed on the wall to assess the impact of the fire. In these experiments, Cohen et al. observed that the walls were sometimes ignited but the fire was not sustained and flameout occurred when the vegetation fire had passed the structure. They also showed that some elements can reduce the radiation received by a structure, such as the presence of trees or the fluctuation of the flame front.

The propagation of a WUI fire to a building can be due to the propagation of the flame front from the vegetation to a building element via combustible material in the vicinity of the constructions [25]. ~~In this work, the fire behaviour of a wooden cladding exposed to a fire front from the burning decks is studied experimentally on a laboratory scale. After quantifying the heat flux received by the~~

~~cladding during the propagation of the flame front on the decking slab, experiments were performed using a Large Scale Heat Release (LSHR) calorimeter to determine the influence of the decking slab (material, orientation and vertical distance) on the vulnerability of the wooden cladding.~~The aim of this article is twofold. Firstly, the fire behaviour of wooden cladding exposed to a fire front coming from the burning of decking slabs is studied experimentally to see whether the type of slabs (wood or thermoplastic) influences the vulnerability of the facade. The influence of the vertical distance between the cladding and the decking slabs on the spread of the flame front is then investigated. In many countries, it is indeed recommended to leave a siding clearance between the cladding and the ground to prevent damage from insects and pests. However, this vertical distance varies from country to country and is a key parameter for the spread of a surface fire towards the building. The approach therefore had to follow several stages. First, the fire behaviour of the cladding was studied using a cone calorimeter to obtain reference data (ignition time as a function of flux, Heat Release Rate (HRR), Mass Loss Rate (MLR)). The combustion of the two types of decking slabs was then studied using an LSHR apparatus to measure the HRR of the decking slabs and the heat flux received by a vertical surface placed at their end. Finally, the fire behaviour of wooden cladding ignited by decking slabs was studied, focusing on two parameters that could affect the vulnerability of the cladding, namely the arrangement of the fixing battens and the vertical distance between the bottom of the cladding and the decking slabs. The article first describes the materials and methods used for the experiments. The results are then presented and discussed.

2. Materials and methods

2.1. Materials

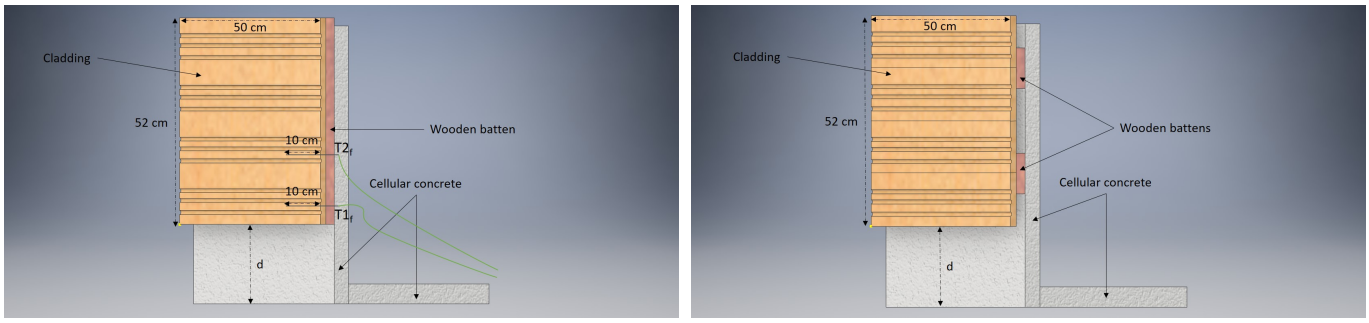
The aim of this work is to study the fire reaction of wooden cladding following the ignition of a decking slab. To this end, two types of decking slabs, thermoplastic and wood, are studied. The fire behaviour of these decking slabs was investigated in previous works [26, 27]. For both materials, the decking slabs measure 40 $\times$40 cm^2 with a thickness ~~height~~ of 2.4 cm for the wooden slabs and 5.3 cm for the thermoplastic slabs. More details about the slabs can be found in the work of Tihay-Felicelli et al. [26], such as their thermal properties or ultimate analysis. The wooden slabs, made of pine, are composed of a succession of 6 cm slats spaced 2.5 cm apart and have a weight of 862 $\pm$ 47 g. The thermoplastic slabs are made up of 16 squares of 8.5 cm arranged in four rows and weigh 1597 $\pm$ 21 g.

2.2. Experimental setup at material scale

In order to characterise the fire behaviour of wood cladding, cone calorimeter tests are carried out according to the norm ISO 5660 in vertical orientation. The samples are taken from the cladding boards and are cut to a size of 10×10 cm^2. Prior to the tests, the wood samples are oven dried at 105 °C for 24 hours in order to remove any remaining moisture according to the European Norm NF EN ISO 18134. This method of drying did not impact the pyrolysis of wood. For each test, samples are wrapped in a double layer of aluminium and placed in a steel sample holder. The rear side is insulated with a ceramic foam and then a ceramic plate, all held in place by the locking system. The distance between the sample and the cone is fixed at 25 mm as specified by the standard. Each averaged result presented is made up of at least four tests. The experiments last between 15 and 20 minutes with imposed heat fluxes ranging from 15 to 45 $kW.m^{-2}$ and a ~~piloted spark~~ pilot placed at the center of the exposed surface.

2.3. Experimental setup at product scale

For the need of these experiments, the wood cladding is fixed on cellular concrete with 28 mm thick pine battens. In order to have the highest fluxes at the level of the cladding and therefore to be in the most penalizing configuration, a single decking slab is placed in front of the cladding to have an almost flat flame front [26] and thus avoid a parabolic front. The cladding is cut to obtain a section of 52×50 cm^2, i.e. four boards stacked vertically at a height of 52 cm. This cladding width prevents the flames from passing directly through the side of the cladding towards the rear. Fig. 1 shows the detailed configuration of the cladding.



(a) Large wooden battens.

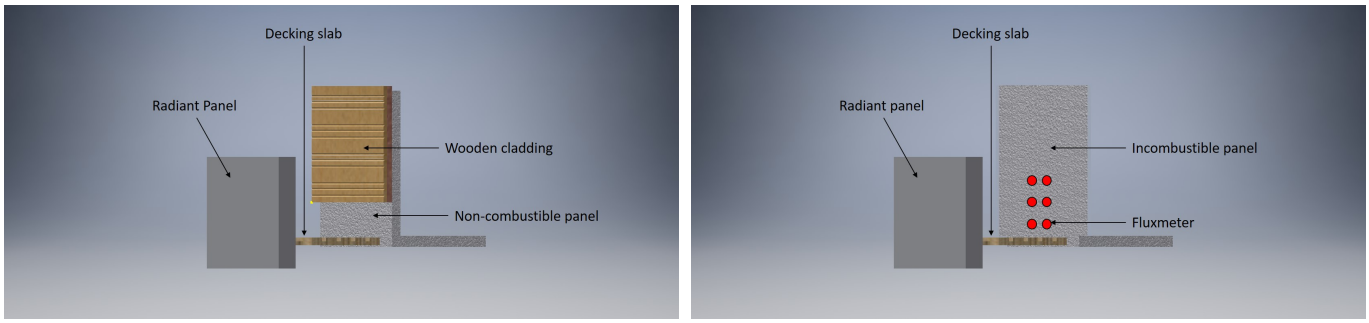
(b) Small wooden battens.

Figure 1: Comparison of the arrangement of the battens that are placed between the cladding and the aerated concrete that will be exposed to the flame front.

Two battens configurations are considered. The first, shown in Fig. 1a, involves fixing the battens along the entire length of the cladding. The cladding/batten assembly has a mass of approximately 2.3 kg. The second, shown in Fig. 1b, consists of fixing the battens between two boards to attach them

at the top and bottom and to hold the structure together, resulting in a total mass of approximately 2.1 kg. The objective of both configurations is to study the effect of the air entrained when the flame passes between the wood and the cellular concrete. Before each test, the wooden decking slabs, battens and cladding are oven-dried for 24 hours at 60 °C to reduce the moisture content.

The experimental setup is located under the hood of a 1 MW Large Scale Heat Release (LSHR) apparatus. The fire spreading tests are carried out on a combustion bench covered with cellular concrete (Fig. 2).



(a) Experimental setup used for the study of fire behavior of the cladding.

(b) Experimental setup used for the study of the heat flux received by the non-combustible panel.

Figure 2: Schemes of the experimental setup at product scale.

Ignition of the decking slab is provided by a 50 × 50 cm^2 radiant panel placed 14 cm away from the edge of the slab. The radiant panel is supplied with propane at a flow rate set to give a constant heat flux of 35 $kW.m^{-2}$ (measured with a total heat flux gauge) at the leading edge of the slab exposed to the panel. An electric igniter is positioned 3 cm above this edge to pilot the ignition. The decking slab is placed against the cladding and the trailing edge of the slab is in contact with the concrete. The distance between the radiant panel and the wooden cladding is therefore 64 cm. Different vertical distances between the decking slab and the cladding, noted d (Fig. 1a), are studied: 2, 10 and 20 cm, in order to observe the effect of the height between both elements on the spread of the flame. The study has been limited to 20 cm because it is the highest value encountered in the clearance recommendations (used to prevent damage from insects and pests) [28]. As a result, the cladding was not uniformly exposed to the radiant flux from the panel at the start of the experiment, but measurements showed that this heat flux, at this distance of 64 cm, did not cause any degradation of the wood for the time it was in operation. A load cell, with an accuracy of ±3 g (maximum mass of 200 kg) and a sampling frequency of 1 Hz, is placed under the combustion bench in order to measure the mass loss over time. Smoke released during combustion is extracted from the laboratory by a 1 $m^3.s^{-1}$ smoke extraction system and the Heat Release Rate (HRR) is measured by oxygen consumption. Four K-type thermocouples are stapled to the cladding. Two are placed on the front,

at 6.5 cm ($T1_f$) and 18.5 cm ($T2_f$) from the bottom of the cladding and 10 cm from the side (Fig.1a). Two more thermocouples are placed in the same position on the rear side: $T1_b$ at 6.5 cm height and $T2_b$ at 18.5 cm height. Grooves are made on the surface of the wood to match the diameter of the thermocouple (1 mm) so that they can be placed and stapled in place, ensuring contact between the tip of the thermocouple and the wood.

According to Tihay-Felicelli et al. [26], the orientation of the wooden decking slab relative to the ignition source can lead to different flame spread and is therefore studied in this work. For the parallel configuration, the slats are oriented parallel to the radiant panel and the cladding, whereas for the perpendicular configuration, they are oriented perpendicular. Fig. A.15 in appendix shows two pictures of the experimental setup with different wooden slabs orientation.

Before that, a first set of experiments is carried out to measure the heat flux received by the cladding during the burning of the decking slab. For these experiments, the wooden cladding is replaced by a non-combustible plate (Fig. 2.b), which is drilled along the vertical axis of symmetry, corresponding to the center of the cladding, at different heights (from 2 cm to 42 cm above the slab). Total heat flux gauges (MEDTHERM 64-10-20T, range [0-200] $kW.m^{-2}$) are inserted in these holes to measure the heat flux received by the plate.

Twenty-six tests have been carried out to investigate the fire behaviour of the cladding (Fig. 2.a). Three tests per decking slab material have been performed to measure the heat flux received by the cladding. The radiant panel and igniter are lit until the decking slab ignites. Once ignited, they are extinguished to allow the flame to spread across the decking slab in a self-sustaining way. Throughout this article, the time t=0 s corresponds to the moment when the decking slabs ignite. This method allows to overcome the differences in the ignition times of the different slabs highlighted by Tihay-Felicelli et al. [26].

3. Results and discussion

This section first presents the results of the fire behaviour of the wooden cladding at the material scale performed with the cone calorimeter, followed by the results at the product scale carried out with the LSHR apparatus.

3.1. ***Results at material scale***

For each test, the presence of the spark igniter allows for the ignition of the samples. Fig. 3 presents the times-to-ignition according to the heat flux applied.

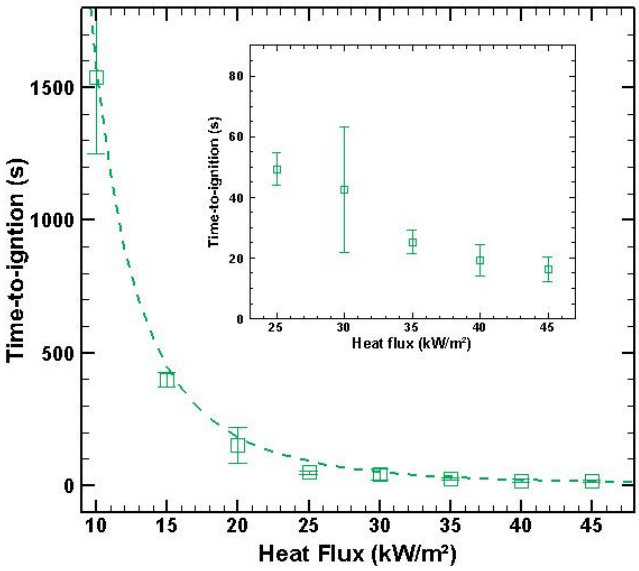


Figure 3: Times-to-ignition as a function of the imposed heat flux.

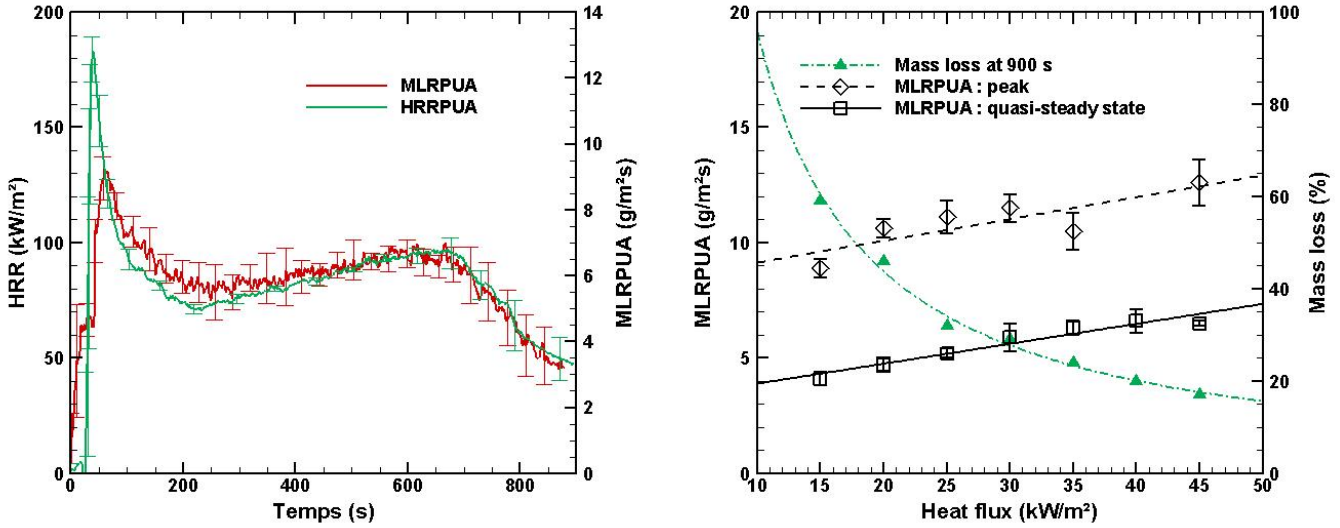
Ignition time decreases with increasing heat flux. The repeatability of the results varies with ~~to~~ the applied heat flux and tends to show greater variability when close to the critical heat flux. The experimental points follow a power law.

Based on the ignition times, the Flux-Time Product (FTP) of the wooden cladding is calculated. The FTP was initially defined by Smith and Satija [29] and is used to estimate the time required for a combustible material to ignite when exposed to incident radiation [30, 31, 32, 33]. The FTP is given by the following equation:

$$FTP = t_{ig}.\left(\dot{q} - \dot{q}_{cr}\right)^{n} \tag{1}$$

where t_{ig} is the time to ignition, $\dot{q}$ is the incident heat flux, $\dot{q}_{cr}$ is the critical heat flux and n is the power law index.

The FTP and the power law index n for the cladding are determined by optimisation (least squares method) by using the time to ignition data according to the incident heat flux. The calculated FTP is equal to 4306 kW.$s^{1.58}$.m^{-2}. This result with the exponent $n = 1.58$ is consistent with the values found in literature [32, 33]. Figures 4a and 4b show the evolutions of the average HRR and MLRPUA of the tests performed at 35 kW.m^{-2} and the mass loss and MLRPUA as a function of heat flux.



(a) Mean MLRPUA and HRRPUA evolutions for 35 kW.m^{-2} heat flux.

(b) MLRPUA (peak and quasi-steady state) and mass loss as a function of heat flux.

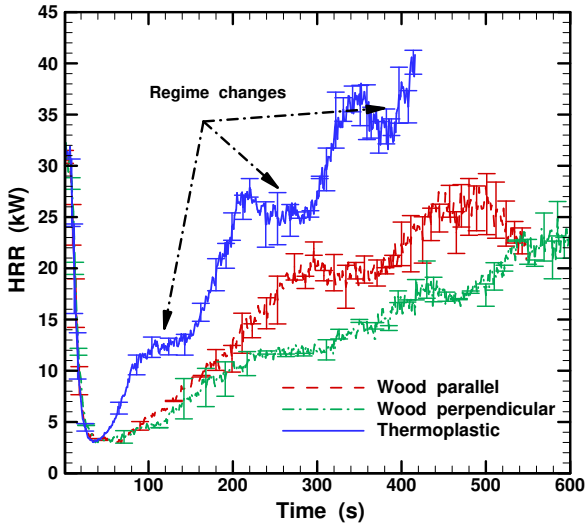
Figure 4: HRRPUA and MLRPUA measured according to the imposed heat flux during the cone experiments.

At 35 kW.m^{-2}, the exposure of virgin wood to the heat flux results in high degradation and rapid ignition due to the high release of pyrolysis gases and the presence of the pilot. The MLRPUA and HRRPUA increase to a peak. ~~Subsequently, the formation of char on the surface causes the MLRPUA and HRRPUA to decrease to a quasi-stationary phase.~~ During the first 100 seconds, a variation of the MLRPUA and the HRR is observed between the experiments. This stage corresponds to a transient state for which the thickness of the pyrolysis zone could vary from test to test and accentuated by the vertical configuration adopted for the experiments. Subsequently, the formation of char on the surface causes the MLRPUA and HRRPUA to decrease to a quasi-stationary phase, for which the experimental variation does not exceed 10 %. Finally, after 500 s, the degradation of the back side of the wood accelerates again, resulting in a second peak that is smaller than the first one. The peak and the quasi-steady MLRPUA increase quasi-stationary with the applied heat flux, while the mass loss after 900 s of test decreases as a power law. The HRRPUA peak ~~also~~ increases also quasi-linearly with values between 135 and 200 kW.m^{-2} for heat fluxes between 15 and 45 kW.m^{-2}. The results obtained on the wooden cladding with the cone calorimeter allowed to collect data on the ignition time and the HRR as a function of the heat flux and to calculate the FTP of the cladding. These data will be used as a reference to discuss the results obtained at the product scale.

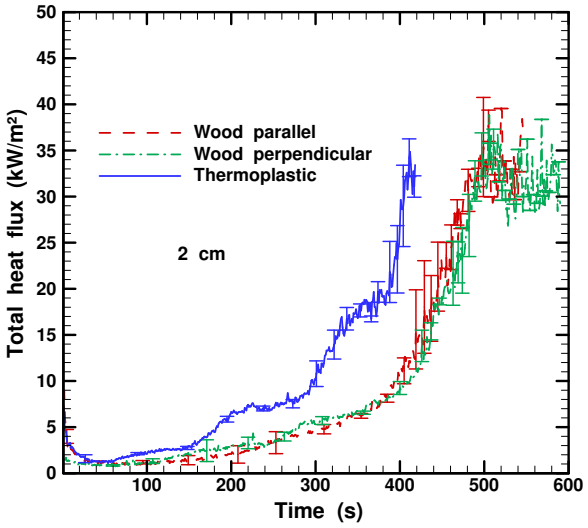
3.2. ***Results at product scale***

3.2.1. Decking slab combustion and heat flux received by the cladding

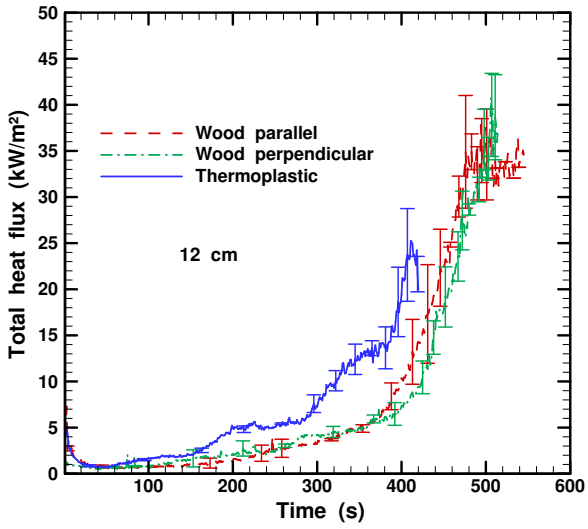
Fig. 5 presents the mean Heat Release Rates (HRR) and total heat flux ~~measured~~ received by the heat gauges at the different heights on the non-combustible plate according to the decking slabs studied. At the beginning of the tests, the total heat flux received by the non-combustible plate is between 7 and 9 kW.m^{-2}. This heat flux is mainly due to the radiant panel. The decrease of the curves at t=10 s corresponds to the extinction of the radiant panel. Immediately after the slab ignition, the HRR released by the burning slabs is only 4 kW, resulting in a total heat flux on the non-combustible plate of about 1 kW.m^{-2}. As the fire front spreads across the slab towards the non-combustible plate, the HRR increases regardless of the slab's material or configuration. However, the behaviour changes depending on the slab considered. The HRR of the thermoplastic slab is higher and increases faster than that of the wooden slabs. These measurements are consistent with the work of Tihay-Felicelli et al. [26]. Three regime changes are observable on the thermoplastic HRR curves, reflecting the spread of the flame to each new row. The first row produces a HRR of 12 kW (Fig. 5a) and a total heat flux between 1 and 3 kW.m^{-2}. The HRR then increases to 25 kW with a total heat flux around 7 kW.m^{-2}. The propagation of the flame front to the third row leads to a HRR around 35 kW and a total heat flux between 12 and 19 kW.m^{-2}. Finally, the total heat flux increases up to 35 kW.m^{-2} at the end of the test, when the flames come into contact with the non-combustible plate. The heat flux measured for the thermoplastic slabs is lower in Fig. 5.b because the experiments have been stopped before the flame came into contact with the non-combustible wall. As highlighted by Tihay-Felicelli et al. [26], the orientation of the wooden decking slab influences the fire behaviour, especially after 200 s. The HRR increase is faster for the parallel configuration than for the perpendicular one. However, the heat fluxes measured on the non-combustible plate are close whatever the orientation considered. After 500 s, the total heat flux ranges between 21 and 45 kW.m^{-2} depending on the height of the heat flux gauge.



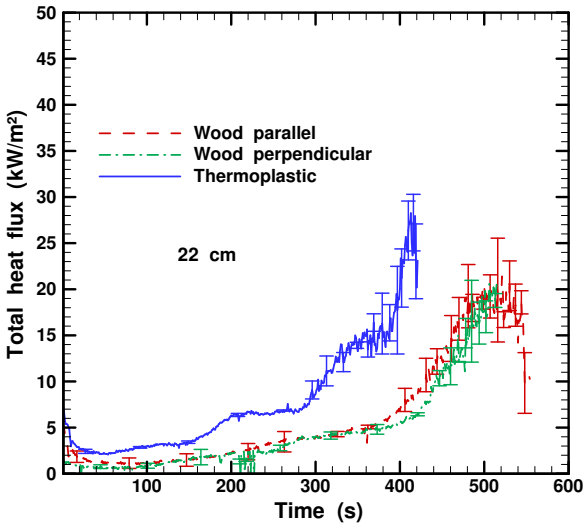
(a) HRR.



(b) Total heat flux at 2 cm height.



(c) Total heat flux at 12 cm height.



(d) Total heat flux at 22 cm height.

Figure 5: Comparison of total heat fluxes received on the non-combustible panel and HRR for the three types of decking slabs.

To better visualise the flux distribution on the non-combustible plate, Fig. 6 shows as an example a mapping of the mean total heat fluxes obtained from the measurements at 2, 12, 22 and 32 cm for the experiments with the thermoplastic slab. Up to 300 s for the wooden slabs and 200 s for the thermoplastic slabs, the heat fluxes are almost constant over each height of the non-combustible plate. The heat flux received at a height of about 2 cm is the highest. Above that, the recorded values are very close. ~~As the fire front propagates through the slab, the base of the flame is indeed thicker generating more radiation at the lower part of the plate.~~ As the fire front propagates through the slab, the shape of the fire front takes on a triangular shape [26]. The base of the flame is thus thicker

generating more radiation at the lower part of the plate. From 400 s, the heat flux increases strongly because the flame front is very close to the fluxmeter and can reaches the sensors. Despite the fact that the flame front coming from the decking slabs is quasi-straight, the heat flux should decrease slightly away from the center, as the view factor also decreases due to the boundary conditions of the experiments.

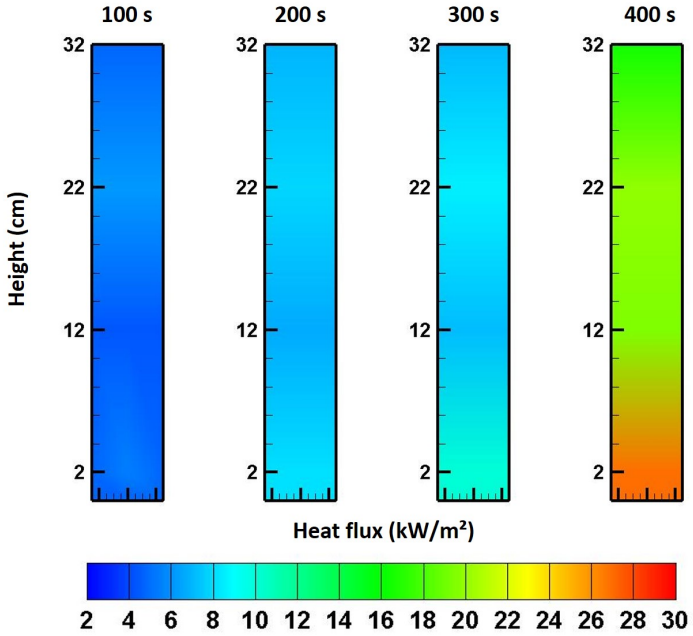
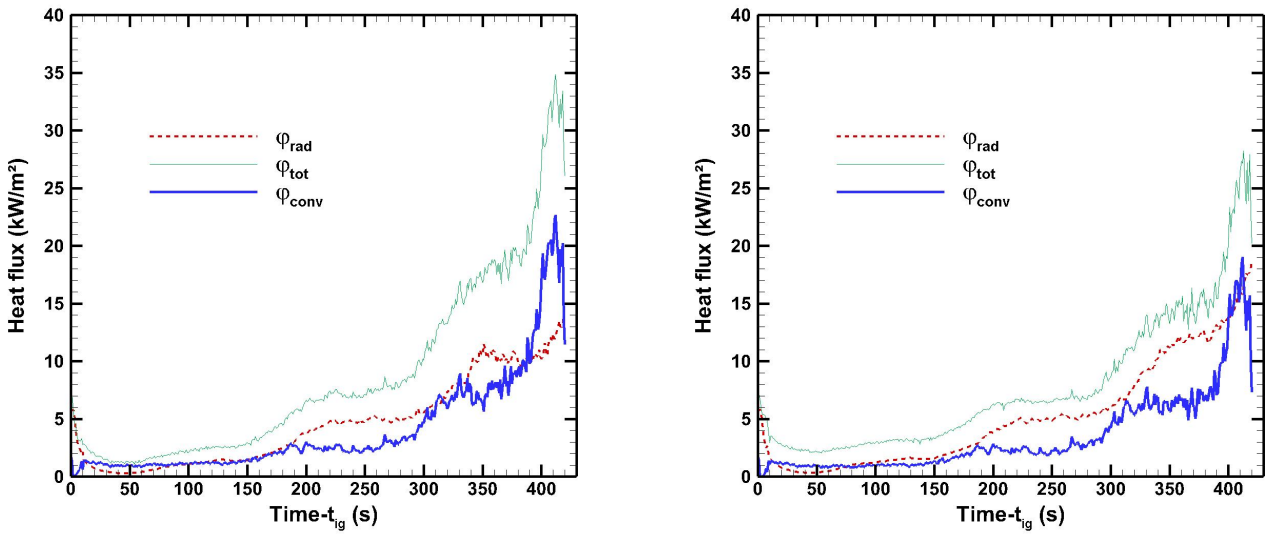


Figure 6: Mapping of mean total heat fluxes measured at 100, 200, 300 and 400 seconds during the experiments with thermoplastic slab and non-combustible plate.

The contribution of radiant and convective heat fluxes during fire propagation on the decking slabs ~~have~~ has been evaluated on the non-combustible plate. This has been done by replacing the total heat flux gauges with radiant gauges in three additional tests with thermoplastic decking slabs. The presence of a convective heat flux (φ_{conv}) is assessed from the radiant heat flux (φ_{rad}) and the total heat flux (φ_{tot}) using the following equation: $\varphi_{conv} = \varphi_{tot} - \varphi_{rad}$. Fig. 7 presents the evolution of the different heat fluxes for two heights after the ignition of the thermoplastic decking slab. From 0 to 150 s, the convective and radiant heat fluxes are close, between 1 and 2 kW.m^{-2}. From 175 s, the radiation is the dominant heat transfer measured at 5 kW.m^{-2}. The cladding will not degrade or ignite at this heat flux value. After 300 s, the flame front approaches the non-combustible plate. The fluctuations increase due to the intensification of the convective part. The radiation is the predominant heat transfer except at 2 cm. At this height, the convection becomes higher when the flame front reaches the non-combustible plate.



(a) 2 cm.

(b) 22 cm.

Figure 7: Evolution of total, radiant and convective heat fluxes for two heights during the burning of a thermoplastic decking slab.

Studying the combustion of the decking only has allowed us to measure the heat release rate of the decking slabs as well as the heat flux received on a vertical surface placed at their end. It has been shown that the flame front propagates with different dynamics depending on the type of decking slab and also on the orientation of the wooden slats. The flux received by the vertical non-combustible panel increases as the flame front approaches, reaching values higher than 35 kW.m^{-2} when the flame front comes into contact with the fluxmeters. The orientation of the slats of the wooden panel does not appear to affect the heat flux received by the vertical panel.

3.2.2. Fire behaviour of the cladding

Fig. 8 shows a typical fire spread test over time, from the ignition of the slab to the extinction of the cladding. The arrangement of the wooden battens was with the small one (Fig. 1b).

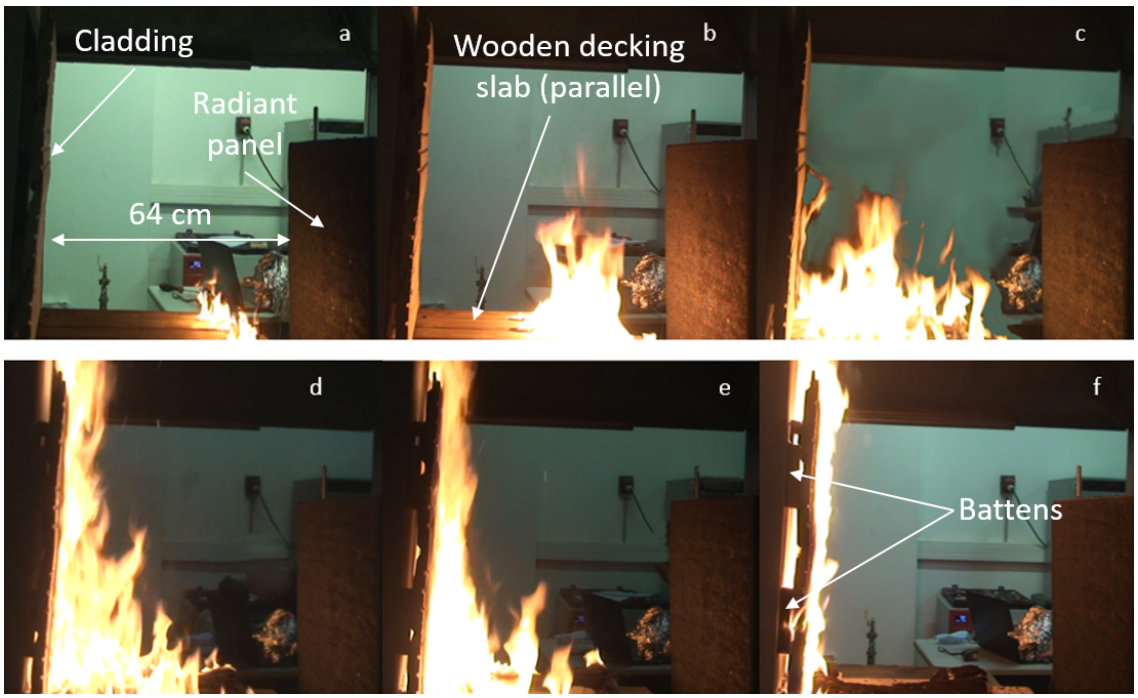


Figure 8: Photographs of a experiment performed with a wooden decking slab in perpendicular configuration and small wooden battens a) Ignition of the decking slab (t=0 s) b) Propagation of the flame front on the slab (t=210 s) c) Ignition of the wooden cladding (t=430 s) d) Propagation of the flame front on the cladding (t=480 s) e) Ignition of the rear face of the cladding (t=550 s) f) Extinction phase (t=840 s).

Fig. 8.a shows the decking slab just ignited by the radiant panel (here turned off). Ignition occurs at the leading edge of the first slat of the slab exposed to the panel due to the ignition of pyrolysis gases by the igniter. The flame front then spreads across the entire width of the slab and advances towards the cladding (Fig. 8.b). The wooden cladding is ignited on its lower part by direct contact with the fire front (Fig. 8.c). Although the heat fluxes received by the wooden cladding may exceed 25 kW.m^{-2} before the flame front reaches it (Fig. 5), it is not sufficient to ignite it without flame contact. This is consistent with the results obtained with the cone calorimeter. Indeed, considering the highest fluxes measured on the non-combustible panel, i.e. at a height of 2 cm of the cladding (Fig. 5), before the flame front reaches the end of the decking slabs, the flux received by the vertical panel exceeds 25 kW.m^{-2} only between 21 and 36 s and 30 kW.m^{-2} only between 10 and 23 s, depending on the decking slabs. These times are much lower than the ignition times measured with the cone calorimeter for these heat fluxes. Once the cladding has ignited, the flame spread over the surface exposed to the fire is very fast resulting in its generalized combustion (Fig. 8.d) with ignition of the rear face (Fig. 8.e). When all the virgin wood on the decking slab surface has turned into char, the flame intensity decreases but the wood continues to degrade until it is completely transformed into char (Fig. 8.f). After the flameout, a smoldering phase occurs on the parts of the cladding that have not collapsed or been completely consumed by the fire.

Fig. 9 shows the HRR and normalised mass loss for wooden cladding located 20 cm above a thermoplastic decking slab. These curves concern the whole test, from the ignition of the decking slab to the extinction of the cladding. The HRR measured before t=0s corresponds to the radiant panel HRR. The panel is switched off at t=0 s when the decking slab ignites. The mass starts to decrease from the beginning of the experiment as it is measured for both the cladding and the decking slab, the latter degrading as a result of its exposure to the radiant panel. The experiment is divided into four stages. The first phase corresponds to the spread of the flame front over the 40 cm of the decking slab (Region A). This zone is similar in intensity and duration to the results presented for the combustion of the thermoplastic slab (Fig. 5). The mass loss is mainly due to the combustion of the decking slab. After the ignition of the wooden cladding (Region B), the mass decreases sharply and the HRR increases very rapidly to reach a first peak. During this phase, the measured mass loss and the HRR are mainly due to the cladding burning, although some is due to the end of the decking slab combustion. A second peak of HRR then occurs at 680 s (Region C), due to the whole burning of the cladding, including its rear face. In fact, the separation caused by the wooden battens between the cellular concrete allows the flame to engulf through this air gap, further intensifying the heat released by the fire. This phenomenon can only be observed at the product scale and shows the interest of studying the fire behavior of the cladding at this scale. After the flameout (Region D), the mass continues to decrease slowly due to the smoldering until the complete extinction. The burning time of the cladding is about 700 s, close to the degradation of the cladding sample at the material scale for an imposed heat flux of 35 kW.m^{-2}. Indeed, Fig. 4 shows that the HRR and MLR at the cone calorimeter decrease rapidly from 700 s onwards, indicating that the virgin wood is fully burnt from this moment.

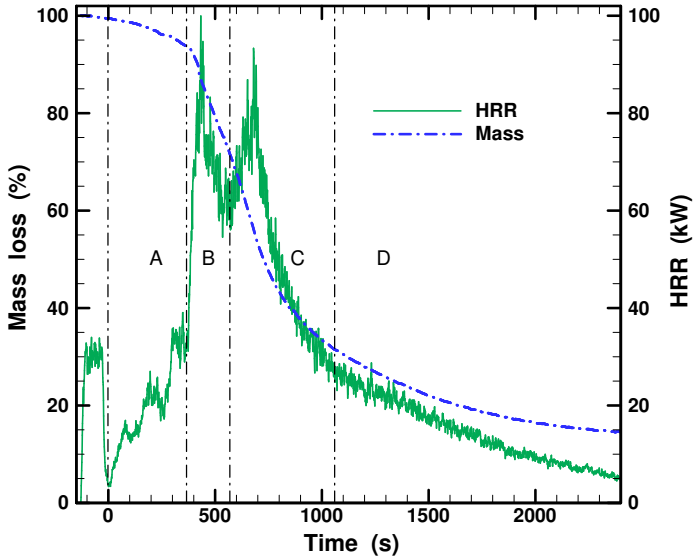


Figure 9: HRR and normalised mass loss of a cladding test located at 20 cm height above a thermoplastic slab. Region A: flame front spreading over the decking slab, Region B: ignition of the wooden cladding, Region C: total combustion of the wooden cladding, Region D: flameout.

Fig. 10 shows the temperatures on the front and rear sides of the cladding at 6.5 and 18.5 cm height for an experiment with a thermoplastic slab (d = 20 cm). The HRR is added to facilitate the discussion of the results. Temperatures cannot be measured throughout the test because the detachment of the sensor from the cladding surface during the degradation of the wood causes significant fluctuations in the measurements. As the fire spreads across the deck slab, the temperature of the front of the wooden cladding slowly increases. The temperature of the lower part ($T1_f$) of the cladding increases more rapidly which is consistent with the higher heat fluxes at the base of the cladding. However, the temperature of the front face of the cladding does not exceed 180 °C until the flame front is close enough to it. This temperature is not sufficient to allow thermal degradation of the wooden cladding, which begins around 220 °C, and therefore ignition by radiation. Once the fire front reaches the end of the slab, the temperature measured on the cladding increases rapidly. This allows the wood to degrade and ignite. The temperature rise of the rear face is shifted from that of the front face. As for the exposed face, the temperature is initially higher at the bottom due to the presence of the flame front. The temperature at the top of the rear face is only high enough to degrade the wood once the first HRR peak has passed, confirming that the second HRR peak is due to the complete combustion of both sides of the cladding.

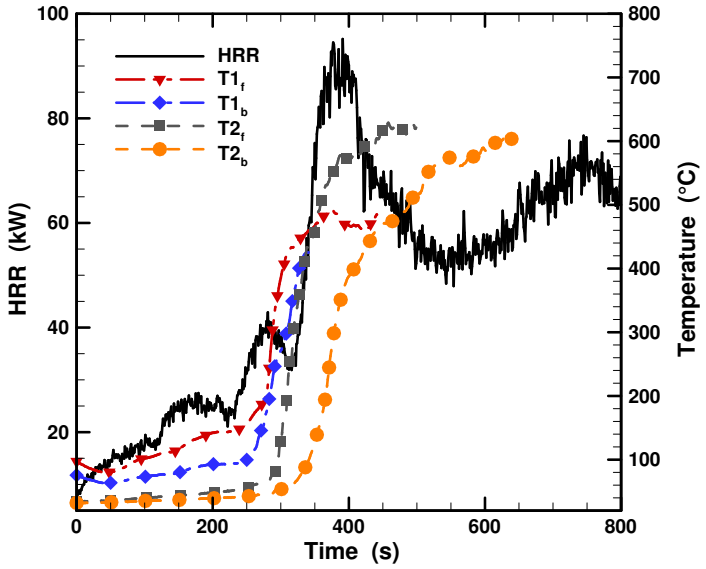
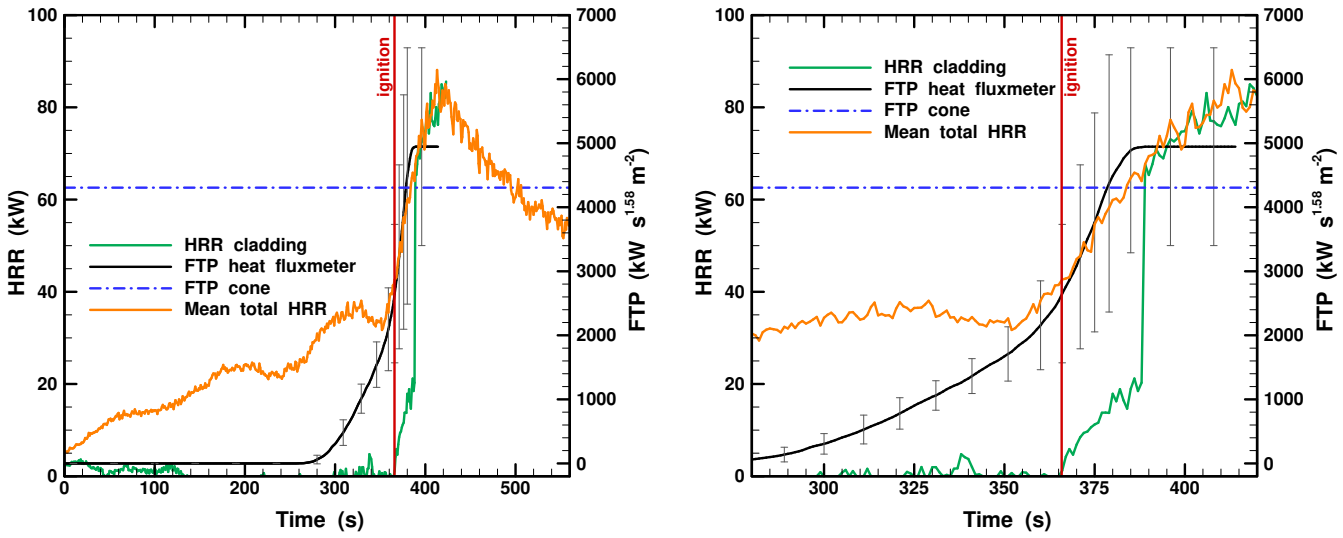


Figure 10: HRR and temperatures on the front and back sides of the wooden cladding for an experiment with a thermoplastic decking slab.

There are many ways to study the ignition of materials, such as ignition temperature, critical mass flux or FTP. In this study, the FTP was tested because this method was used by Cohen et al. [24] to determine the ignition of wood cladding in large-scale tests. To investigate whether the FTP determined at the material scale is an appropriate criterion for predicting the ignition of the cladding, the FTP over time calculated from the heat fluxes measured on the non-combustible panel at 2 cm height (Fig. 5) is plotted in Fig. 11. This is performed only for the thermoplastic slab, which had the highest repeatability. The dotted horizontal line corresponds to the FTP value determined at the material scale. The HRR of the cladding has been obtained by subtracting the mean total HRR (thermoplastic slab and wooden cladding) and the HRR measured during experiments with thermoplastic slabs only. Ignition occurs slightly before the FTP reaches the value corresponding to the ignition. This is probably due to pilot ignition which is more effective with flame contact than with the cone calorimeter igniter. Despite this small shift, the FTP appears to give a satisfactory prediction of cladding ignition. The cone calorimeter appears to be an experimental setup that enables the piloted ignition of materials to be predicted fairly accurately, but it is necessary to carry out tests on a product scale in order to understand overall fire behaviour, from ignition to extinction.

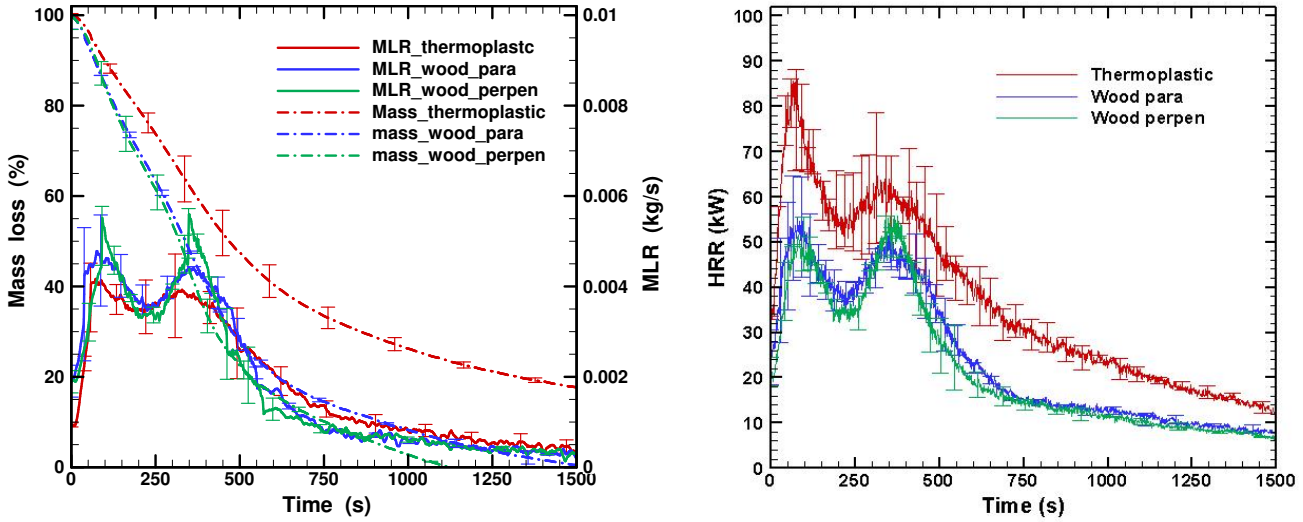


(a) Throughout the experiment.

(b) Zoom at ignition.

Figure 11: HRR and FTP for an experiment with a thermoplastic slab.

In order to compare the fire behaviour of the cladding after its ignition, the average mass loss, mass loss rate and HRR are plotted in Fig. 12 for the three types of decking slabs. Due to the greater spread of the flame front, wood cladding has always ignited more quickly with thermoplastic slabs. In this figure, t=0 s corresponds to the ignition of the cladding to facilitate the comparison. Table 1 summarises the main fire indicators. Regardless of the configuration considered, the MLR and HRR curves show two peaks, corresponding to the two combustion phases of the cladding. The first peak occurs at about 100 s after the cladding ignition and the second one at about 400 s. The evolution of HRR, MLR and mass loss is very similar for both wooden slab configurations, whether the slab is parallel or perpendicular to the cladding. The two peaks of MLR are between 4.4 and 5.6 g.s^{-1}, while the two peaks of HRR are in the range of 51-55 kW. The HRR of the thermoplastic slabs is higher than that of the wooden slabs throughout the tests. In fact, the first peak of the HRR reaches an average of 86 kW, while the second peak reaches 65 kW. This increase is due to the combustion of the thermoplastic slab which releases an HRR of approximately 20 kW higher than that of the wooden slabs (Fig. 5a). Once ignited, the fire dynamics of the cladding are therefore little influenced by the ignition source. At the end of the experiments, only ashes remain for the tests with the wooden decking slab and the cladding. For the tests with the thermoplastic slab, it remains 0.42± 0.06 kg, corresponding mainly to the residue coming from the calcium carbonate used as a filler in the thermoplastic decking slab.



(a) Mass loss and MLR.

(b) HRR.

Figure 12: Evolution of MLR, mass loss and HRR of the cladding placed 20 cm high and ignited by the three decking slab types.

Table 1: Mass loss at 600 s, peaks of HRR and MLR for the different decking slabs and and a gap of 20 cm between the slab and the cladding.

Material	Orientation	Mass loss at 600 s (%)	MLR_{peak_1} ($g.s^{-1}$)	MLR_{peak_2} ($g.s^{-1}$)	HRR_{peak_1} (kW)	HRR_{peak_2} (kW)
Thermoplastic		60±3	4.2±0.7	3.9±0.9	86±12	65±20
Wood	Parallel	79±1	4.8±1.0	4.4±0.1	55±11	51±1
	Perpendicular	81 ±1	5.5±1.0	5.6±0.8	51±5	55±1

The study of the fire behavior of the cladding has shown that the cladding is ignited at the bottom by direct contact with the flame front coming from the slabs. The heat flux received by the cladding during the propagation of the fire on the slabs does not allow the temperature of the cladding to rise enough to allow ignition by radiation. Once ignited, the combustion dynamics of the cladding is not influenced by the type of decking slabs. Combustion begins on the exposed face and then spreads to the back face, resulting in a generalized burning of the cladding.

3.2.3. Effect of the batten arrangement

Fig. 13 compares the HRR and the mass loss after the cladding ignition for the long and short battens configurations for a distance of 20 cm between the slab and the cladding. The evolution of the HRR is similar for both battens. The change in size and configuration does not seem to have a

significant influence on the overall behaviour of the cladding once it is ignited. The difference in HRR is a maximum of 7 and 9 kW for the first and second peaks respectively. Otherwise it is between 1 and 5 kW, which is within the standard deviation of the experiments. The evolution of the mass loss is generally similar, although the mass loss of the long batten configuration decreases more rapidly. This can be explained by the addition of fuel from the battens themselves, but above all by the greater chimney effect caused by the presence of the long battens, which favours the combustion of the wood at the rear face. Thus, the combustion of the cladding is little affected by the size of the battens. This parameter does not seem to be a key parameter in the fire behavior of the cladding.

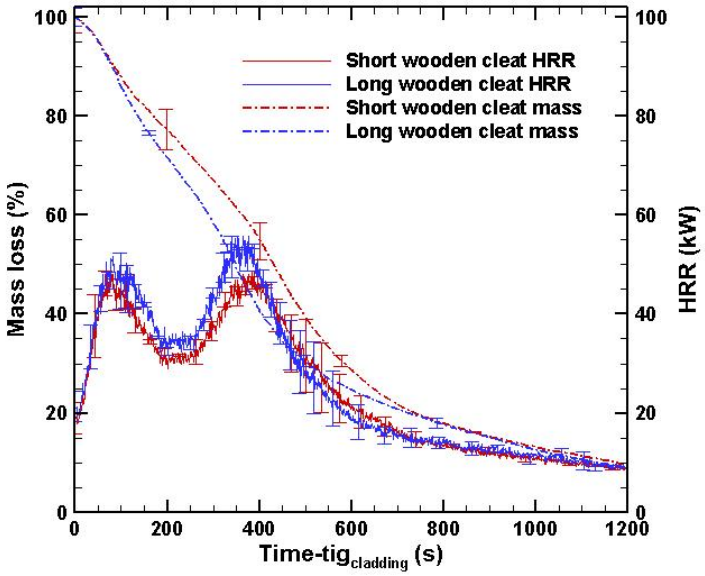
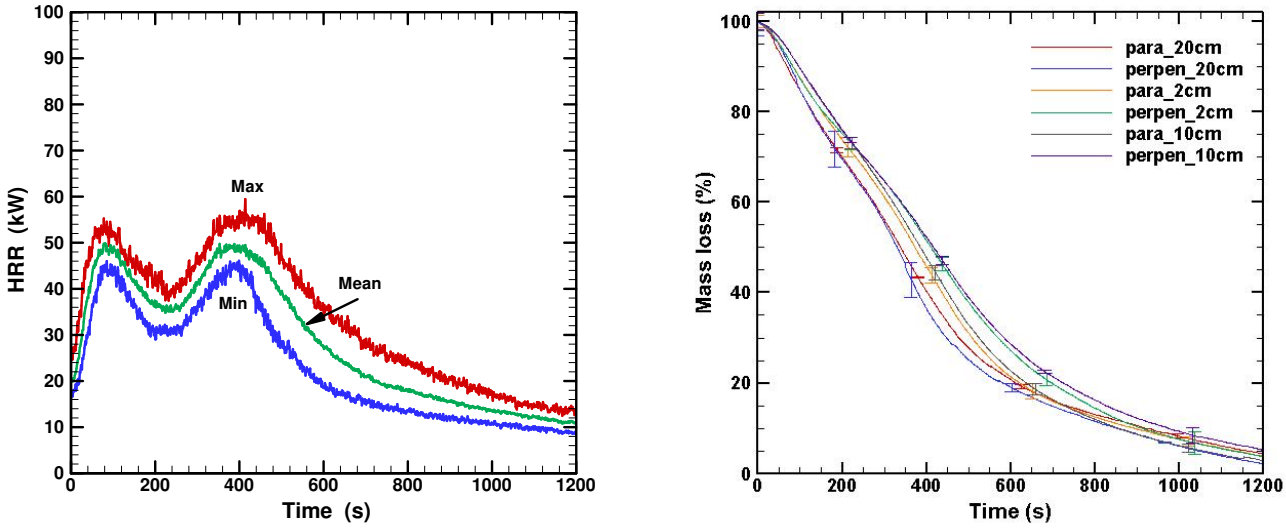


Figure 13: Comparison of HRR and normalised mass losses according to the type of wooden battens.

3.2.4. Effect of vertical distance on the fire behaviour of cladding and wooden slabs orientations

The influence of the vertical distance between the cladding and the decking slab is only studied for the wooden decking slabs. Three distances are tested: 20, 10 and 2 cm. In France, the DTU 41.2 standard [28] stipulates that the distance between the ground and the cladding must be equal to 20 cm. However, owners may have to change the layout of their home, in particular by installing a terrace at a later date. Fig. 14 shows the mean HRR, mass loss and MLR for the different distances and both orientations of the wooden decking slabs. Table 2 presents the main fire indicators for the different heights and configurations of wooden slabs.



(a) HRR.

(b) Mass loss.

Figure 14: Evolution of HRR and mass losses for the different gaps between cladding and wooden decking slabs (height of 2, 10 and 20 cm).

Table 2: Mass loss at 600 s, peaks of HRR and MLR for the different gaps between cladding and wooden decking slabs.

Orientation	d (cm)	Mass loss at 600 s (%)	MLR_{peak_1} ($g.s^{-1}$)	MLR_{peak_2} ($g.s^{-1}$)	HRR_{peak_1} (kW)	HRR_{peak_2} (kW)
parallel	2	79±2	3.8±0.2	4.1±0.1	52±5	56±3
	10	78±1	3.4±0.2	3.9±0.01	49±5	59±2
	20	79±1	4.8±1.0	4.4±0.1	55±11	51±1
perpendicular	2	73±2	3.7±0.2	3.5±0.3	53±2	50±3
	10	72±1	3.5±0.3	3.4±0.1	52±4	53±6
	20	81 ±1	5.5±1.0	5.6±0.8	51±5	55±1

The tests are slightly more repeatable at a distance of 2 cm compared to 20 cm. This observation is due to the higher heat fluxes received on the lower part of the cladding (Fig. 5), which facilitates a homogeneous ignition of the wooden cladding. With regard to the influence of the decking slab, the spacing between the decking slab and the cladding does not have a significant impact on the fire behaviour of the cladding once it has ignited. Indeed, the evolution of HRR and mass loss is similar for all configurations (Table 2). The mass loss at 600 s varies between 72 and 81 % to reach a residual mass at 1200 s between 2 and 5 %, mainly ashes. The two HRR peaks are between 49 and 59 kW with no particular trend observed. The MLRs also have similar peaks between 3.4 and 5.6

g.s^{-1}, with slightly higher peaks for a spacing of 20 cm. ~~This weak influence of the spacing on the fire behaviour of the cladding is probably due to the fact that the flames produced by the wooden decking slabs are approximately 33 cm in length, resulting in direct contact regardless of the spacing tested. Since ignition occurs by direct contact, it would be safer to require an additional horizontal discontinuity between the decking slab and the cladding.~~ Thus, no effect on the vulnerability of the cladding was observed for the distances tested between the decking slabs and the cladding. A vertical distance of 2, 10 or 20 cm always induces ignition of the cladding by the flame front resulting from the combustion of the decking slabs. This weak influence of the spacing on the fire behaviour of the cladding is probably due to the fact that the flames generated by the wooden decking slabs have a length of approximately 33 cm, resulting in direct contact regardless of the spacing tested. Since ignition occurs by direct contact, it would be safer to require an additional horizontal discontinuity between the decking slab and the cladding.

4. Conclusion

The experimental setup in this study allows the investigation of the propagation of a flame front from a horizontal material used in the exterior of a dwelling (decking slab) to a vertical material such as wooden cladding. The influence of the decking slab material and its orientation as well as the vertical distance between the slab and the cladding were investigated. For the three slab configurations tested, the radiant heat flux is the dominant heat transfer mode during the fire propagation on the slab. Ignition of the wooden cladding occurs only by direct contact, as the temperature increase on the cladding is not sufficient to allow an ignition by radiation. The 21 tests performed to study the fire behaviour of the cladding have shown that:

- Slab configuration has little effect on cladding combustion once it is ignited. There are two peaks in the MLR and HRR. The first one is due to the ignition of the front face of the wooden cladding, whereas the second peak corresponds to the ignition of the back face after the penetration of the flame into the gap separating the cladding from the cellular concrete wall.

- The vertical spacing (for the range considered in this study, 2 cm to 20 cm) between the decking slab and the cladding does not impact significantly the fire behaviour of the cladding.

These tests have shown that in the absence of extreme conditions such as wind, wooden cladding positioned at the end of a combustible decking slab will ignite and burn completely. A vertical spacing of 20 cm (according to the standards) does not prevent the spread of the fire. It therefore seems

necessary to recommend an additional horizontal separation, since ignition takes place by direct contact with the flame front. It would also be interesting to recommend the use of an incombustible barrier between the cladding and the wall to avoid the chimney effect and the ignition of the rear face.

Appendix A. Appendices

(a) Perpendicular orientation.

(b) Parallel orientation.

Figure A.15: Orientation of wooden decking slabs for a vertical distance of 2 cm between the cladding and the slab.

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