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Determination of the critical conditions leading to the ignition of decking slabs by flaming firebrands

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the ignition by flaming firebrands of two decking slabs used in French dwellings located in Wildland–Urban Interface. The first decking slab was made of pine and the second one was a thermoplastic composed of polypropylene and calcium carbonate. Flaming firebrands were produced by heating and igniting wood chips of different shapes (square, longitudinal and rectangular) with a cone calorimeter. The firebrands generated preserved their shape during their heating. Their projected area was between 0.07 and 12.00 cm^2 and their mass ranged from 0.57 mg to 2.66 g. The location of flaming firebrands, the minimal mass and the minimal number of firebrands needed to ignite the slabs were analysed in order to determine the critical conditions of ignition. The ignition of the decking slab only occurred when the firebrands were positioned at the interstices of the wooden slabs and against the leg of the thermoplastic slabs. No ignition occurred when the firebrands were located on the surface of the decking slab. A minimum mass of firebrands of 0.31 g and 0.80 g was necessary to ignite the wooden slabs and the thermoplastic ones, respectively. Less firebrands were needed to ignite wooden slabs than thermoplastic ones.

1. Introduction

Structure ignition problem has become one of the major concerns in countries affected by Wildland–Urban Interface (WUI) fires. According to the International Association of Wildland Fire (IAWF) [1], the number of structures lost per year has increased from around 900 per year in the 1990's to almost 3000 per year in the 2000's. As a result of climate change, fuel management policies and the expansion of rural areas, the frequency and the severity of devastating WUI fires has indeed increased dramatically in recent decades [2].

Fires spread to structures through three fundamental pathways: radiant exposure, direct flame contact exposure and firebrand attack [3]. Radiant exposure occurs when large flames are close to the exposed structural elements. Direct flame contact exposure happens when flames are in contact with structural elements, for example because of hedges. Finally, fires can spread through the transport of firebrands by fire plumes. Among these solicitations, firebrands have been identified as one of the primary sources of ignition in the WUI [2,4]. However, this source of ignition is much less studied than the ignition by radiant exposure or flame contact. The studies on firebrands can be divided in three categories. The first category investigates the production of firebrands from burning vegetation [4–9]. The second type of investigation works on the firebrand transport [10–18]. Finally, the last studies assess the vulnerabilities of structures to ignition from firebrand attack. Not many works concern this topic [19–22] that therefore deserves to be expanded with studies for the different building elements.

According to the post-fire damage investigations [23,24], deck assemblies have been identified as vulnerable materials to ignition. These materials could be ignited with firebrands in many ways. The firebrands can ignite the deck assemblies by accumulating on the top of decks, in interstices, or in the space between the deck slab and an exterior wall. They can also ignite unmanaged debris that accumulates under the deck. Despite these facts, traditionally, deck material is tested by their flame spread properties and the ignition potential from direct flame contact [25,26]. Recently, some works have investigated the role of firebrands. In California, a research project developed by the Office of the State Fire Marshal (OFSM) [27] allowed to develop new test configurations of deck ignition with firebrands (SFM 12-7A-4 Part B). In this test, firebrands are placed on the top of a section of deck under an air flow. Based on this test, Hasburg et al. [21] conducted experiments on a sequoia terrace. These studies have underlined that interstices/gaps are elements facilitating the decks ignition due to the re-radiation that occurs in these

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spaces. Recent development of the Firebrand Generator by the National Institute of Standards and Technology (NIST) have also advanced understanding of vulnerabilities of structures to firebrands significantly. The Firebrand Generator allows generating a controlled and repeatable size and mass distribution of glowing firebrands. With this device, a series of experiments [19] were conducted with similar wood decking assemblies to those of Hasburg et al. [21] in order to examine possible vulnerabilities to continuous wind-driven firebrands. Some countries or states have developed standards and guidelines [28–30] including decking slabs in order to reduce the vulnerability of dwellings in WUI. However, these standards are not harmonized and there are still many questions about the critical conditions that could induce ignition of building materials.

In the present work, the critical conditions leading to the ignition by flaming firebrands of two decking slabs, often used in French dwelling, was determined. The current paper is divided in two parts. The first section describes the materials and methods. The results and discussion are provided in the second section. The firebrand geometry as well as the firebrand flammability are first presented. Then, the influence of the firebrand position on ignition is highlighted and the mass and number of firebrands required for ignition are provided. Finally, some recommendation is given for the use of such slabs in WUI.

2. Material and methods

2.1. Decking slabs and wood chips

Two kinds of decking slabs were used in this study (Fig. 1). The first one was made of wood and the second one was made of thermoplastic. These items were chosen to test two different types of materials that can be easily purchased at Do It Yourself (DIY) stores. Both decking slabs measure 40 × 40 cm^2. The wooden slabs were made of pine with a density of 530 kg/m^3. They were treated by the manufacturer with Impralit KDS to be protected against insects and wood-destroying fungi. This product (manufactured by RÜTGERS Organics GmbH) is a water-resistant preservative for underground and aerial applications. It is composed of copper, boric acid and betaine polymer (DPAB) [31]. The thermoplastic decking slabs are made of polypropylene and calcium carbonate. Calcium carbonate (CaCO3) is a filler frequently associated with thermoplastic materials in order to improve their mechanical properties [32]. The calcium carbonate was mixed with the polypropylene by the manufacturer prior to moulding the decking slabs. Before each experiment, the decking slabs were first oven-dried at 65 °C during 24 h before the experiments to get closer to the summer conditions in France. A maximum moisture of 3% was measured at the beginning of the experiments for the decking slabs.

The firebrands were created from chips in pine wood oven dried at 65 °C for at least 48 h in order to remove their moisture. The ultimate analysis of the wood chips is given in Table 1. The gross-heat of combustion (GHC) and the net heat of combustion (NHC) were determined according to the standard NF EN ISO 18125. Values of 19.6 MJ/kg and 18.3 MJ/kg were obtained for the GHC and the NHC respectively. The value of the GHC is in the range of the GHC reported by Ganteaume and al. [4] for different forest fuels (18.87–27.65 MJ/kg). Our wood chips correspond to forest fuels with medium GHC according to the classification proposed by Elvira and al. [28]. As the firebrands produced by fires can have different forms depending on the part of the plants that creates them [4] (barks, needles, leaves …), several shapes and sizes of wood chips were tested. The wood chips were classified into three classes depending on their shape. The wood chips of class C1 have square shape (Fig. 2). The wood chips belonging to class C2 have a longitudinal shape. Finally, the wood chips of class C3 have a rectangular shape and are very thin. According to Refs. [5,7–9] the majority of the firebrands generated by forest fires have a projected areas less than 10 cm^2. Therefore, we focused our study on this range of values. Since the selected range of projected area and thickness were still quite large, we subdivided classes C1 and C2 according to these two parameters. The class C1 was divided into four subclasses (C11, C12, C13 and C14) while class C2 was split into three subclasses (C21, C22 and C23) (Fig. 2).

Table 1
Ultimate analysis of the wood chips (percentage on dry basis).

C (%)	H (%)	O (%)	Ash (%)
49.9	6.06	42.2	1.6

As the wood chips belonging to a same subclass were all different, we characterized their geometrical properties (length, width and thickness) and their mass with a mathematical law. For this, 50 wood chips of each subclass were used. Their geometrical properties and their mass were measured by using a precision caliper, a micrometer and a precision balance. Different statistical laws were tested. The best agreement was obtained with a normal distribution law, for which the probability density function $f(x)$ is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu^2}{\sigma}\right)\right) \quad (1)$$

where μ is the mean of the distribution and σ the standard deviation. Table 2 presents the statistical parameters obtained for each subclass. As an example, Fig. 3 presents the results obtained for the wood chips of subclass C11. The experimental results were represented as a cumulative distribution function, noted *F*. The probability density function, noted *f*, is also plotted in grey.

For the wood chips of subclass C11, the length distribution is in the range of 10.48–22.80 mm. The mean value is 14.44 mm with a standard deviation of 2.38 mm. An average relative discrepancy of about 8% was found between the experimental data and a normal law (see Fig. 3a), which shows a good agreement. The probability density function shows that 80% of the length are smaller than 17 mm. The width varies between 5.42 and 12.40 mm with a mean value of 8.90 mm and a standard deviation of 1.49 mm. Results show a good agreement between numerical and experimental distributions with a mean discrepancy of 9%. The thickness distribution is in a range of 1.05–3.54 mm. The mean value is about 2.10 mm with a standard deviation of 0.62 mm. The mean relative discrepancy between experiments is about 10%. The mass

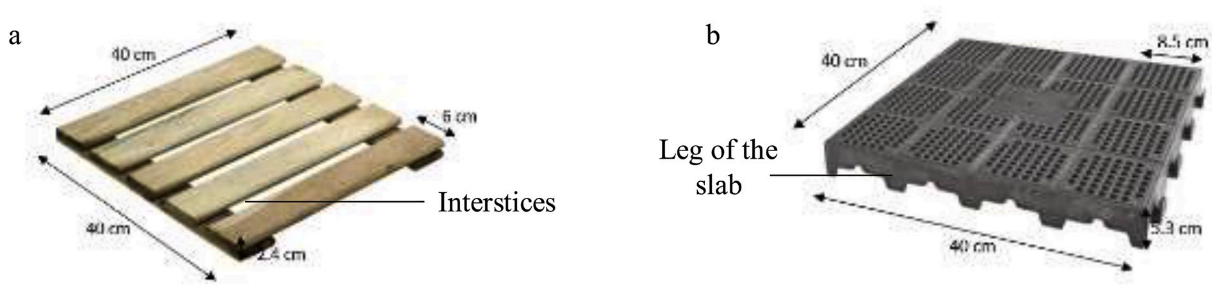

Fig. 1. Decking slabs made of a) wood b) thermoplastic material.

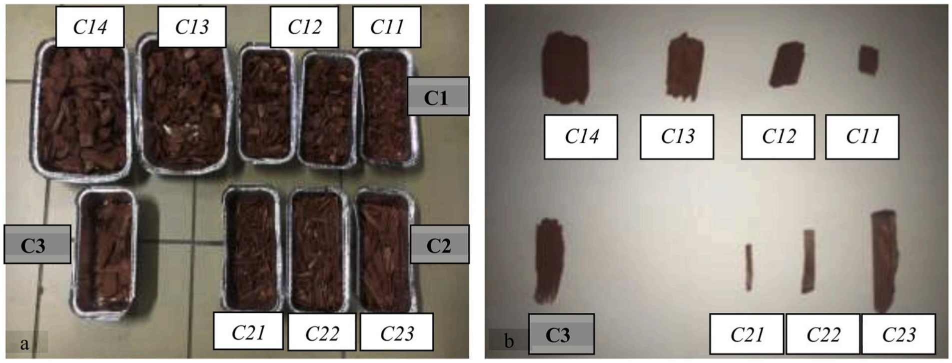

Fig. 2. Wood chips used to create the firebrands - a) sorted by classes and b) a specimen of each subclass.

Table 2
Parameters of the geometrical and mass distributions of the wood chips subclasses.

Parameters		Length		Width		Thickness		Mass	
Distribution law		Normal		Normal		Normal		Normal	
Law parameters		μ (mm)	σ (mm)	μ (mm)	σ (mm)	μ (mm)	σ (mm)	μ (g)	σ (g)
Subclass	C11	14.44	2.38	8.90	1.49	2.10	0.62	0.08	0.04
	C12	26.04	4.96	14.58	2.88	4.89	1.45	0.50	0.19
	C13	30.61	4.28	16.46	2.62	5.36	1.51	0.72	0.21
	C14	36.72	5.65	23.31	3.72	6.44	2.20	1.46	0.52
	C21	29.68	6.89	3.49	1.12	1.83	0.80	0.06	0.04
	C22	32.59	7.12	8.37	1.29	4.37	1.29	0.31	0.11
	C23	63.98	14.19	10.68	3.57	5.05	2.35	1.03	0.66
	C3	38.38	9.96	15.41	5.50	1.85	0.69	0.26	0.14

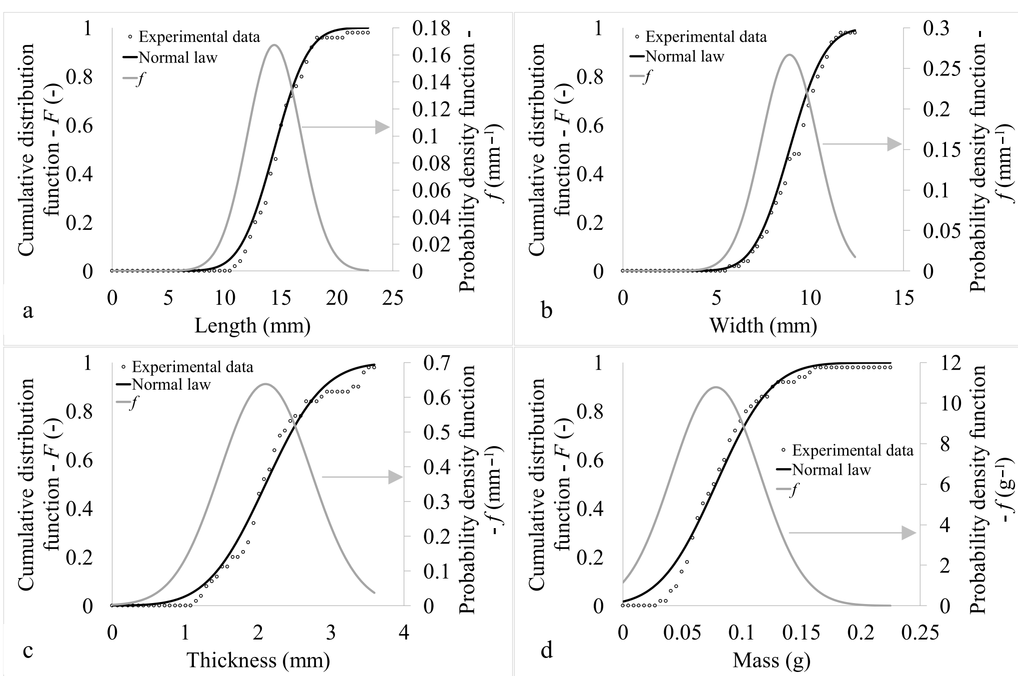

Fig. 3. Geometry and mass distributions of wood chips subclass C11 a) length, b) width, c) thickness and d) mass.

presents the most significant variation between numerical and experimental distributions with a mean discrepancy of 12%. Experimental results vary between 0.02 and 0.22 g and the mean value is about 0.08 g with a standard deviation of 0.04 mm.

2.2. *Wood chip burning*

2.2.1. *Wood chip flammability*

The flammability of the wood chips was characterized with a cone calorimeter. This apparatus consists of a cone heater, a shutter, a load cell, and an exhaust system with gas analyzers (Fig. 4a). The radiant flux produced by the cone heater was calibrated with a fluxmeter before each

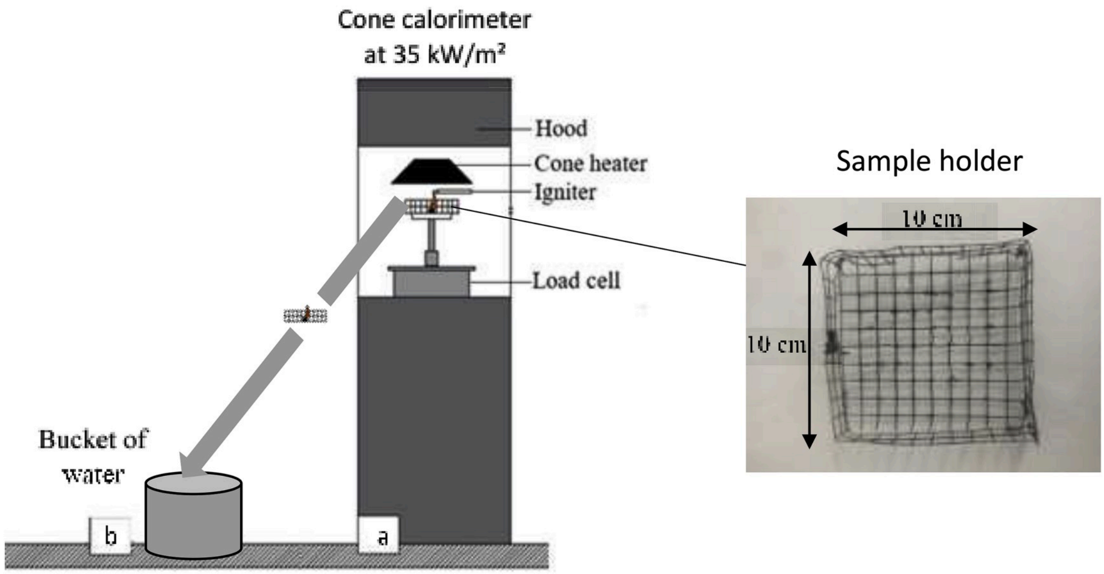

Fig. 4. Diagram of the cone calorimeter and picture of sample holder - Study of a) the wood chip flammability b) the firebrand geometry. Critical position of firebrands leading to slab ignition.

test. An insulating ceramic plate was used to protect the load cell from the effect of the radiant heat flux. For each subclass of firebrands, a single wood chip was placed in a sample holder mesh basket of 10 × 10 cm^2 made of stainless steel at 25 ± 1 mm from the lower edge of the cone heater. A radiant heat flux of 35 kW/m^2 was imposed on the wood chips and a piezoelectric igniter was used. The following parameters were studied: the ignition time (which corresponds to the appearance of a sustained flame), the flame residence time (which corresponds to the time between the ignition and the flameout) and the glowing time (corresponding to the time between the flameout and the total extinction). For each subclass, at least three repetitions were done. The results show a good reproducibility.

2.2.2. Firebrand geometry

We studied the variation of the wood chips geometry after their ignition. A single wood chip of all subclass (excepted C11 and C21) was placed in a sample holder, under the cone calorimeter and exposed to a radiant heat flux of 35 kW/m^2 until piloted ignition occurred. For C11 and C21, 10 wood chips were used in order to reach ignition. Once ignited, the firebrands were removed from under the cone calorimeter and placed in a bucket of water to stop their combustion (Fig. 4b). Then, the firebrands were oven dried at 65 °C for at least 48 h in order to remove the water. They were weighed and their length, width and thickness were measured. Then their volume and projected area were calculated. For each class, 50 firebrands were analysed.

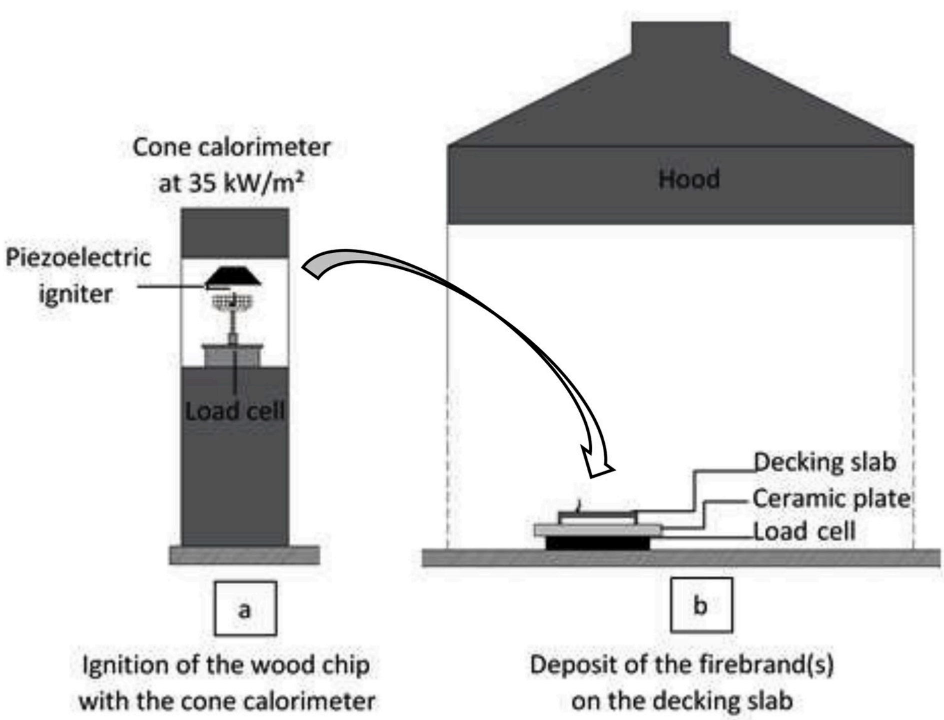

Fig. 5. Layout of the slab ignition with flaming firebrands.

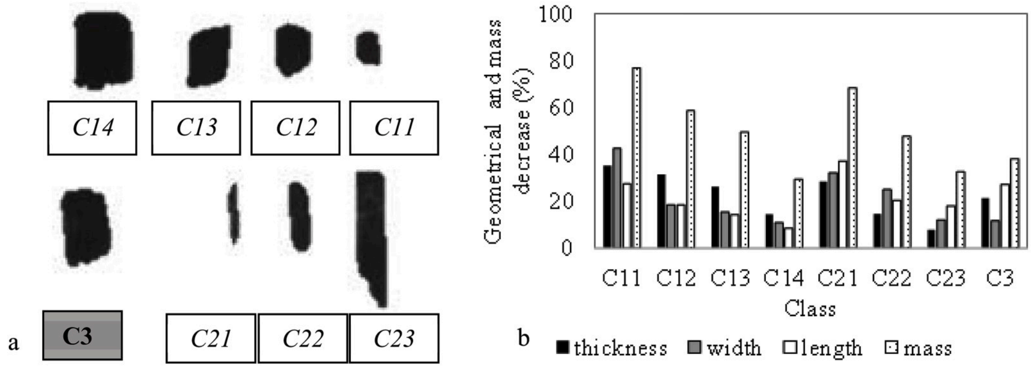

Fig. 6. a) Photography of firebrands b) Decrease of the geometrical characteristics and mass of the wood chips after becoming firebrands.

2.3. Slab ignition with flaming firebrands

The study of the slab ignition with flaming firebrands was divided in two steps. First of all, the influence of the firebrand position on the slab ignition was investigated. Then, the minimal mass and number of firebrands needed to ignite the slabs were determined. For both steps, the same procedure was used. The decking slabs were positioned over an insulating ceramic plate and placed under a hood. The wood chips were turned into firebrands with the cone calorimeter (Fig. 5a). For this, the wood chips were positioned in a sample holder located at 25 $\pm$ 1 mm from the lower edge of the cone heater and were exposed to a radiant heat flux of 35 kW/m2 with piloted ignitor. Once ignited, the sample holder with the flaming firebrands were removed from under the cone and the firebrands was brought manually to the slab (Fig. 5b).

The influence of the position of firebrands was studied with flaming wood chips of subclass C14 that had the highest ability to sustain the flames. For each kind of slab, two setups were investigated. For wooden slabs, the firebrands were located either on the surface or between the interstices of the slab. For the thermoplastic slabs, the firebrands were positioned on the surface or against the leg of the slab. The position for which the ignition occurred corresponds to the critical position. For each position tested, only one firebrand was first used. If no ignition occurred, we increased the numbers of firebrands up to a mass of 50 g (corresponding to about 45 firebrands). When several firebrands were used, they were arranged in piles in order to accumulate the energy sources.

2.3.1. Critical mass and number of firebrands leading to slab ignition

Once the critical position has been found, the minimal mass and number of firebrands needed to ignite the slabs were determined. For this, firstly, a single flaming firebrand was used for each subclass and positioned on the slab at the critical position. If the slab was not ignited, the number of firebrands was increased until the ignition of the slab occurred. In that case, as mentioned above the firebrands were put in piles. The minimal number of flaming firebrands allowing the slab ignition is called the critical number and the corresponding mass (recorded with the cone calorimeter just before the removal of the firebrands) is defined as the critical mass. For each configuration, at least three repetitions were performed. The results show a good reproducibility.

3. Results and discussions

3.1. Firebrand geometry

The procedure to obtain the firebrands allows keeping the initial shape of the wood chips (Fig. 6a). The decrease of the size of the wood chips varies according to the subclass. For a given subclass, the smaller the chips were, the more their mass decreased (Fig. 6b). For square-shaped chips (class C1), the dimension showing the highest decrease was the thickness, excepted for subclass C11 for which the width was mainly reduced. For chips with a longitudinal or rectangular shape (C2 and C3), the greatest decrease was in length except for subclass C22 for which it was the width. For wood chips with close projected area, the decrease in length and width was similar whatever the shape of the chips.

Fig. 7 presents the firebrands distribution and Table 3 gives the mean projected areas for the different subclasses. The generated firebrands have a projected area between 0.07 and 12.00 cm^2 and a mass ranging from 0.57 mg to 2.66 g. By using size classes adopted by Thomas et al. [7], 14.0% of the firebrands generated during our study had a projected less than 0.5 cm^2, 12.1% between 0.5 and 1 cm^2, 15.6% between 1 and 2 cm^2, 17.5% between 2 and 3 cm^2, 20.8% between 3 and 5 cm^2, 18.9% between 5 and 10 cm^2 and only 1.1% above 10 cm^2 (Fig. 6a). Concerning the mass, the majority of the firebrands have a mass less than 0.4 g. The ranges 0–0.02 g and 0.2–0.4 g have the largest number of particles (19.5 and 21.1% respectively). Only 1.1% have a mass greater than 2.0 g (Fig. 6b). Therefore, we produced a majority of firebrands with projected area less than 10 cm^2 and with mass less than 0.4 g. The

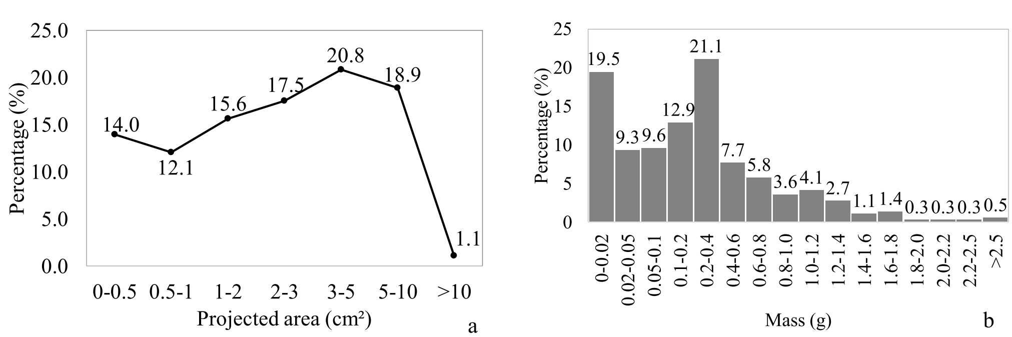

Fig. 7. Firebrand distribution as function of a) the projected area b) the mass.

Table 3
Mean projected area of the firebrands for the different classes.

	C11	C12	C13	C14	C21	C22	C23	C3
Projected area	0.56 (±0.28)	2.52 (±0.80)	3.66 (±0.91)	6.90 (±1.29)	0.47 (±0.33)	1.63 (±0.45)	4.96 (±2.34)	3.77 (±1.30)

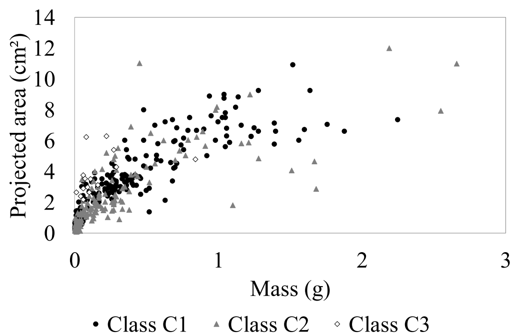

Fig. 8. Projected area plotted as a function of the masses of the firebrands.

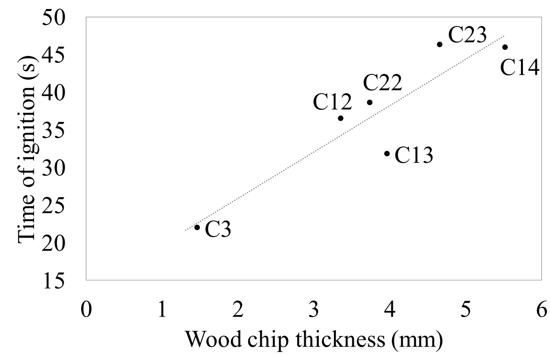

Fig. 9. Mean ignition time as a function of the thickness of the wood chips.

firebrands obtained with the wood chips are representative of those collected during actual forest fires. Houssami et al. [8] and Filkov et al. [9] observed that the greatest number of firebrands had a mass in the range of 0.01–0.02 g during prescribed burnings in forests dominated by pines. In addition, in their studies, about 80% of firebrands had a projected area less than 2 cm^2. According to Thomas et al. [7], the majority of the firebrands were smaller than in these previous studies, i.e. with a projected area less than 0.5 cm^2 for the same kind of fires. During the burning of 4.0 m Korean pine trees performed in a laboratory, Manzello et al. [5] obtained a large percentage of the firebrands with a mass less than 0.3 g. For these experiments, the firebrands had a cylindrical shape with average diameter and length of 5.0 mm and 34 mm respectively, which corresponds to a projected area of 1.7 cm^2. For Douglas-fir tree [5], the firebrands had also a cylindrical shape. The 2.6 m Douglas-fir trees generated [5], firebrands with an average diameter of 3 mm and a length of 40 mm. This corresponds to a projected area of 1.2 cm^2. For the 5.2 m Douglas-fir trees, the firebrands were slightly bigger with in average a diameter of 4 mm and a length of 53 mm, which gives a projected area of 2.12 cm^2. For both tree sizes, a large percentage of the firebrands were less than 0.3 g. No firebrand with a mass greater than 2.3 g was observed for 2.6 m Douglas-fir trees whereas firebrands with masses up to 3.5–3.7 g were obtained for the 4.0 m Korean pine and 5.2 m Douglas-fir trees.

Fig. 8 presents the projected area plotted as a function of the firebrand mass. The projected area of the generated firebrands scales with firebrand mass for all class. For the range of mass investigated, no distinction was observed for the three classes.

3.2. Firebrand flammability

Table 4 presents the mean values of the ignition time, the flame residence time, and the glowing time obtained for each wood chip subclass. Good repeatability was obtained for all parameters excepted for the glowing time. Indeed the char oxidation can be marginal because of free convection. Despite the heat flux of 35 kW/m^2 imposed with the cone heater and the presence of the igniter, no ignition occurred for the chips of the subclasses C11 and C21. As a single chip was used, the mass of these subclasses was too weak in order to release enough degradation gases and reach the lower flammability limit. For the other subclasses, the ignition always occurred. As shown by the standard deviation, there is a significant variability in the ignition time for subclass C12 (between 26 and 47 s) and also for subclass C22 (between 25 and 52 s). For these subclasses the mass of wood chips was just enough to release a quantity of gases reaching the lower flammability limit. This could explain the significant variations in their ignition time. Fig. 9 presents the mean ignition time as a function of the wood chip thickness. The ignition time increases proportionally to the thickness of the wood chips. This result is consistent with the ignition theory for thermally thin solids, for which the ignition time t_{ig} is given by Ref. [33]:

$$t_{ig} \approx \frac{\rho c_p d \left(T_{ig} - T_\infty\right)}{\dot{q}''} \tag{2}$$

where ρ, c_p, and d are the density, specific heat, physical thickness of the solid, respectively. T_{ig} and T_∞ are the ignition temperature and ambient temperature, respectively. $\dot{q}''$ represents the incident radiant heat flux density.

For a given class, the flame residence time and the glowing time increase also as the mass of the wood chips increases. It is difficult to compare the flammability properties across the different subclasses since their initial mass are different. However, it seems that for a same mass, the flame residence time tends to be higher for firebrands with a square shape (subclass C12, C13 and C14) than with longitudinal (subclass C22 and C23) and rectangular (class C3) ones. This finding is consistent with the result of flaming duration obtained by Ganteaume et al. [4] for similar firebrands. Mean values of 58.51 (±26.97) s was obtained for firebrands with a square shape, while longitudinal (subclass C22 and C23) and rectangular (class C3) shape firebrands exhibit a duration of 35.43 (±10.47) s and 35.73 (±15.20) s respectively. On the contrary, the firebrands with a longitudinal shape (subclass C22 and

Table 4
Flammability properties of the wood chips subclasses.

	C11	C12	C13	C14	C21	C22	C23	C3
Ignition time (s)	No ignition	36.5 (±7.63)	31.83 (±6.51)	46 (±2.16)	No ignition	38.66 (±11.02)	46.33 (±2.49)	22 (±4.96)
Flame residence time (s)		30.2 (±6.00)	47.90 (±3.30)	83.8 (±17.83)		27.93 (±10.30)	43.26 (±0.65)	35.73 (±15.20)
Glowing time (s)		121.6 (±55.70)	222.2 (±27.92)	221.6 (±18.20)		163.2 (±72.24)	285.6 (±124.81)	178.66 (±59.87)

Fig. 10. Firebrands of class C14 placed in piles on the surface of the wooden slab a) moment of deposit t = 0 s, b) after total extinction of firebrands t = 88 s and c) after the removal of the firebrands.

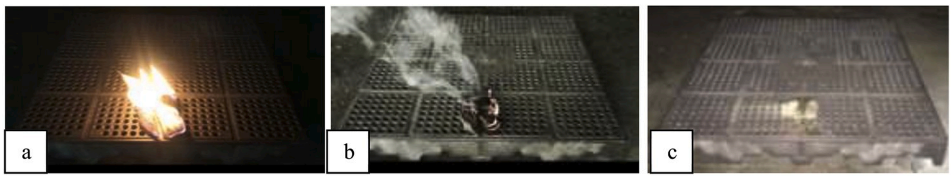

Fig. 11. Firebrands of class C14 placed in piles on the surface of the thermoplastic slab a) moment of deposit t = 0 s, b) after total extinction of firebrands t = 180 s (smoke in released by thermoplastic) and c) after the removal of the firebrands.

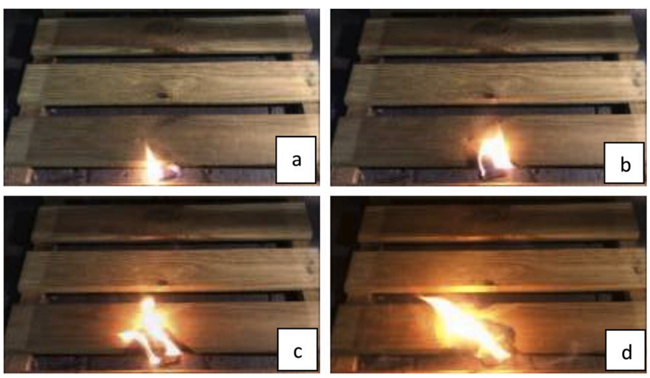

Fig. 12. Ignition of a wooden slab with one firebrand of subclass C14 at time a) 10 s, b) 32s, c) 144 s and 300 s.

C23) have the highest glowing time. Mean value of 224.56 (±119.25) s was obtained for those firebrands while the square and rectangular firebrands exhibits glowing time of 190.66 (±57.66) s and 178.66 (±59.87) s respectively. The wood chips of class C3 have the lowest ignition time. The flame residence time and glowing time of their corresponding firebrands are between those of subclasses C12 and C13. According to these results, the firebrands with the highest ability to sustain the flames are those of subclass C14. These firebrands have therefore a high potential to ignite combustible material after they have landed, even over long distance.

3.3. Influence of the firebrand position on ignition

Figs. 10 and 11 shows pictures of the experiments for which the C14 firebrands were placed on the decking slab surfaces. Whatever the mass of firebrands placed on the slabs, no ignition occurred for both types of slabs. During these experiments, smoke was released by the slabs. The wooden slabs were blackened and the thermoplastic slabs slightly melted on the surface. However, as previously, no ignition occurred. These results are in agreement with the study performed by Dowling [34], who conducted an experiment by placing up to 600 g of firebrands on the horizontal surface of a wooden deck. No sustained ignition was observed.

Then the second setup of firebrand location was tested. A single firebrand of subclass C14 was placed in between the interstices of a wooden slab (Fig. 12) and against the leg of the thermoplastic slab (Fig. 13). After a few seconds of exposure (between 10 and 19 s for the wooden slab and between 8 and 17 s for the thermoplastic one), in both cases an ignition occurred and the flame spread from the chip to the slab. These setups are therefore more favourable to promote the ignition of the decking slabs since the flames produced by the firebrand are directly in contact to the slab. Therefore, the interstices and contours of the slabs clearly constitute ignition vulnerabilities areas. Those results are consistent with literature in which these tested positions lead to ignite the material [18–20,27,28].

3.4. Mass and number of firebrands required for slab ignition

The mass and number of flaming firebrands required to ignite slabs, when located between the interstices for the wooden slab and against the leg for the thermoplastic slab, were also investigated in order to

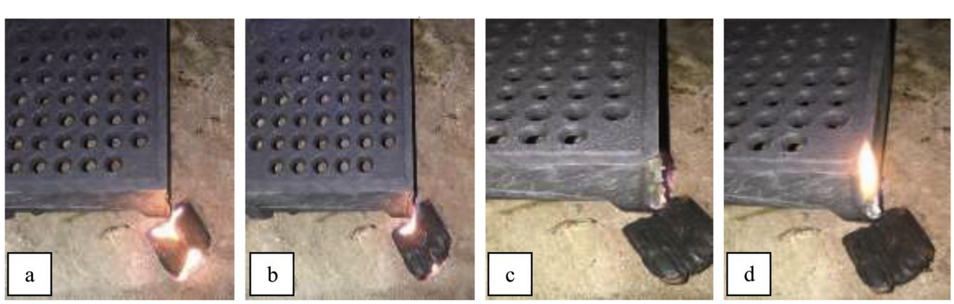

Fig. 13. Ignition of a thermoplastic slab with one firebrand of class C14 at time a) 3s, b) 16 s, c) 44 s and d) 67 s.

Table 5
Critical conditions leading to the slab ignition.

Subclass	Critical number of firebrands		Critical mass of firebrands (g)	
	Wooden slab	Thermoplastic slab	Wooden slab	Thermoplastic slab
C11	39 (±2)	47 (±3)	1.30 (±0.02)	1.60 (±0.08)
C12	1	3	0.33 (±0.04)	1.50 (±0.06)
C13	1	2	0.31 (±0.20)	1.50 (±0.25)
C14	1	1	0.31 (±0.01)	1.60 (±0.04)
C21	38 (±1)	46 (±6)	1.80 (±0.03)	2.20 (±0.04)
C22	3	3	0.65 (±0.10)	0.80 (±0.10)
C23	1	3	0.37 (±0.07)	1.80 (±0.05)
C3	3	3	0.78 (±0.19)	1.10 (±0.10)

determine the critical conditions. Table 5 presents the number of firebrands required for slab ignition and the critical mass for each subclass. Whatever the subclass, less firebrands were required to ignite wooden slabs than thermoplastic ones. Between 1 and 39 firebrands, according to their size, were required to ignite the wooden slabs while for thermoplastic slabs, the number of needed firebrands varies between 1 and 47. It deserves to mention that single firebrands belonging to the subclasses C12, C13, C14 and C23 were able to ignite the wooden slabs. On the other hand, the ignition of thermoplastic slabs with a single firebrand only occurred for the firebrands of subclass C14. As expected, the highest number of firebrands leading to ignition was obtained for the smallest firebrands belonging to subclasses C11 and C21. Concerning the mass of firebrands required to ignite the slabs, the values range from 0.31 to 1.80 g with a mean value of 0.73 g for the wooden slabs whereas they are between 0.80 and 2.20 g with a mean value of 1.75 g for the thermoplastic ones. Therefore, the minimal mass of firebrands leading to the slab ignition is equal to 0.31 g for the wooden slabs (obtained with firebrands of subclasses C12 and C13) and 0.80 g for the thermoplastic ones (obtained with firebrands of subclass C22). Even with these low masses, the slabs ignited and a sustained combustion was observed. After the complete extinction, it remained some ashes and unburned pieces on the edges for the wooden slabs (Fig. 14a). For the thermoplastic slabs, it remained white powder corresponding to the calcium carbonate added as filler in the slabs (Fig. 14b). Few data are available in the literature concerning the mass of firebrands needed to ignite building material. To our knowledge, there is only the works of Manzello et al. [19,35] which give values for decking assemblies. By using their dragon to generate the firebrands and with a wind speed of 6 m/s, the mass of firebrands required to ignite wood decking assemblies was between 85 and 283 g. For a wind speed of 8 m/s, the values were lower (between 7.5 and 24.1 g), probably because of a higher surface temperature of the firebrands [19]. Our values are therefore much lower

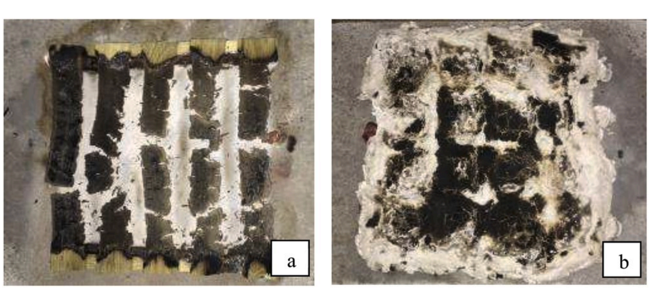

Fig. 14. Residue after total extinction of a) the wooden slab b) the thermoplastic slab.

than those obtained by Manzello et al. with the Firebrand Generator. This is likely due to the combustion mode of the firebrands. The firebrands produced by the Firebrand Generator were indeed not all in flaming combustion. Some of them had rather a glowing combustion. An advantage of our experimental device is the control of the experimental conditions. We control the size and mass of the firebrands as well as their positioning. In addition, all the firebrands are in the same combustion phase, namely a flaming combustion. Thanks to these elements, it is possible to define the critical conditions leading to the ignition of the slabs by the firebrands.

4. Conclusions and recommendations

In this study, the critical conditions leading to the ignition of decking slabs used in French dwellings with flaming firebrands were determined. Two kinds of slabs were investigated. The first ones were made of pine wood whereas the second ones were in thermoplastic made of a mixture of polypropylene and calcium carbonate. The flaming firebrands were created by placing wood chips with various shapes (square, longitudinal and rectangular) and sizes under a cone calorimeter. The obtained firebrands had a projected area between 0.07 and 12.00 cm^2 and a mass ranging from 0.57 mg to 2.66 g that are representative of firebrands produced by actual forest fires. In order to determine the position of the firebrands that induce an ignition of the slabs, two positions were investigated for each decking slabs: on the surface and between the interstices for the wooden slab and on the surface and against the leg for the thermoplastic slab. No ignition occurred when the firebrands were on the slab surface. On the contrary, the slabs were ignited by the firebrands when these last ones were located in between the interstices for wooden slabs and against the leg for thermoplastic slabs. The number of firebrands inducing the slab ignition varied between 1 and 47 depending on the firebrand size and on the type of slabs. For wooden slabs, a mass of 0.31 g of firebrand was sufficient to induce ignition while it was necessary to have at least 0.80 g for thermoplastic slabs. The studied wooden slabs are therefore more ignitable than the thermoplastic ones.

Because of the small number (or mass) of firebrands needed to ignite the studied decking slabs, it is clear that their use in WUI areas increases the vulnerability of surrounding building. Unfortunately, in France, there is no standard for testing the flammability of decking slabs against thermal stress in the case of forest fires. This problem is not only limited to this country and it also concerns other European countries. Therefore, we recommend the development of a European or even global standard for qualifying the vulnerability of decking slabs in WUI areas. In the meantime, we suggest following the recommendations of existing standards for these materials [28–30], i.e. the use of treated decking slabs with flame retardant products and appropriate dimension of the interstices.

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.

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