TEST&E 2019
Monitorizar e Preservar
2º Congresso de Ensaios e Experimentação em Engenharia Civil

ATAS DO 2º CONGRESSO

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PREFÁCIO

O 2º Congresso de Ensaios e Experimentação em Engenharia Civil – TEST&E 2019 – foi realizado de 19 a 21 de fevereiro de 2019 no Instituto Superior de Engenharia do Porto, numa organização conjunta da RELACRE (Associação de Laboratórios Acreditados de Portugal), do ISEP (Instituto Superior de Engenharia do Porto) e do IST (Instituto Superior Técnico).

Este congresso pretendeu proporcionar um amplo fórum de divulgação e partilha de conhecimentos e experiências entre os seus participantes das áreas da investigação e ensino, indústria e serviços, sob o tema principal: Monitorizar e Preservar.

No atual ciclo de atividade com enfoque na preservação e valorização do património construído, este congresso pretendeu dar a devida importância à monitorização como ferramenta de apoio imprescindível à gestão desses mesmos ativos, com a finalidade última da sua melhor preservação no ciclo de vida. A monitorização assume ainda maior relevância no âmbito da utilização de novos materiais ou processos construtivos, sobretudo na reabilitação ou reconstrução, onde interessa aprofundar conhecimentos relativos ao seu comportamento em serviço. A implementação das mais variadas técnicas de monitorização, usufruindo com vantagem das tecnologias de informação e comunicação da atualidade, baseia-se em grande medida em ensaios e experimentação que estão em permanente evolução.

Neste livro são apresentados os 68 artigos de 204 autores, de acordo com os seguintes temas:

1. Reabilitação do património
2. Novos materiais
3. Hidráulica, ambiente e recursos naturais
4. Geotecnia e transportes
5. Inovação e tendências futuras
6. Ensaios não destrutivos
7. Vibrações e higrotérmica

Os editores expressam os seus maiores agradecimentos: aos autores, pela confiança na divulgação dos seus trabalhos neste congresso; à Comissão Científica, pela contribuição dada à qualidade técnica e científica dos artigos; à Comissão Organizadora Local e à Comissão Executiva, pela garantia de concretização do congresso com todo o sucesso. Um agradecimento geral é dirigido a todos os que direta ou indiretamente contribuíram para a excelência da qualidade deste congresso.

Lisboa, julho de 2019.

Os editores
José Neves (CERIS, IST, ULIsboa)
Diogo Ribeiro (ISEP, CONSTRUCT)
Álvaro Ribeiro (LNEC, RELACRE)

MODELO DE CÁLCULO AVANÇADO CALIBRADO COM ENSAIO EXPERIMENTAL DE LAJES EM MADEIRA EXPOSTAS AO FOGO

ADVANCED CALCULATION MODEL CALIBRATED WITH EXPERIMENTAL TEST OF WOODEN SLABS EXPOSED TO FIRE

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RESUMO

As lajes em madeira são elementos estruturais com larga aplicação, em particular, na reabilitação de edifícios, espaços interiores e construção de novas estruturas em edifícios. As propriedades mecânicas, térmicas e acústicas fazem deste material uma solução ideal para lajes de pavimentos e coberturas. No entanto, quando expostas a uma ação de acidente tipo fogo é necessário a avaliação do seu comportamento vulnerável com rigor. Neste trabalho, apresenta-se um modelo de cálculo avançado, com base na utilização de elementos finitos, calibrado com os resultados experimentais obtidos. Os ensaios experimentais foram realizados em lajes de madeira expostas a uma frente de fogo por baixo do elemento. As lajes foram instrumentadas com termopares para medição da temperatura em diferentes pontos de controlo ao longo da ação de incêndio num forno de resistência ao fogo, com a utilização da curva de incêndio padrão ISO 834. O modelo de cálculo avançado permite também a obtenção das temperaturas em regime transiente e incorpora as propriedades não-lineares da madeira. O comportamento físico da laje é ainda condicionado pela formação da carbonização, sendo este fenómeno também considerado no modelo de cálculo avançado.

ABSTRACT

The wooden slabs are structural elements with wide application, in particular, in building rehabilitation, interior spaces and in new building structures. The mechanical, thermal and acoustic properties make this material as an ideal solution for floor and roof slabs applications. However, when exposed to an accidental fire condition it is necessary to assess their vulnerable behaviour accurately. In this work, an advanced calculation model is presented, based on the use of finite elements, calibrated with experimental results. The experimental tests were performed on wooden slabs exposed to a fire from below the element. The slabs were instrumented with thermocouples to measure the temperature at different control points along the fire duration in a fire resistance furnace, following the standard fire curve ISO 834. The advanced calculation model also allows the obtained the transient effect and incorporates the non-linear wood properties. The physical behaviour of the wooden slab is conditioned by the char layer formation, and this phenomenon is also considered in the advanced calculation model.

1 - INTRODUCTION

The perforated wooden slabs combine the aesthetics and the acoustic properties, based on design, style, in strength and stability of the element. The wooden slabs or typical wood panels offer a rustic and decorative look to almost all building structures (auditoriums, offices, restaurants, concert halls, schools, hotels, gymnasiums, etc.). The perforations in these panels are available in a large variety of patterns, sizes and finishes.

Considering the behaviour of wood when submitted to a developing fire, wood-based materials will burn and are rated as combustible. Wood material when exposed to fire produces a surrounding charring depth layer, with no mechanical resistance, resulting a reduced cross-section. In perforated cellular wooden slabs, the size of perforations influences the fire effect over the slab and the temperature evolution in the unexposed side. The constructive elements should be design in accordance, to prevent and delay the fire damage effect, allowing that the slab could remain in service for long time. The perforations increase the slab surface exposed to the fire effect, facilitating the penetration of flames and heat flow.

Several researchers have presented experimental and analytical methods to calculate the physical degradation of wood due high temperatures, (White, 1999), (Poon, 2003), (Janssens, 2004). The charring rate of different species when exposed to fire conditions has been examined by others

researchers in different countries, (Schaffer, 1967), (White, 1992), (White, 1992), (Konig and Walleij, 1999), (Gardner and Syme, 1991), (Collier, 1992), (Pun et al., 1997), (Frangi and Fontana, 2003), (Pinto and Junior, 2007), (Frangi et al., 2008), (Cachim and Franssen, 2010), (Fonseca and Barreira, 2009), (Fonseca and Barreira, 2010), (Fonseca and Barreira, 2011), (Fonseca et al., 2012). Also, empirical models for determining the charring rate and the heat transfer conditions were developed by (Schaffer, 1967), (White, 1992).

The main goal of this work is to present an advanced calculation model, calibrated with experimental tests, to predict the time-temperature evolution, during a fire scenario, using a finite element method. Different constructive solutions of wooden slabs, with different sizes of rectangular and circular perforations will be analysed. The influence of the size effect was verified and is determinant to the temperature evolution inside the cellular wooden slabs. This factor has a bigger effect when compared with the geometry shape effect. This study carries out the results according others previous investigations developed by the authors of this work (Fonseca et al., 2013), (David et al., 2015), (Jorge et al., 2015).

2 - EXPERIMENTAL TESTS AND RESULTS

Four wooden slabs with perforations were considered for test and analysis. The spruce specie was used for all the wooden slab. The constructive model considers three different cellular zones (two cells with different perforations and one cell with no perforation). Slab 1 and slab 2 present two types of rectangular perforations with different sizes, R1=250x20 mm in Cell 3 and R2=50x20 mm in Cell 1. Slab 3 and Slab 4 present circular perforations with different diameters, d1=20mm in Cell 3 and d2=10mm in Cell 1. Fig. 1 represents all dimensions used in the constructive solution model, being each slab made by four beams inside with a thickness equal to 27mm, and an external framework composed by two beams S200x37 and two beams S200x39.

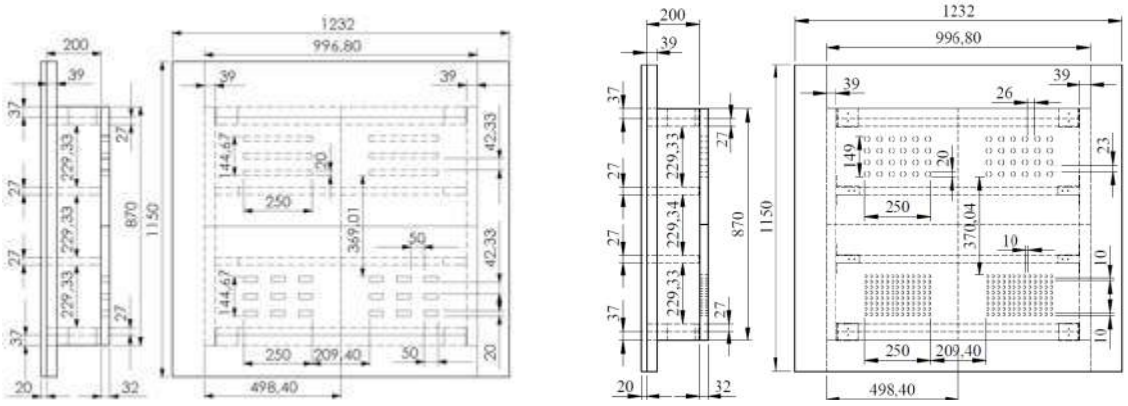


Figure 1 – Geometry of wooden slabs: a) Slab_1_2 rectangular perforations, b) Slab_3_4 circular perforations

The dimension of each perforation is compared between Cell 1 and Cell 3, for each wooden slab, see Table 1. Cell 1 has a similar open space between slabs with rectangular and circular perforations. Cell 3 with circular perforations represents only 50% open space in comparison to the higher rectangular perforations.

Table 1 - Size of the openings in each cell

	SLAB 1 AND 2 (RECTANGULAR PERFORATIONS)	SLAB 3 AND 4 (CIRCULAR PERFORATIONS)
Cell 3, mm^2	30000 (R1)	15072 (d1≅50%R1)
Cell 1, mm^2	18000 (R2≅60%R1)	16328 (d2≅91%R2)
Total, mm^2	48000	31400 (≅65% Slab_1_2)

In the experimental tests, thermocouples were installed to measure the temperature in different locations (ceiling plate, beams and cellular zones) and located in the same positions in all slabs, based on the criteria defined by the European standard (EN 1365-2, 1999), as presented in Fig. 2. Three types of thermocouples were used: single wire for spot measurements, copper discs protected with plasterboard for measuring the temperature in the unexposed side and plate thermocouples for measuring the temperature within the cellular zones. The thermocouples signal acquisition was made with a HBM system (MGC Plus and Spider 8).

Figure 2 – Thermocouples installation and data acquisition systems

The bottom surface of each slab (perforated side) was submitted to standard fire. The slabs were tested in the fire resistance furnace at the Polytechnic Institute of Bragança, see Fig. 3. This furnace is equipped with 4 burners running with natural gas, with a total power of 360kW, and a working volume of $1m^3$, prepared to work with any standard fire curve, in particular to the standard fire curve ISO834 (ISO TC 92, 1999).

Figure 3 – Fire resistance furnace in laboratory, before and after the test

At the end of the fire exposure, cells without perforations do not exceeded 100ºC, while cells with perforations presented a triple of this value. The temperature measured with plate thermocouples, within the cellular zones, is proportional to the size of the openings. Fig. 4 represents the char layer in all tested slabs. The charring rate was also determined at the end of the test.

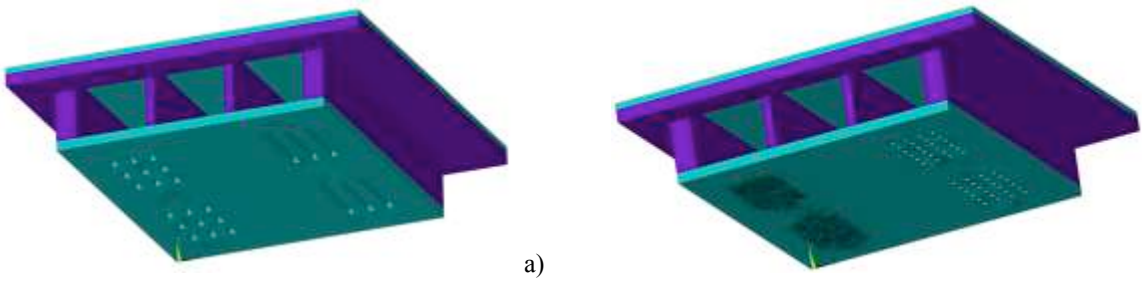
Laje_1 Laje_2 Laje_3 Laje_4

Figure 4 – Char layer in all four wooden slabs, after the experimental test

The charring rate of the perforated Cell is almost the double in comparison to the non-perforated cell, which also justifies the temperatures recorded within the cellular cavities of each slab. The temperature evolution in Cell 3, for rectangular perforations (Slab_1_2) enables a faster heating process with higher temperatures compared to the circular perforations (Slab_3_4). The temperature evolution in Cell 1 has similar behaviour independently of the shape of the perforated wooden slabs (circular or rectangular). The shape of perforated zone is not a relevant factor to the temperature evolution inside the cellular slab. For the same time of the fire exposure, Slabs_3_4 have a better behaviour in terms of the char layer formation through the bottom surface, when compared with Slabs_1_2.

3 - NUMERICAL MODEL AND RESULTS

A 3D finite element (Solid70) with 8 nodes was used for thermal and nonlinear transient analysis, using Ansys program. In order to fully satisfy the nonlinear conditions of the numerical problem, an iterative procedure in each time step it is necessary to apply. A modified Newton-Raphson method was adopted to solve the nonlinear problem, and the time interval considered for each step was equal to 10s. Fig. 5 shows the mesh used in all numerical simulations, respectively for each constructive solution.



a) b)

Figure 5 – 3D numerical model for each: a) Slab_1_2, b) Slab_3_4

The bottom surface of the wooden slab was exposed to fire during 900s.

For fire calculation we have used a standard temperature-time curve ISO 834 according Eurocode 1 (EN1991-1-2, 1995) with the following expression and represented in figure 6:

$$T_{\infty} = 20 + 345\log_{10}(8t + 1) \tag{5}$$

where *t* is the time in minutes min.

The temperature on the boundary (exposed surface and internal cavities) follows real heating curves obtained during experimental tests, measured with plate thermocouples. The convection coefficient is taken equal to 25W/m^{2}K (EN1991-1-2, 2002) inside cavities and in the exposed surface. At the unexposed surface the room temperature is kept constant and the value of convection coefficient is equal to 9W/m^{2}K. The emissivity of the flames is taken equal to 1.0 for exposed side and internal cavities (EN1991-1-2, 2002).

The non-linearity due to the temperature dependence of the material properties will be considered during the numerical simulation. The thermal properties of wood vary considerably with temperature and was applied according Eurocode 5 (EN1995-1-2, 2003), figure 6.

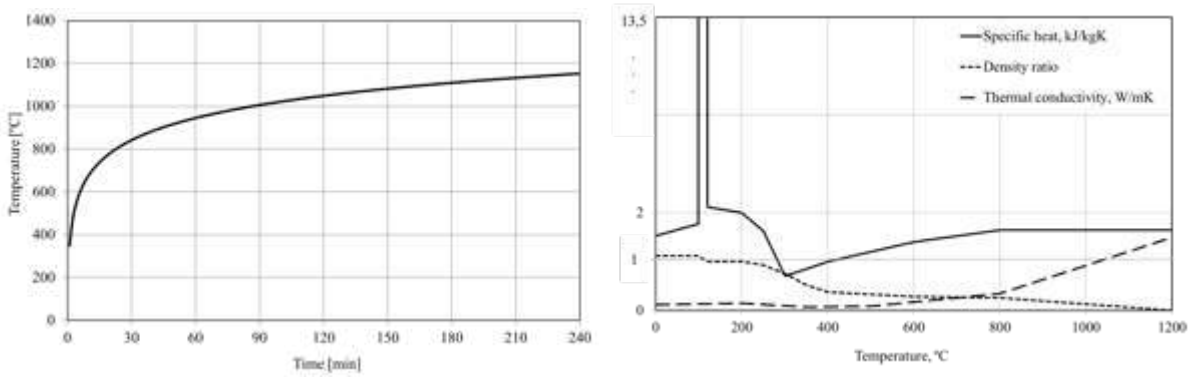


Fig. 6 – Nominal fire curve (ISO 834) and wood thermal properties.

Fig. 7 represents the char layer formation for all numerical models of the slabs at the end of the fire exposure, in grey colour. For the last time step a criterion for determine the carbonized layer is applied, that will be compared with the experimental record obtained in each slab (Fig. 4), allowing to evaluate the residual cross section and the influence of different perforations on the fire resistance.

The assessment of the charred layer allowed to verify that the cavity without perforations presents the lowest values of charring rate (between 0,65 – 0,8 mm/min), being the perforated rectangular layer that reaches higher temperatures values (between 1,0 – 1,4 mm/min). It is possible to confirm that wooden slabs with perforations can limit the use of these constructive elements in terms of fire resistance.

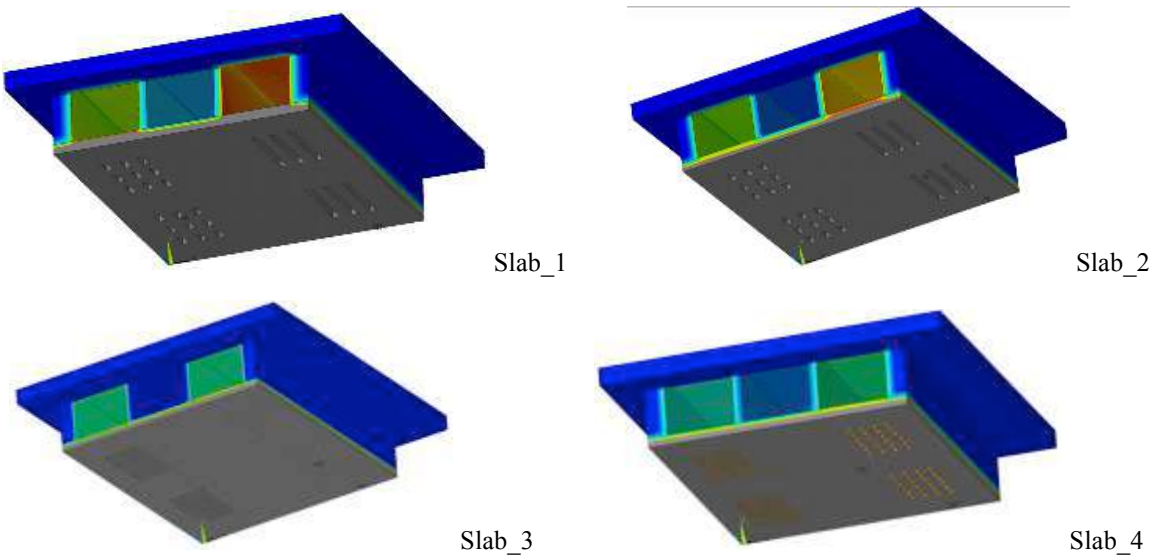


Figure 7 – Char layer in all four wooden slabs with 3D numerical model, t=900s.

4 - TEMPERATURE EVOLUTION IN PERFORATED CELLS

The temperature evolution for each wooden slab was compared between the experimental (T_exp) and numerical (T_num) results. Fig. 8 shows some graphs with the time-temperature history in perforated cells (Cell 1 and Cell 3) for different thermocouples and nodal positions. The numerical results are in agreement with the experimental results.

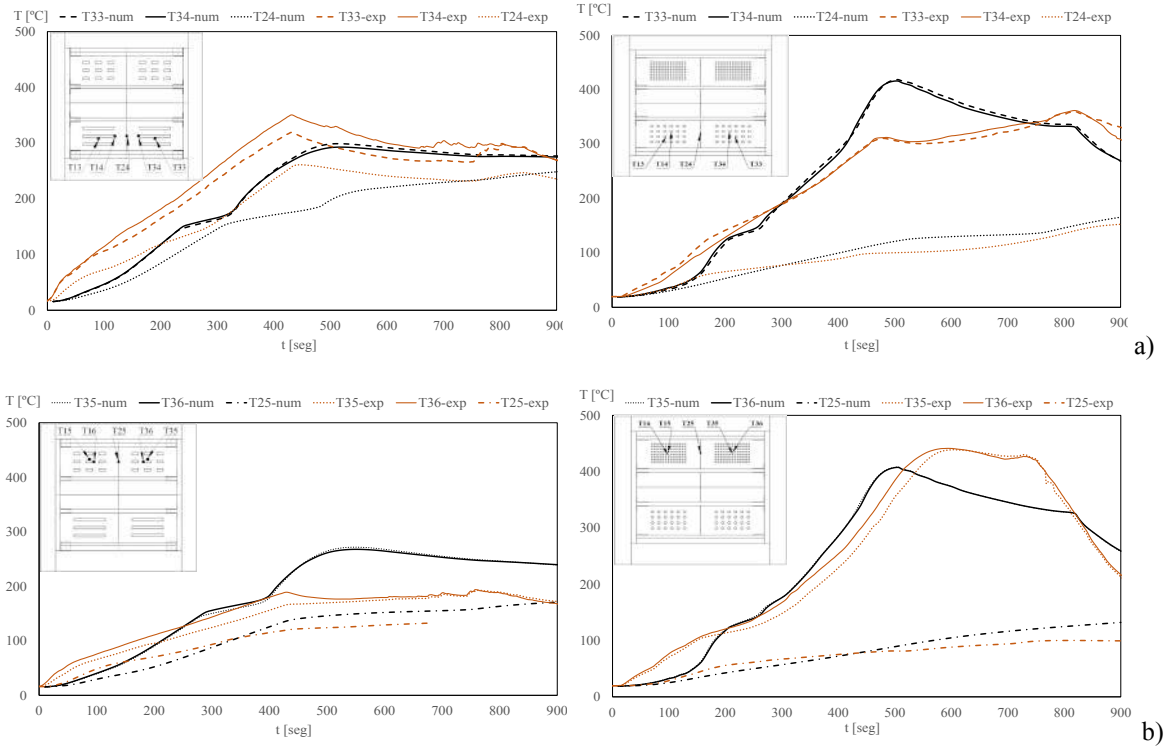


Figure 8 - Time-temperature history for wooden slab (Slab_1_2 and Slab_3_4): a) Cell 3, b) Cell 1

Wood material when exposed to fire presents a thermal physical degradation. The evolution of the temperature inside the cellular zones was characterized and the shape and size of perforations could be compared with the unperforated cell.

In the border of the rectangular slots (T33=T13 and T34=T14, Cell 3) and circular slots (T35=T15 and T36=T16, Cell 1) the values of temperatures are higher when compared with all inside nodal positions which remain at lower temperatures (T24 and T25, Cell 3 and Cell 1, respectively).

Attending to the Table 1, the circular perforations for Cell 1 or Cell 3 have almost the same open space in Slab_3_4, which allows to conclude a similar temperature evolution (T24 and T25) inside the Cell. In Slab 1_2 the temperature inside Cell 3 is higher when compared with Cell 1, which agrees with the calculated open space between R1 and R2. In Cell 3 and Cell 1 the temperature increases until switch off the furnace (450-500s) and decreases after this time.

The results in Cell 2 have similar behaviour in all tested wooden slabs with temperatures below 100ºC.

5 - CONCLUSIONS

During the real fire test exposure, the insulation criteria were verified, in both wooden slabs, since the temperature rise on the unexposed surface did not exceed 180ºC on any of the disc thermocouples or 140ºC in average with respect to the initial average temperature, defined according to the European standard for fire resistance tests (EN 1365-2, 1999). The integrity criteria were also verified during experimental tests using the cotton ignition test, where no flame appearance occurred during the wooden slabs testing (EN 1365-2, 1999). The time-temperature numerical simulation results are in agreement and have the same behaviour with the experimental results. The size effect of the perforation is responsible for the temperature evolution, as expected, and the shape of the perforations has no significant effect, in particular for the tested perforations models.

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