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TOWARD A STANDARDIZED UNIFORMLY DISTRIBUTED CELLULOSIC FIRE LOAD

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ABSTRACT

This paper describes a series of experimental tests performed on uniformly distributed fire load made of wood sticks. The aim of this campaign was to define a fuel load arrangement that would lead to a fire with the characteristics recommended for office building occupations in EN 1991-1-2. This means a fire load density of 511 MJ/m² and a medium fire propagation.
The ignition procedure that was developed is described as well as the fuel arrangement that leads to a continuous isotropic fire propagation. For the 11 tests performed, the evolution of the radius of the fire is given as a function of time as well as the constant t_α that characterises the t^2 fire. The size of the sticks is not the dominant parameter that influences the fire spread, whereas the presence or not of a ceiling has an overwhelming influence and the volumetric ratio of wood in the fire load allows controlling the fire spread. Values of the volumetric ratio are proposed that should lead to a slow, a medium or a fast fire.

1 INTRODUCTION

A huge number of so-called “natural” fire tests have been performed over the years in full scale compartments with cellulosic fire load. The objectives of these tests were diverse, either linked to the fire dynamics (temperature development, determination of the relationship between the opening factor and the rate of heat release, occurrence of flashover, occurrence of backdraft…) or to the structural behaviour (development of the tensile membrane action, behaviour of particular structural elements) [1]. The recent interest in the so-called “travelling fires” brought a renewed attention to these “natural” fire tests. It turned out yet that the lack of a standardized procedure lead to the fact that different fuel load arrangements were used in these tests. Wood cribs have been used most of the time, but with cribs of different dimensions, timber sticks with different sections and different distances between the cribs. In some tests the cribs were ignited and the fire was left to develop uncontrolled [2], whereas in other tests the cribs have been linked to each other with a steel U channel filled with paraffin to guarantee a rapid fire spread and a rapid development toward a uniform temperature in the compartment [3]. In some tests the fire did not develop as expected and the scientists in charge had to manipulate the fire, either by creating new openings [4], introducing a forced ventilation or adding some liquid fuel to the initially cellulosic fire load [5]. This diversity in procedures makes it impossible to compare the results between each other and to come to conclusive findings. Within the context of the Research Found for Coal and Steel research project “TRAFIR” (Characterization of TRAvelling FIRes in large compartments) sponsored by the E.U. Commission, the fire lab of Liège University has recently performed a series of fire tests with uniformly distributed cellulosic fire loads, with the aim of defining an arrangement of the wood sticks that would lead to a desired fire development. The objective was, using a fire load density as recommended in Eurocode 1 for office buildings, i.e. 511 MJ/m^2, to come to a fuel arrangement that would lead to a medium fire development also recommended for office buildings [6]. This paper reports the tests that have been performed and the results in term of fire spread and time constant t_α of the t-square fire.

2 FIRST SERIES OF TESTS

A first series of five tests has been performed in the fire lab of Liege University in order to, first, establish an ignition procedure that would ensure a reliable and reproducible ignition of the fire load and, second, to investigate at a reasonable cost some important parameters, thus allowing to take first important decisions before performing the more expensive tests that should lead to the final conclusions.

2.1 Ignition procedure

After several attempts based on trials and errors, the ignition procedure was based on a steel cylinder container with a diameter of 106 mm and a height of 25 mm in which 40 ml of denatured ethanol at 96% were placed. This liquid releases enough combustible vapours at ambient temperature to ensure an easy ignition, but not that fast that all liquid would have disappeared by the time the timber fuel load has been installed.

Two electrical igniters were located overhead the cylinder as shown in *Fig. 1.a* to allow ignition from a distance by connecting the igniters to the two poles of a 9 V battery (or to a 19 V transformer taken from a desktop computer, because the battery may fail to trigger the igniters if the wires from the battery to the igniter are too long).

Fig. 1. a) Electrical igniters b) Two layers of lath

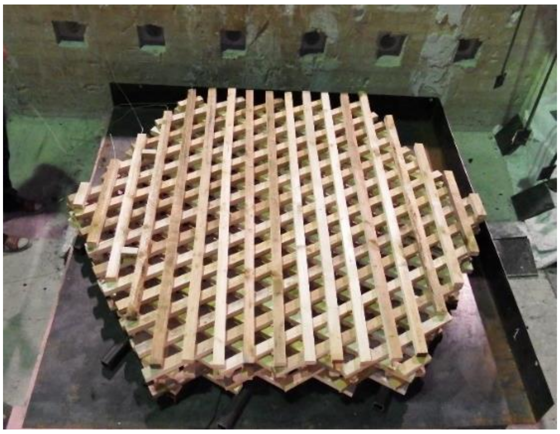
Four laths of 15 mm x 18 mm made of *Picea abies* (spruce) were placed on the cylinder and another layer of 4 similar laths on top and perpendicularly to the first layer as shown in the circle drawn in *Fig. 1.b*.

In the 11 tests that were performed, ethanol was ignited by a single electrical igniter in 8 tests, the first electrical igniter failed to ignite the ethanol and the second electrical igniter had to be used in 2 tests, and one test needed a third igniter to be inserted to the steel cylinder among the wood sticks already installed. For all tests, ignition of the ethanol lead to a subsequent ignition of the timber cribs.

2.2 Fuel load arrangement

A 3 mm thick steel plate was used on which 4 steel tube 50 mm x 50 mm were laid to create a clear space between the steel plate and the first layer of wood cribs (the steel cylinder of the igniter was directly laid on the steel plate).

It was decided from the beginning that the fuel load would be laid uniformly on the floor area, as opposed to an arrangement in wood cribs, in order to lead to a continuous horizontal fire propagation, as opposed to a propagation in steps from crib to crib.
It was also decided that the sticks would not be laid in only 2 perpendicular directions but in 3 directions rotated by 60 degrees from layer to layer as shown in *Fig. 2.a* for a test of the first series, in order to favour a horizontal fire propagation as isotropic as possible. *Fig. 2.b* for example, shows a nearly circular shape of the burnt area for a test of the second series where the upper layers have been removed after the test.



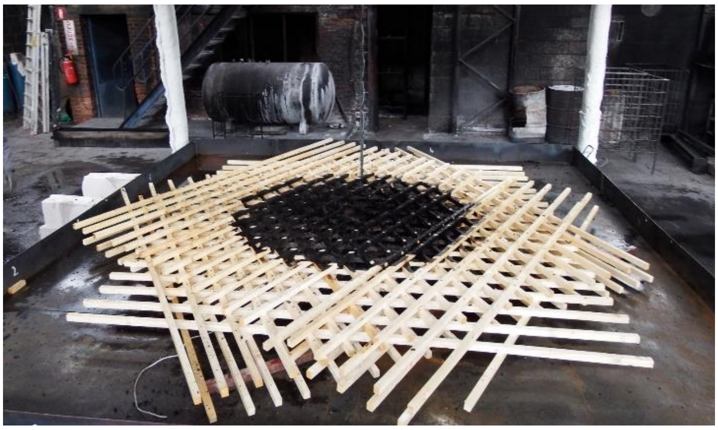


Fig. 2. a) Fuel arrangement before the test b) Isotropic horizontal propagation

In most tests, the sticks in any direction were located in the same position for different layers. This means that the sticks of layer *i+3* were laid above the sticks of layer *i* as shown in *Fig. 2.a*. In some tests, the sticks were shifted laterally by half the distance between the sticks. This means that the sticks of layer *i+6* were laid above the sticks of layer *i* whereas the sticks of layer *i+3* and those of layer *i+9* were shifted laterally as shown in *Fig. 2.b*.
These tests were made with a 2 meters diameter fire load. The test set up was located in the horizontal furnace of the fire lab that is 4 meters long, 3 meters wide and 1.41 meters deep. As the steel plate was located approximately 0.41 m above the floor of the furnace, the walls of the furnace extended 1 meter above the fire load (that is, approximately, 0.8 m above the upper layers of sticks).
Wood sticks were made of *Picea abies* with an average density between 443 kg/m³ and 478 kg/m³ and a moisture content, with respect to the dry mass, on the day of the test between 13.2% and 14.2%.

2.3 Measurements

The horizontal fire spread on the upper layer was measured by two different methods.

1) Visual observation of the flaming appearing on the horizontal surface of the upper layer of sticks during the test, as long as the radiation from the fire would allow.
2) Observations of pictures from a still camera that was taking shot at a 30 seconds interval.

The evolution of the mass loss was recorded continuously by 3 load cells that supported to steel plate. A grid of perpendicular timber beams spaced at 0.57 meter was installed to support the steel plate and transfer the load to the 3 load cells. One layer of gypsum was laid on the timber beams to separate them from the steel plate. From the 5^{th} test, an additional layer covering the whole surface was installed as combustion of some timber beams had started at the end of test L_A 4.
The evolution of the Rate of Heat Release as a function of time, *RHR*(*t*), was computed by means of a backward finite difference scheme with a time step of 60 seconds, see *Eq. (1)*. An effective combustion heat of 14 MJ/kg was used for wood, from a combustion factor m of 0.8 and a net calorific value H_u of 17.5 MJ/kg as recommended in Eurocode 1 [6].

$$RHR(t) = -14\,\frac{\Delta m}{\Delta t} \tag{1}$$

where m is the mass (fuel load + steel plates + gypsum layers + timber beams)
t is the time.

Other quantities have been measured but are not reported here due to space constrains: temperatures on the surface of some sticks of the upper layer, heat flux on vertical and horizontal surfaces in some points just above the upper layer, heat flux on a vertical surface at some points away at a distance from the fire, vertical flame length above the fire and temperature evolution in the centreline of the plume.

2.4 Results

The first parameter that was investigated was the influence of the size of the sticks. Three tests were performed with respectively 6 layers of B x H = 35 x 30 mm² sticks with a pitch (axis distance) of 80 mm for test L_A1, 6 layers of 45 x 35 mm² sticks with a pitch of 124 mm for test L_A2, and 3 layers of 45 x 60 mm² sticks with a pitch of 110 mm for test L_A3.

Although the sticks differed in dimensions of the section, with a specific surface of respectively 124 m²/m³, 102 m²/m³ and 78 m²/m³, no significant difference was observed in terms of spread rate (0.65 mm/s, 0.7 mm/s and 0.6 mm/s) with no correlation between the specific surface and the spread rate. Also the time constant t_α of the t-square model did not show a clear variation with values of 10.4 min, 13.2 min and 13.2 min (see *Fig. 6* that illustrates the best fit method used for calculating the values of the time constants). It appeared also that the growth rate was far above the target value of 5 minutes that was aimed at for an office building.

A second group of two tests was then performed with the same sections and same pitch as those used for tests L_A1 and L_A2, now rotated by 90 degrees (B x H = 30 x 35 mm² and 35 x 45 mm²). The major difference is that a ceiling made of insulating fibre boards was placed above the fuel load (vertical distance between the fuel load and the ceiling = 990 mm and 915 mm). A clear layer of 280 mm was left between the walls of the furnace and the ceiling. This, plus the fact that the ceiling covered only 2.66 meters of the 4 meters long furnace lead to the fact that the fire was not air controlled.

The propagation rates were significantly influenced by the presence of the ceiling. In test L_A4, the spread rate was observed at 0.9 mm/s during the first 10 minutes of the test and increased to 2.95 mm/s for the last 3 minutes. In tests L_A5, the spread rate was observed at 0.85 mm/s during the first 11 minutes of the test and increased to 7 mm/s for the last 2 minutes. The difference between the first 3 tests and the 2 tests with a ceiling can be observed on *Fig. 3* that gives the evolution of the radius of the fire as a function of time. The time constant t_α for these tests was 6.9 minutes in test L_A4 and 5.5 minutes in tests L_A5.

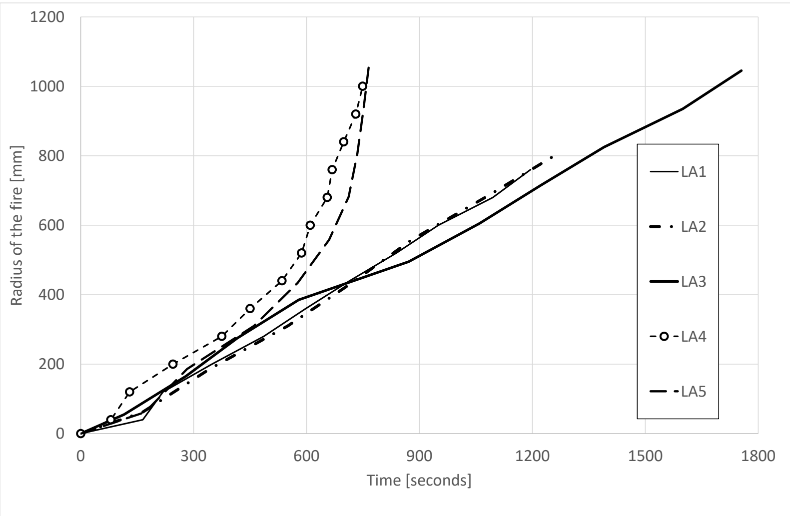


Fig. 3. Evolution of the radius of the fire in the tests L_A

3 SECOND SERIES OF TESTS

A second series of six tests was performed in larger facility where fire loads of 3 meters in diameter located on a 4,40 x 4,40 m² steel platform could be tested.

3.1 Description of the ceiling

From the results of the first test series, it was decided that all tests would be made with a ceiling located above the fire load due to the high influence of the ceiling on the fire dynamics (See *Fig. 3*). The ceiling was made of 4 timber columns suporting a grid of timber beams under which OSB board were fixed. Mats of insulating fibres were used to protect the columns and the OSB boards from the attack of the fire. The lower surface of this ceiling was 2.50 meters above the steel platform. The dimension in plan were 4.88 x 4.72 m² and a downstand of 0.35 m was running on the 4 sides of the ceiling.
Fig. 4 shows the ceiling during a test, at the beginning of the fire. Plate thermometers used to recompute the radiative flux as well as the grid supporting a thermocouple tree in the centreline of the fire are also visible. The results of these measurements are still under interpretation at the time of writing this paper and will be presented in subsequent communications.

Fig. 4. The ceiling used in the second series of tests

3.2 Tested configurations and results

Different tests were performed in a couple of days, capitalising from each test to define the next one, in the limits of the available material that had to be purchased beforehand. In test L_B5, some laths of 15 x 15 mm² of the species *Pinus sylvestris* were inserted to see whether this would favor a faster fire spread compared to companion test L_B1. In test L_B4, bands of PMMA have been inserted in three layers. Based on a specific mass of 1180 kg/m³ and a gross heat of combustion of 26.8 kJ.kg for PMMA [7], a value of 15.215 MJ/kg was used for the average heat of combustion to compute the rate of heat release from the mass loss, see *Eq. 1*.
The main parameters of these tests as well as the main results are summarized in *Table 1*.

Table 1. Parameters and results of the second series of tests

Test	B [mm]	H [mm]	Number of layers	Pitch [mm]	Density [kg/m³]	Moisture content [%]	t_α [min.]
L_B1	30	35	6	80	468	16.9	10.9
L_B2	34	45	6	135	502	16.6	9.4
L_B3	30	35	12	160	468	14.1	2.1
L_B4	34 100	45 3	5 3	135 270	502 1180	20.2 (PMMA)	4.2
L_B5	30 15	35 15	5 4	80 80	468 554	16.9 13.5	7.3
L_B7	30	35	9	120	468	16.9	7.5

The evolution of the radius of the fire is shown on *Fig.* 5.

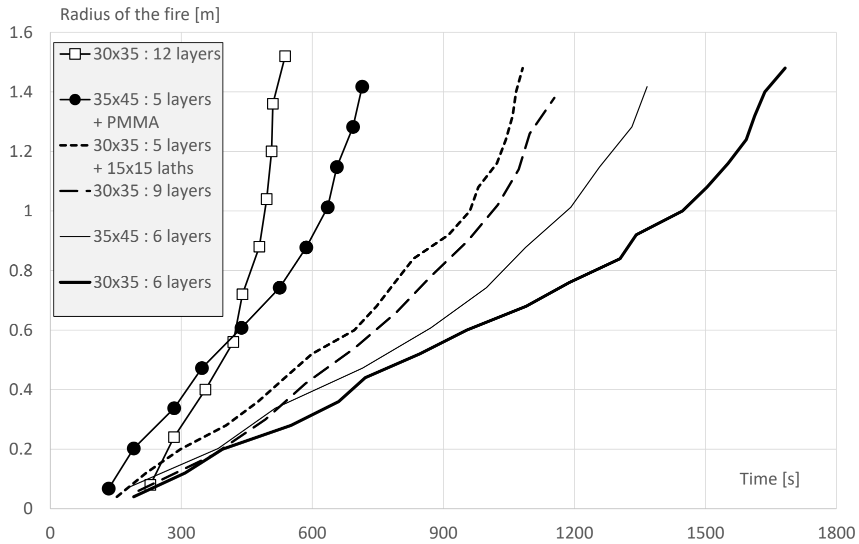


Fig. 5. Evolution of the radius of the fire for the second series of tests

The procedure to derive for each test the best fit t^2 curve from the experimental Rate of Heat Release curve involves a certain degree of human decision. The best fit curve ends at the last point that was recorded before water was applied on the fire to stop the tests. It starts with an horizontal tangent on the time axis. A human decision has to be taken as where to fix the starting point of the curve. In fact, each test is characterised by an ignition phase when only noise is recorded that has to be eliminated. *Fig. 6*, for example, shows the best fit curve derived for test L_B7 when the starting time is set to 6 minutes.

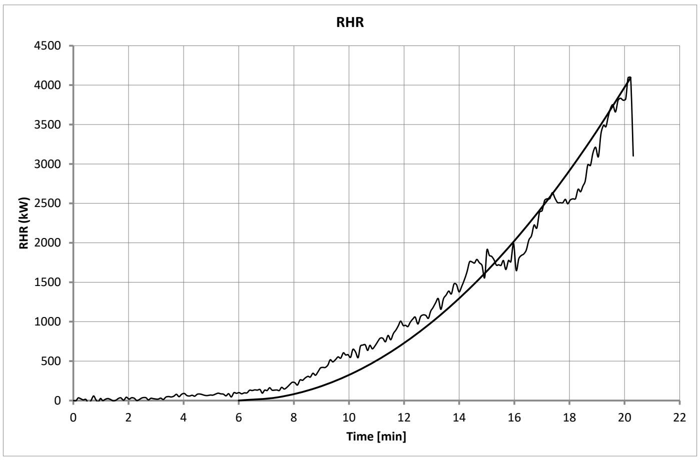


Fig. 6. Recorded RHR curve and best fit curve

The clearest interpretation of the test results is obtained when only the tests made of the section 30 x 35 mm² are considered. For the tests L_B3, L_B7 and L_B1, *Fig. 7* shows the values of the parameter t_α in minutes that was calculated as a function of the volumetric percentage of wood contained in the fuel load. Three values are presented for each test in order to reflect the degree of uncertainty linked to the choice of the starting time of the best fit curve. For each test, the lowest value of t_α (grey dots) is derived from the latest reasonable choice of the starting time, whereas the highest value (orange dots) is derived from the earliest reasonable choice and the value represented by the blue dots is the best choice if only one value has to be mentionned, from the agreed decision of the first two authors. From the best linear regression on the three test results, it appears that a fast fire can be produced with wood content of 17 ±1%, a medium fire with a wood content of 22.5±1.5% and a slow fire with a wood content of 33.5±3%.

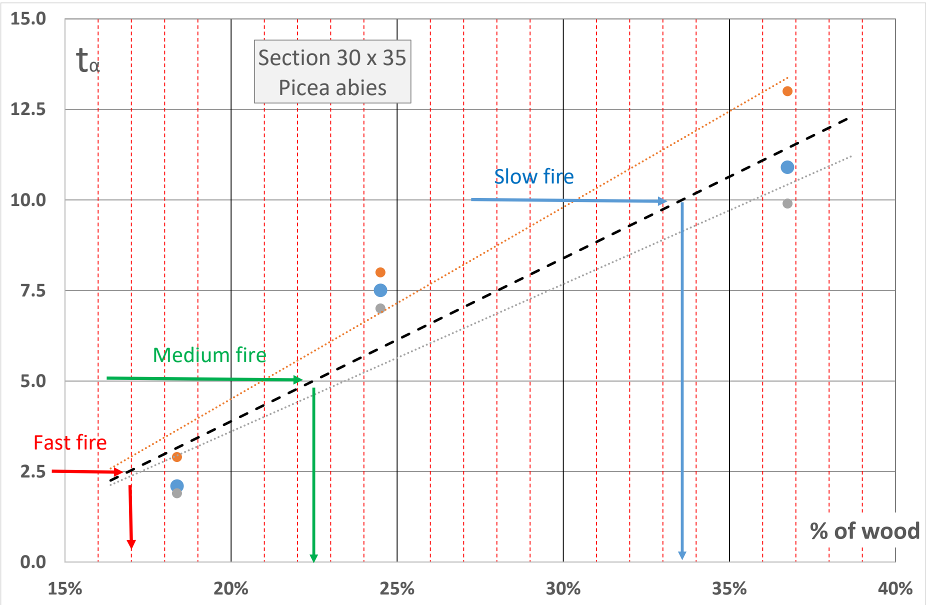


Fig. 7. Parameter t_α (in minutes) as a function of the volumetric wood content in the fire load

4 CONCLUSIONS

- 40 ml of denaturised ethanol in a 106 mm diameter cylinder on which two perpendicular layers of 15 x 18 mm² laths of *Picea abies* are located is an appropriate means for igniting a wood crib.
- A continuous layer made of several layers of wood sticks turned by 60° from layer to layer ensures a progressive and isotropic fire spread.
- Within the limits of the dimensions tested (from 30 x 35 to 45 x 60 mm²), the size of the sticks does not influence the spread rate significantly.
- The presence of a ceiling above the fire load influences significantly the fire spread. The influence of the distance between the fire load and the ceiling has not been investigated here.
- For a given configuration and dimensions of the wood sticks, the volumic wood content in the fire load has a very high influence on the spread rate.
- With sections of 30 x 35 mm² of pine tree that is commercially dry (moisture content from 14 to 17%) and with a ceiling that is approximately 2.20 meters above the fire load, a medium t^2 fire is likely to develop with a volumetric wood content around 22.5 % (17 % for a fast fire and 34% for a slow fire). The reproduceability of these results could not be investigated in this experimental campaign
- All tests results are available as open data: https://orbi.uliege.be/handle/2268/233374

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