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Perforated cellular wooden slabs under fire: Numerical and experimental approaches

David L.P. Couto[a], Elza M.M. Fonseca[b,*], Paulo A.G. Piloto[b], Jorge M. Meireles[a], Luísa M.S. Barreira[a], Débora R.S.M. Ferreira[c]

[a] *Master in Industrial Engineering, Laboratory of Mechanical Technology, Polytechnic Institute of Bragança, Portugal*
[b] *LAETA, INEGI, UMNMEE, Department of Applied Mechanics, Polytechnic Institute of Bragança, Portugal*
[c] *Department of Applied Mechanics, Polytechnic Institute of Bragança, Portugal*

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ABSTRACT

This work presents a numerical and experimental approach in order to predict the fire resistance of perforated cellular wooden slabs. The wooden slabs are lightweight, easy installation, excellent architectural, thermal and acoustic characteristics. However, its high vulnerability to fire, requires their behaviour assessed accurately. Wood material produces a surrounding char layer in depth, when exposed to fire resulting in a reduced residual section. For this purpose, different cellular wooden slabs, with the bottom surface perforated, including different small and large rectangles and circles, were tested and submitted to fire exposure. The experimental study was conducted in laboratory in accordance with European standard (EN1365-2, 2012), using a fire resistance furnace which complies the requirements of European standard (EN1363-1, 2012). Also a three-dimensional thermal and transient numerical model, using a finite element program Ansys®, was validated with experimental tests at real scale. The numerical and experimental results show good agreement. The numerical model can easily be adjusted for other constructive solutions, in order to facilitate fire safety tests, in buildings with wooden slabs used in floors or in ceilings applications.

1. Introduction

The wooden slabs are structural elements with increasing application, particularly in the rehabilitation of existing elements, suitable of large interior spaces and new building structures. The excellent mechanical properties, associated with high thermal and acoustic properties make the wood an ideal solution for floor slabs and roofs [1–3]. There are a wide range of wood applications that demonstrate the strength and stability of the material. Wood-based materials will burn when exposed to fire and are rated as combustible. They produce a surrounding char layer in depth, with no mechanical resistance, resulting a reduced residual section. Nevertheless, wood is a poor heat conductor and therefore there is a very low transmission of heat into remaining unburned material, and this has many benefits. If wood is submitted to a sufficient heat, a thermal degradation process (pyrolysis) occurs, producing gases accompanied by loss in weight and serviceable cross-section. The thermal degradation of wood occurs in stages. The degradation process depends upon the heating rate and the temperature. The factors which affect the burning behaviour of wood will determine the charring rate, as the level of radiant heat exposure, the char layer formation, the moisture content, the wood species and the cross section dimensions, [4]. Many researchers have worked with several models for the pyrolysis in solid materials, as referred by Weng et al. [5]. Weng [5] evaluated the accuracy of the above pyrolysis model for charring material under different ambient oxygen concentrations. Design models of wood structures submitted to high temperatures take into account the loss in cross-section due to char layer and the temperature dependent reduction of strength and stiffness of the uncharred residual cross-section, [6]. The stiffness and strength of wood decrease with increasing temperature, [7]. The charring rate of the wood has been studied using empirical models, experimental tests and analytical equations [8–17]. The charring rate is almost constant and mainly depends on the density and moisture content of wood species, external heat flux and oxygen concentration. The interface between charred and uncharred wood is defined by a plane between black and brown material, characterized by the isothermal of 300 °C, Eurocode 5 [18]. The charring rate for different types of species exposed to the standard time-temperature curve has been studied by many researchers, [15,19,20]. As a pointed of remark, the char layer thickness is a good insulator, which protects the wood section core. The

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[*] Corresponding author.
E-mail address: efonseca@ipb.pt (E.M.M. Fonseca).

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type of perforations and the size of openings influences the fire performance of the perforated cellular wooden slabs. In wooden slab with perforations, the shape and the size of perforation can limit the use of these constructive elements in terms of fire resistance. Typical prefabricated wooden slabs under fire in real tests conditions were tested by Frangi et al. [21] to determine the fire resistance and the thermal performance. Nevertheless, the size of perforations increase the slab surface exposed to fire, facilitating the penetration of flames. For this purpose, different configurations will be analysed. Also, a numerical model is validated with experimental tests to predict the temperature evolution during a fire scenario. The finite element model is a valid tool to determine the fire resistance, which contributes for a safe design in typical perforated wooden slab. The constructive elements should be designed in accordance, to prevent and delay the fire collapse, allowing the slab to remain in service during more time. The char layer is an important parameter to determine the fire resistance of the wooden slab. This work will present a numerical model, with appropriate material properties and boundary conditions, for the transient thermal analysis, based on the finite element method.

2. Perforated cellular wooden slab construction

For evaluation of the fire performance, four tests were performed on cellular wooden slabs (each one with 3 cells) with different perforations (small and large rectangles and small and large circles) in the bottom surface of the slab. These slabs are composed with rectangular beams (three layers) attached to the main wood structure (Kerto beams) with Simpson metal connectors and using three layers wood panels for ceiling and floor. Each slab has four Kerto beams, allowing the creation of three independent cells (cell without drilling in the centre, side cells with two types of rectangle and two types of circles), Fig. 1.

The wooden slab with perforations will be set up on the top of a fire resistance furnace, prepared to run with the ISO834 standard fire curve [22], as represented in Fig. 2.

The construction of the four cellular wooden slabs are according the defined dimensions, as shown in Figs. 3 and 4. Slab 1 and 2 present two types of rectangle perforations in the exposed surface (250×20 mm in cell 3, and 50×20 mm in cell 1), Fig. 3. Slab 3 and slab 4 present two types of circle perforations with a diameter equal to 20 mm in cell 3, and 10 mm in cell 1, as represented in Fig. 4. Each slab is also composed of a main wood structure, consisting of two beams Kerto S200×37 and two beams Kerto S200×39.

Table 1 summarizes the main characteristics of each wooden slab, type of perforation and the opening size of the perforated cellular zone.

3. Experimental model

The slabs were instrumented with wire type K thermocouples on specific measuring points, copper disks thermocouples over the unexposed floor surface panel and plate thermocouples for measuring the temperature in the fire compartment or cells, as defined in Fig. 5, based on the specifications of EN1365-2, [23].

The acquisition signal of the thermocouples was made with thus data acquisition systems from HBM (MGC Plus and Spider 8). The slabs were tested on a fire resistance furnace at Polytechnic Institute of Bragança. The furnace is equipped with 4 burners running with natural gas, with a total power of 360 kW, presents a working volume of 1 m^3 and is prepared to work with any standard fire curve, Fig. 6.

Fig. 1. Wooden slab with cellular zones.

Fig. 2. Wooden slab set up in the fire resistance furnace.

The temperature of the exposed surface follows the real furnace heating curves (Slab_1_2 and Slab_3_4), as represented in Fig. 7. Wood is combustible and a lot of energy is released during wood combustion, which justifies these real furnace heating curves. The furnace was switch off between at 450 s and the front door opened at 900 s. The temperature inside the three cellular cavities follow the curves based on data obtained during each fire test, using the plate thermocouples readings (TPi, cell i=1,3 for Slab_1_2 and Slab_3_4), also represented in Fig. 7. The fire resistance is determined in standard fire tests, where the time-temperature curve represents a more severe heating condition compared with typical natural fire events. In a well-ventilated compartment the duration and the time-temperature curve severity is smaller than a standard fire test according ISO834 standard fire curve [22]. The effect of ventilation and the severity of fire load results in different typical time temperature curves of fire events. The non-ventilated compartments, like a furnace, experienced higher temperatures, as happened during the experimental tests.

The standard measure of an element fire resistance is generally classified by the following failure criteria: stability - R (to prevent the structural collapse of the element); integrity – E (to prevent the fire and the smoke transmission through the element) and the insulation – I (to prevent an unacceptable amount of heat being transmitted through the element), [23,24].

In the present work, and during the experimental tests, the integrity criterion (E) was verified using the cotton ignition test, where no flame appearance occurred through all tests, following the major guidelines of standards EN1365-2 [23] and EN1363-1 [24]. The insulation criterion (I) was also verified, since the temperature rise on the unexposed surface did not exceed 180 °C on any of the disc thermocouples or 140 °C in average with respect to the initial average temperature, defined according to the European standard for fire resistance tests (EN 1363-1), [24].

The temperature measurements of plate thermocouple (TPi, cell i=1,3) within the cellular zones were affected in proportion with the opening size of the perforations.

Cell 1 has a similar opening size for rectangular (18,000 mm^2) and circular perforations (16,328 mm^2), respectively for Slab_1_2 and Slab_3_4, as presented in Table 1. The plate thermocouple TP1 represents values of temperature almost similar between both wooden slabs, but slightly higher in Slab_1_2.

Cell 3 has a higher opening size for slabs with rectangular slots (30,000 mm^2) when compared with circles perforations (15,072 mm^2), respectively for Slab_1_2_ and Slab_3_4, Table 1. The plate thermocouple TP3 presents also higher values of temperature in Slab_1_2.

The similar opening size between Slab_1_2 for cell 1 (rectangle slots, 18,000 mm^2) and Slab_3_4 for cell 3 (circle slots, 15,072 mm^2) presents a similar behaviour between TP1 and TP3, but slightly higher in Slab_1_2.

The plate thermocouple TP2 for cells without perforations have similar behaviour during all fire tests.

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