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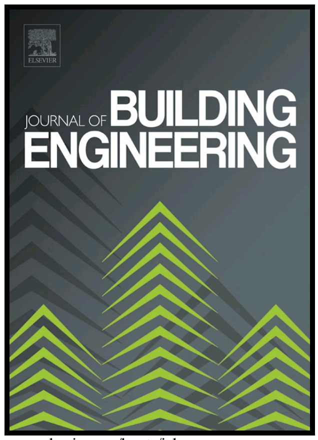

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Behaviour on Non-Loadbearing *Tabique* Wall Subjected to Fire – Experimental and Numerical Analysis

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Abstract. *Tabique* construction is one of the most used traditional building techniques and it can be found almost everywhere in Portugal with special incidence in the northeast region. *Tabique* construction elements can be described as a timber structure filled on both sides with an earth-based render. *Tabique* elements can be found in ancient buildings, from simple construction as rural dwellings to more urban sophisticated ones. This paper presents a study of the behaviour of *tabique* walls, concerning its fire resistance. Therefore, an experimental analysis was performed using *tabique* wall panel specimens. Such wall panels were made in pine wood with an earth-based render finishing. In order to assess the thickness effect of the earth-based render on the fire resistance of the wall, three specimens with different render thicknesses of 15 mm, 10 mm and 5 mm were tested in a fire-resistance furnace according to the ISO 834 [1] standard fire curve. Fire resistance is a measure of the ability of a building element to resist a fire, usually the time for which the element can meet appropriate criteria during exposure to a standard fire resistance test. By this way it is possible to increase the safety of people and property. Two performance criteria were verified which are the integrity and the insulation. In addition, a numerical model was also developed in order to assess the *tabique* wall behaviour under fire conditions, which was validated using the obtained experimental results.

Keywords: *tabique wall; fire resistance; traditional construction; timber; non-loadbearing wall.*

1 Introduction

In the historic city centres of the north of Portugal, most of the existing buildings are ancient and they were built using techniques that have fallen in disuse due to the natural technological progress of the construction sector. Several of these buildings are abandoned and show an advanced state of degradation. Thus, it is important to perform rehabilitation and conservation processes of this heritage.

The usage of natural materials such as wood, earth and stone has evolved to industrialized solutions that result in environmental impacts. In recent decades, the sustainable construction concept has been developed based on the principles of recycling and maximizing resources, protecting and stimulating the creation of healthy environment, leading to the reduction of the environmental impact of the construction sector. In order to support the different stakeholders in the above referred sector, research projects and knowledge dissemination on sustainable development construction have been conducted [2].

The *tabique* is one of the main Portuguese traditional building techniques based on raw materials such as earth and wood, which was extremely relevant until the introduction of the reinforced concrete technique in the beginning of the 20th century. The *tabique* building technique consists of using natural and non-processed building materials, with simple procedures. In general, a *tabique* wall is composed by a simple timber structure covered with an earth-based material. The timber frame elements are nailed to each other and the most common timber frame solution is formed by vertical boards linked to each other by horizontal elements. In general, both materials are locally available in abundance, can be recycled, and are consequently more sustainable [3].

Tabique walls may be key structural elements because they connect horizontal structural elements located at different levels of a building. They contribute for bearing capacity during the occurrence of an earthquake, due to energy dissipation. For instance, during the earthquake that occurred in Lisbon in 1755, constructions built with *tabique* walls (or similar) had presented better structural behaviour under seismic action compared than the ones built with masonry walls.

Some research studies have highlighted the advanced deterioration level of this type of construction and the recommended the need for retrofitting actions [4-6]. At the same time, it was also stated that there is still a lack of publications related to *tabique* constructions which may be available to scientific and technical communities.

Therefore, the main goal of this research work is to study experimentally and numerically the behaviour of real-scale *tabique* walls subjected to fire conditions using different earth-based render thicknesses. Thus, three wall panels with different render layer thicknesses of 15 mm, 10 mm and 5 mm were tested. The overall dimensions of the panels are 990×975×95 mm^3. It was concluded that the earth-based render works as fire protection of the timber frame which allows the *tabique* wall to present adequate behaviour under fire conditions. The obtained results may give guidance for rehabilitation actions in buildings with a significant state of deterioration [7, 8] and also provide new information about the behaviour of this *tabique* non-loadbearing wall under fire.

2 *Tabique* panels and construction details

The timber structure of the *tabique* panels is formed by vertical boards which are connected to each other by laths placed on both sides [9]. It was used *Pinus pinaster* and taking into account that it corresponds to a current applied solution [3]. These timber elements are nailed. This timber structure was then covered with an earth-based render corresponding to a traditional building solution. Fig. 1 shows some building details of typical *tabique* walls.

Fig. 1 *Tabique* wall building details.

In order to evaluate the behaviour against fire, three *tabique* panels were manufactured by this way in the Strength of Materials Laboratory at Polytechnic Institute of Bragança.

2.1 Timber structure

As it was stated above, vertical boards and laths are the main elements of the timber structure. Both elements are separated to each one 35 mm. The respective cross section is 170×25 mm^2 and 30×25 mm^2. These dimensions correspond to average values obtained from [9]. Fig. 2 shows some stages of the manufacturing of the timber structure of the panels. Meanwhile, Fig. 3 schematically presents the geometrical detail of the timber structure.

Fig. 2 Some stages of the manufacturing of the timber structure of the panels.

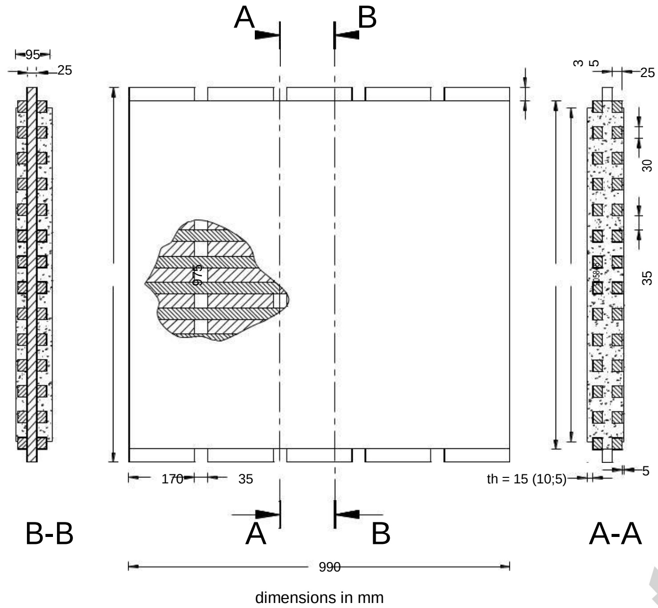


Fig. 3 Geometrical detail for timber structure of panels.

2.2 Earth-based render

The timber structure of the panels was covered with an earth-based render applied on both sides. At a first stage, it was adopted the render composition delivered in previous studies [4] which do not considered lime or cement necessary. However, in this case and after some preliminary tests, it was concluded that it was convenient to include a 8% mass content of cement CEM II/B-L-32,5 R (white). The application of the render was performed in two main stages. In the first stage, the empty spaces of the timber structure were filled with the render (Fig. 4). In the second stage, the final coating was applied (Fig. 5). After this procedure, the panels remained in hygrometric controlled conditions of the laboratory for 30 days and they dried naturally at a room temperature around 18ºC and air humidity of about 75%.

Fig. 4 Timber structure filled with earth-based render.

Fig. 5 Final coating.

2.3 *Tabique* wall instrumentation

The thermal behaviour of *tabique* walls exposed to the fire was evaluated using several thermocouples for measuring both internal and external temperatures of the wall. The entire procedure is based on European standard for the general requirements for fire testing [10] and the specific requirements for the fire testing of non-loadbearing walls (testing conditions, specimen preparation, specimen fixation, conditioning and instrumentation) [11]. According to these standards two performance criteria should be evaluated through all tests: the insulation and integrity criteria.

The insulation criterion is the time, in completed minutes, for which the test specimen continues to maintain its separating function during the test without developing temperatures on its unexposed side which increase the average temperature above the initial average temperature: i) by more than 140ºC, ii) or increase more than 180ºC at any location of the unexposed side above the initial average temperature.

The integrity is the ability to prevent the fire and the smoke transmission through the element. The integrity criterion will be verified throughout the experiments by employing a cotton wool pad saturated in ethyl alcohol.

As it was stated above, the main goal is to study experimentally and numerically the behaviour of *tabique* walls subjected to fire conditions using different earth-based render thicknesses. Hence, wire type K thermocouples have been placed at different depths in order to obtain temperature records inside the render (TA) and the wood (TM). The unexposed surface was also instrumented using type K thermocouples welded on copper discs protected by plasterboard (TD) used for measuring temperatures at specific panel points in order to assess and to verify the insulation criterion. The thermocouples were placed according to Fig. 6.

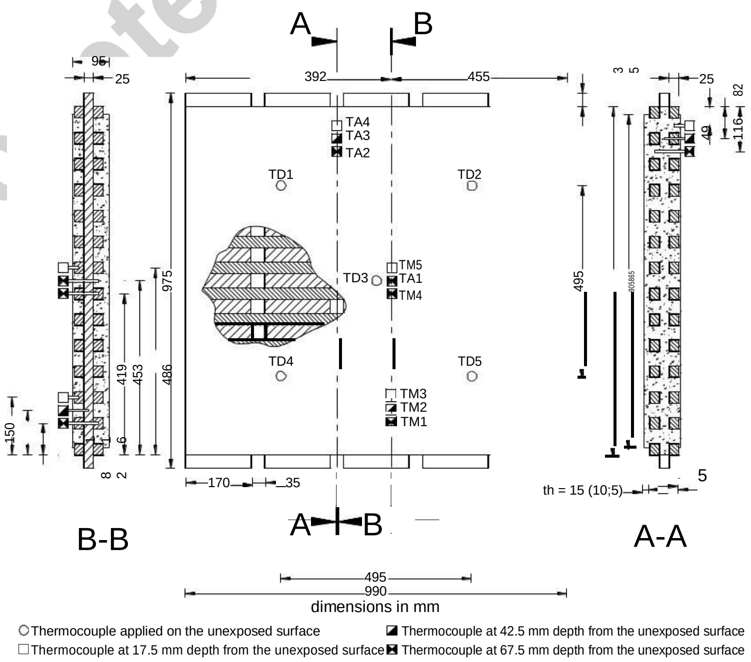


Fig. 6 Panels geometry and thermocouples location.

2.4 *Tabique* panel coupled to the fire-resistance furnace

Before coupling the panel, a 50 mm thick rock wool was nailed along the perimeter of the panel in order to avoid gas or flame escaping between the rim and the panel, Fig. 7. The *tabique* panels were then fixed into a support and coupled to the furnace, Fig. 8.

Fig. 7 Isolation of *tabique* panel.

Fig. 8 *Tabique* panel coupled to the furnace.

3 Experimental tests

The experimental *tabique* panels were tested in the fire resistance furnace existing in the Strength of Materials Laboratory at Polytechnic Institute of Bragança, which is able to carry out ISO 834 standard fire tests, as defined in Fig. 9.

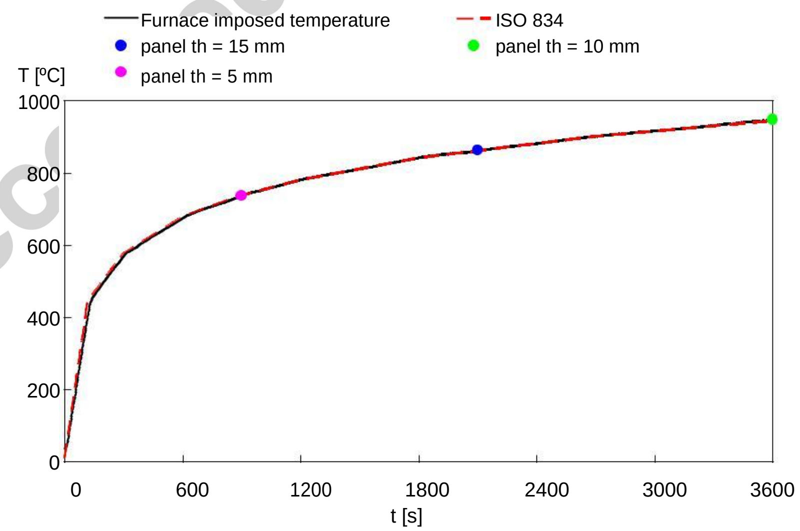


Fig. 9 ISO 834 and imposed temperature curves

At the beginning of the tests, the *tabique* wall panels were at the ambient laboratory temperature of about 21°C and air humidity around 65%.

During the test, the integrity of the wall was evaluated throughout the cotton wool pads test (Fig. 10). The insulation of the panels was also evaluated during experiments by assessing the unexposed surface temperature according to European standard [10]. At the final stage of the tests, a significant amount of smoke releasing from burning wood (Fig. 11) was noticed.

In order to evaluate the fire insulation behaviour of the earth-based render thickness effect, the three panels were covered with different render layer thicknesses (th) equal to 15 mm, 10 mm and 5 mm.


Fig. 10 Integrity criterion proofing.


Fig. 11 Smoke release.

3.1 *Tabique* panel with th = 15 mm of earth-based render

The first tested sample was the wall panel with th = 15 mm of earth-based render. The lack of knowledge on *tabique* fire behaviour and the smoke release from the burning timber, which could indicate the ignition of the wood panel, led us to finish the test after 35 min. Fig. 12 shows the wall panel when the furnace door was opened. It can be observed that the earth-based render did not crack nor collapsed and that the laths burnt due to the small spaces created near the anchorage points of the wall panel. The earth-based render of the fire exposed surface of the panel was removed for a better perception of the fire effect on the laths, see Fig. 13. In general, it was noticed that the timber did not suffer significant damage. However, a char layer was created around the laths. In terms of the performance criterion, there was no deformation of the panel regarding load-bearing capacity. On the other hand, the integrity criterion was also verified because there was no flame or ignitions of the cotton. At the same time, the insulation criterion was as well verified taking into account that the higher value of temperature measured in thermocouple TD3 was of 55°C.


Fig. 12 *Tabique* wall panel at the end of the test.


Fig. 13 Timber structure after the test.

3.2 *Tabique* panel with th = 10 mm of earth-based render

From the analysis of the results obtained in the previous test (th = 15 mm) it was decided to extend the test duration from 35 min to 60 min in this case (*tabique* wall panel with th = 10 mm). Nevertheless, both insulation and integrity criteria were met. The recorded temperatures of the unexposed surface of the panel were always below 90°C. There was also no deformation of the panel. Fig. 14 shows the timber structure burning during the test. Meanwhile, Fig. 15 shows the panel in flame when the door of the furnace was opened.

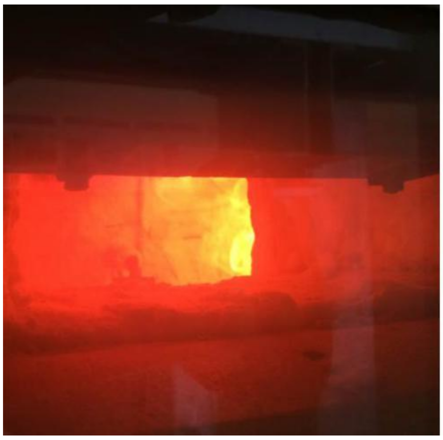


Fig. 14 Flame from wood combustion. **Fig. 15** *Tabique* wall panel when the door was opened.

Afterwards, the flame was extinguished and the *tabique* wall panel was forced to cool using tap water. At this stage, it was possible to observe the existence of cracks in the exposed surface of the panel. A large vertical crack was formed at the centre of the *tabique* wall panel and also some other small ones in horizontal direction (Fig. 16). The final aspect of the timber structure can be observed in Fig. 17, which shows the complete carbonization of the horizontal (laths) and the vertical timber elements of the *tabique* wall panel. Based on the scale of damage caused to the *tabique* wall panel and the large amount of smoke release it was decided to shorten the duration of the third test.

Fig. 16 Cracks in the earth-based render.

Fig. 17 Timber structure after the test.

3.3 *Tabique* panel with th = 5 mm of earth-based render

The third *tabique* wall panel (th = 5 mm) was tested during 15 min, which was the duration found to be the one corresponding to the plateau of the graphs that can be observed from Fig. 28 to Fig. 32. When the furnace door was opened and the *tabique* wall panel was cooled (using water spray), the fire exposed surface presented signs of spall. In fact, the earth-based render layer separated rapidly from the wooden structure due to the thermal shock generated by the water particles in contact with the hot surface. Fig. 18 shows the aspect of the *tabique* wall panel at the end of the test and Fig. 19 shows the timber structure after removing the earth-based render layer. It is possible to verify that the timber structure remained intact. In terms of the performance criterion, it was also verified that there was no deformation of the panel. The integrity criterion was also met because there was no flame or ignitions of the cotton. Finally, the insulation criterion was as well met since the higher temperature value measured by thermocouple TD3 was 21°C.

Fig. 18 *Tabique* wall panel after opening the furnace door.

Fig. 19 Timber structure after the test (th = 5 mm).

4 Numerical analysis

A finite element analysis was performed using the Ansys software. A nonlinear thermal and transient analysis was conducted using plane elements with 8 nodes (Plane 77). Two different cross-sections of the *tabique* wall, AA and BB as shown in Fig. 3, were modelled in numerical simulation. Particular attention was given to the non-linearity due to the thermal properties dependence of wood and earth-based render material used in *tabique* walls [12].

The wood thermal properties have a nonlinear behaviour that depends on the evolution temperature as defined in annex B of Eurocode 5 [13]. The thermal properties to be considered are the thermal conductivity, the specific heat and the density, as shown in Fig. 20. It was considered a density and an emissivity of the wood equal to 450 kg/m^3 and 0.8, respectively.

The render properties were determined according to several documents that characterize the thermal behaviour of the soil as it is stated in the Eurocode 6 [14] and in Nguyen [15]. The considered thermal properties of the soil used in the *tabique* wall panels were established and adjusted after several numerical simulations which were validated using the obtained experimental results. Fig. 21 presents the thermal properties of the earth-based render considered in the numerical analysis. The density and the emissivity of the render were considered equal to 1290 kg/m^3 and 0.85, respectively.

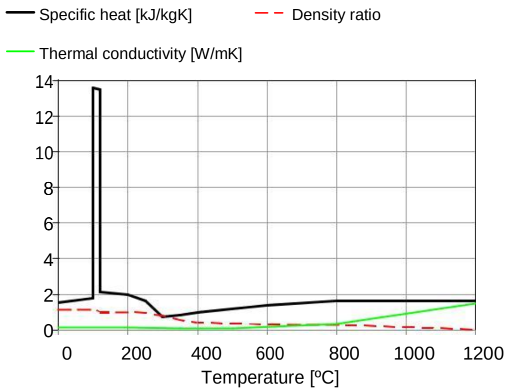


Fig. 20 Thermal properties of wood.

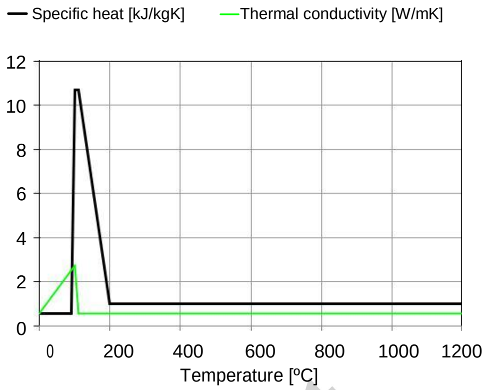
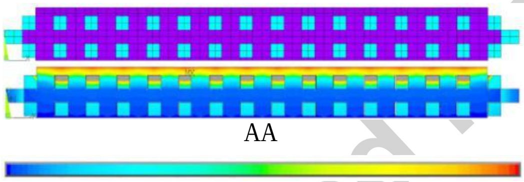


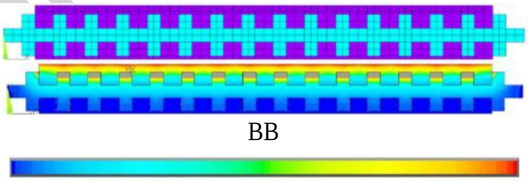
Fig. 21 Thermal properties of earth-based render.

The following figures (Fig. 22 to Fig. 27) show the mesh used in the numerical model with the two different materials and also the obtained temperature patterns for each section (AA and BB, see Fig. 3) in the last time step for *tabique* wall panels with th = 15 mm (Fig. 22 and Fig. 23), th = 10 mm (Fig. 24 and Fig. 25), and th = 5 mm (Fig. 26 and Fig. 27), respectively.



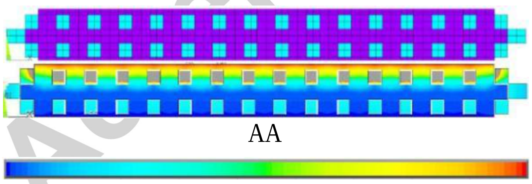
62.5°C 834.7°C

Fig. 22 Temperature results in section AA – *tabique* wall panel with th = 15 mm, t = 35 min.



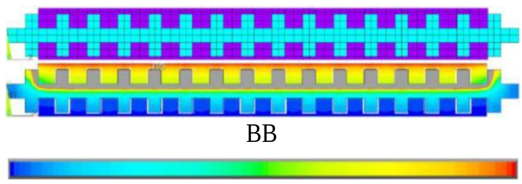
28.2°C 834.7°C

Fig. 23 Temperature results in section BB – *tabique* wall panel with th = 15 mm, t = 35 min.



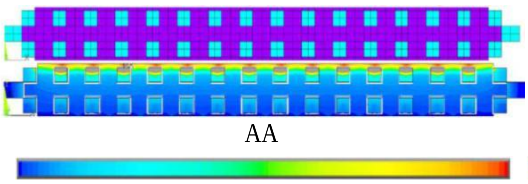
74.85°C 926.39ºC

Fig. 24 Temperature results in section AA – *tabique* wall panel with th = 10 mm, t = 60 min.



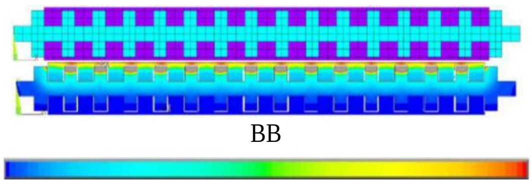
39.13°C 930.35°C

Fig. 25 Temperature results in section BB – *tabique* wall panel with th = 10 mm, t = 60 min.



30.93°C 711.81°C

Fig. 26 Temperature results in section AA – *tabique* wall panel with th = 5 mm, t = 15 min.



17.42°C 712.44°C

Fig. 27 Temperature results in section BB – *tabique* wall panel with th = 5 mm, t = 15 min.

The grey colour is related to the burned timber, according to the criterion of char layer formation applied by the isothermal of 300 ºC, defined by Eurocode 5 [13].

5 Experimental and numerical results

The following graphs (from Fig. 28 to Fig. 33) show the experimental time-temperature evolution of the fire exposed surface (T_e) and the corresponding numerical results (T_n) of the *tabique* wall panels with 15 mm, 10 mm and 5 mm render thickness, respectively, and related to the thermocouples located on the wooden structure (TM) and on the earth-based render (TA).

5.1 *Tabique* panel with th = 15 mm of earth-based render

For the *tabique* panel with th = 15 mm, the test was performed over a period of time of 35 min corresponding to a maximum real temperature in the furnace of 863ºC.

From Fig. 28, it can be seen that thermocouples TM1 and TM4 (which are placed in the wood at 67.5 mm depth from the unexposed fire surface) recorded the highest temperatures of approximately 100°C. Concerning the thermocouples located near the unexposed surface (17.5 mm deep), the temperature remained almost unchanged (ambient temperature). The covering layer isolated the heat coming from the furnace for a period of 140 s approximately until it reached the laths existing in the fire exposed face. At that moment, the temperatures recorded by thermocouples TM1 and TM4 rose linearly until 97°C. At that temperature, the thermocouples inserted in the vertical boards (TM2) and in the laths of the unexposed side (TM3 and TM5) began to register an increase of temperature. The plateau occurred at the temperature of 97°C is due to water evaporation. In this process, both materials accumulate energy in an endothermic process. When the water evaporation ended, the temperatures measured by thermocouples TM1 and TM4 increased again, following the same evolution that in the first stage of the test. At the end of the test (2100 s), temperatures of 29°C and 132ºC were registered in thermocouples TM3 and TM4, respectively.

Although the maximum recorded temperature in the furnace was of 863ºC, it must be noticed that the corresponding temperature recorded near the exposed surface was of 132ºC, which represent a temperature reduction of 85%.

Temperature measurements were recorded through earth-based render thickness. Higher temperature was recorded in thermocouples located near the fire exposed surface, as it was expected.

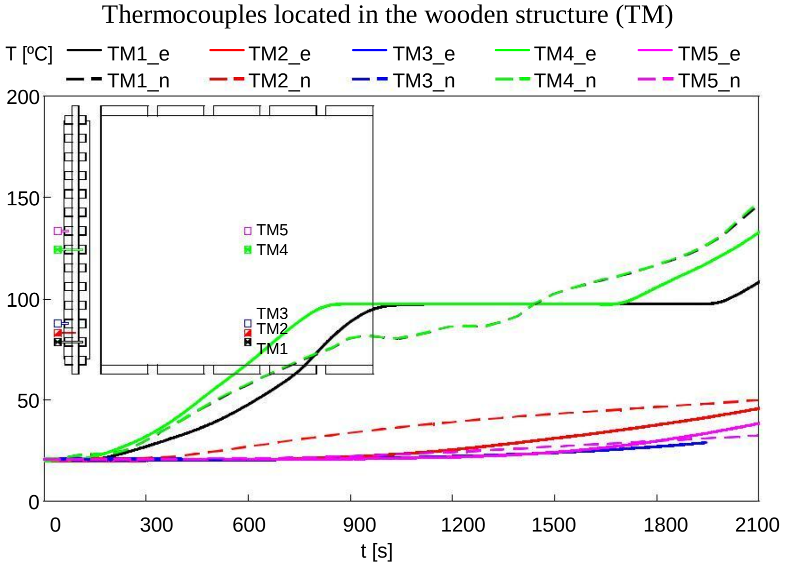


Fig. 28 Time-temperature evolution of the wooden structure of the *tabique* wall panel with th = 15 mm.

Regarding the results obtained for the earth-based render (Fig. 29), the thermocouples placed near the fire exposed side (TA1 and TA2) started to record an increasing temperature after approximately 300 s until attain the moisture loss plateau, at 600 s. The duration of this plateau was about 670 s while the temperature increased from 90°C to 100°C, followed by a temperature increasing until the end of the test. The thermocouples inserted near to the unexposed surface (TA3 and TA4) behaved similarly, measuring an initial temperature rise until the moisture loss plateau, recording lower temperatures compared to TA1 and TA2, due to the render layers. The highest recorded temperature was about 180°C which was measured near the fire exposed side. In contrast, the lowest temperature (about 80°C) was registered in 17.5 mm depth in the render.

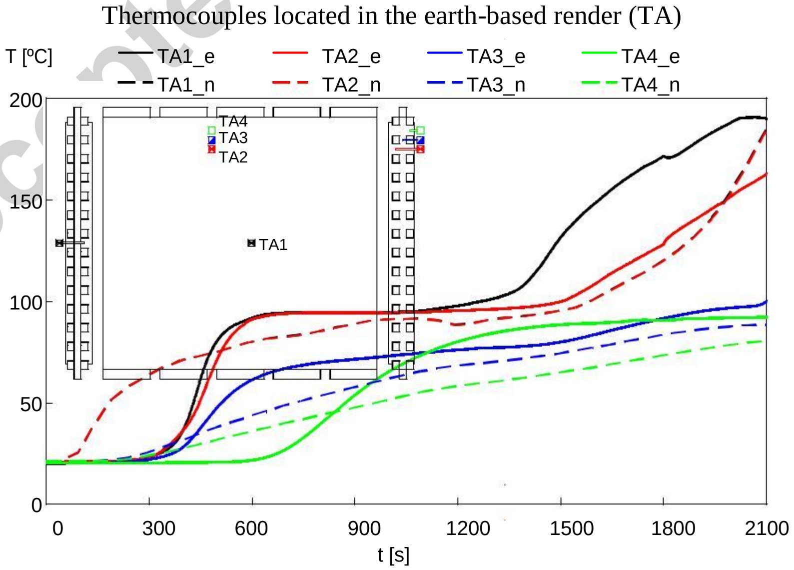


Fig. 29 Time-temperature evolution of the earth-based render of the *tabique* wall panel with th = 15 mm.

5.2 *Tabique* panel with th = 10 mm of earth-based render

For the *tabique* panel with th = 10 mm, the test was performed over a period of 60 min corresponding to a maximum temperature in the furnace of 947°C.

From Fig. 30 it can be seen that the measurements of the thermocouples TM1 and TM4 which were placed in the wood (at 67.5 mm depth from the unexposed fire surface), indicate that the temperature started to rise at t = 200 s until the wood moisture evaporation plateau was reached. This plateau was longer than the occurred in the previous test due to the fact that the render of the exposed fire surface was rebuilt and it had less drying time in the laboratory. After the moisture loss plateau the temperature curves followed a similar trend until the end of the test. The thermocouples TM1 and TM4 recorded the highest temperatures of 240°C approximately.

For t = 2100 s the same temperature of 100ºC approximately was recorded in both *tabique* wall panels with 15 mm and 10 mm of render thickness. Regarding the measurements of the thermocouples located near the unexposed surface, 17.5 mm deep, the temperature remained practically unchanged until t = 1200 s, increasing to around 100ºC at the end of test.

Although the maximum recorded temperature in the furnace was of 947ºC, it must be noticed that the corresponding temperature recorded near the exposed surface was of 240ºC, which represent a temperature reduction of 75%.

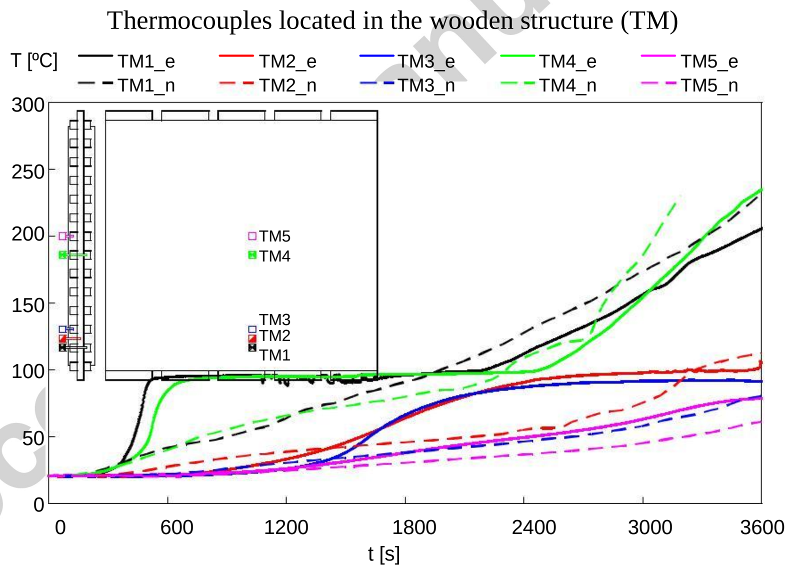


Fig. 30 Time-temperature evolution of the wooden structure of the *tabique* wall panel with th = 10 mm.

Regarding the earth-based render (Fig. 31), the higher measured temperature of about 380°C was recorded near to the fire exposed side for t = 3600 s. For t = 2100 s, it was measured the temperature of 180ºC approximately which corresponds to a similar testing scenario as occurred in the panel with 15 mm render thickness. The lowest temperature (about 100°C) was recorded at a 17.5 mm depth in the render.

Thermocouples located in the earth-based render (TA)

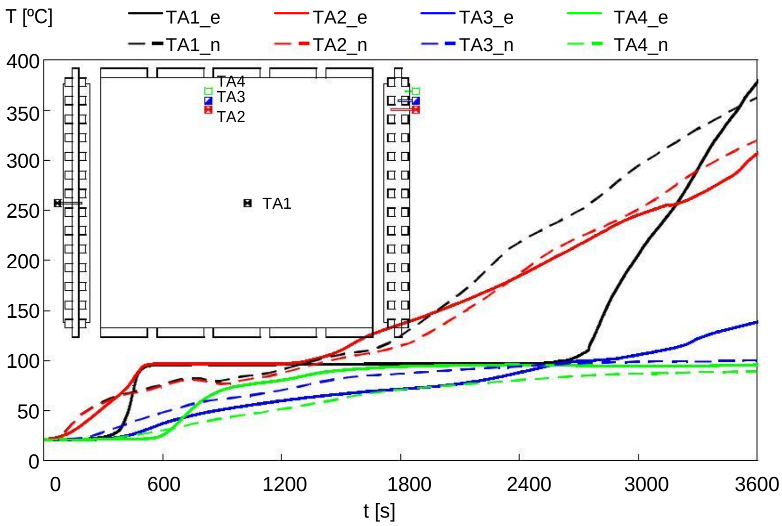


Fig. 31 Time-temperature evolution of the earth-based render of the *tabique* wall panel with th = 10 mm.

Comparing Fig. 29 and Fig. 31 it is noticed that there is a plateau around the temperature of 100°C. This is due to the moisture content of each panel. This phenomenon would be more expected in the panel which had the higher render layer thickness. This fact did not happen because the panel with th = 10 mm broke when it was placed in the test frame and it was required to rebuild it. The test was performed 24 hours afterwards and the amount of water of the render was superior to that existing in the panel with th = 15 mm.

5.3 *Tabique* panel with th = 5 mm of earth-based render

For the *tabique* panel with th = 5 mm the test was performed over a period of 15 min corresponding to a maximum temperature in the furnace of 737°C.

It can be seen in Fig. 32 that the thermocouples TM1 and TM4 recorded the highest temperatures of 100°C approximately. At the end of the test, the moisture loss plateau was not complete. Regarding the thermocouples located near the unexposed surface, 17.5 mm deep, the temperature remained practically unchanged during the entire test duration.

Although the maximum recorded temperature in the furnace was of 737ºC, it must be noticed that the corresponding temperature recorded near the exposed surface was of 100ºC, which represent a temperature reduction of 85%.

Thermocouples located in the wooden structure (TM)

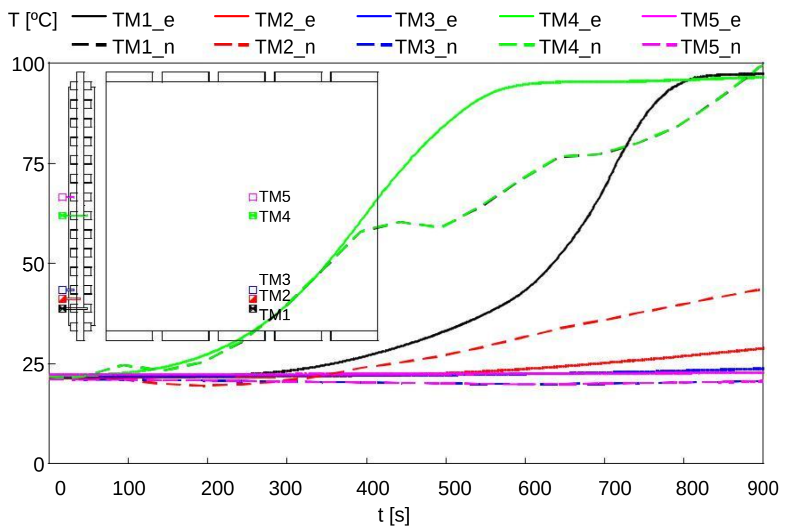


Fig. 32 Time-temperature evolution of the wooden structure of the *tabique* wall panel with th = 5 mm.

Concerning the earth-based render (Fig. 33), the higher measured temperature of about 80°C were recorded near to the fire exposed side. Meanwhile, the lowest temperature (about 50°C) was registered at 17.5 mm depth.

Thermocouples located in the earth-based render (TA)

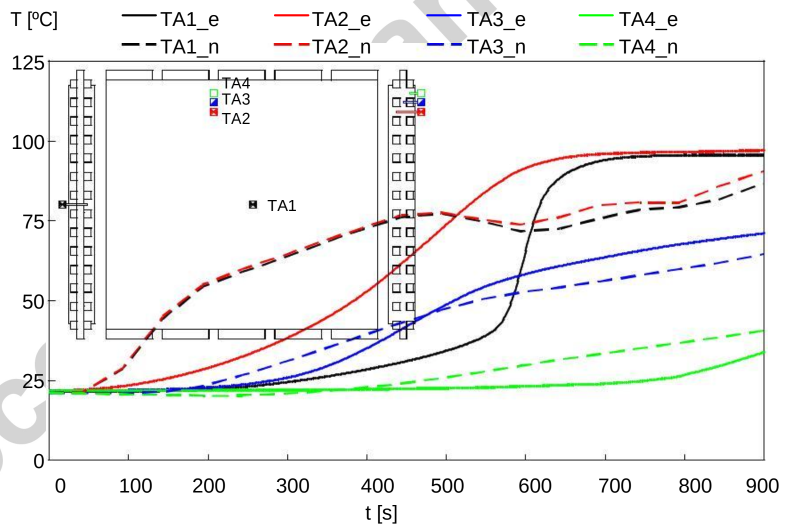


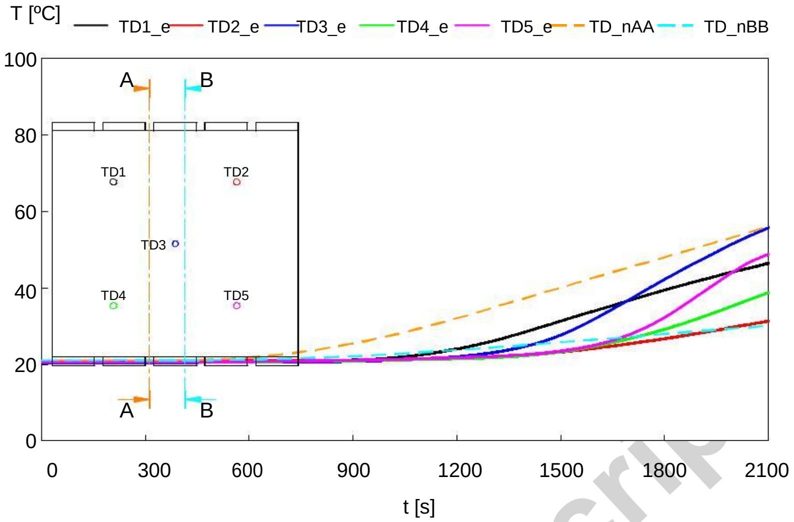
Fig. 33 Time-temperature evolution of the earth-based render of the *tabique* wall panel with th = 5 mm.

In terms of the numerical simulation, the time-temperature evolution of both earth-based render and timber is in accordance with the experimental results. The material moisture release phenomenon estimated by the thermocouples TM1 and TM4 was simulated numerically with accuracy. The discrepancies between experimental and numerical results may be due to different causes such as the natural *tabique* wall panel performance, the existence of some internal cracking that may affect the measurements, the possible thermocouples displacement, the material heterogeneity, among other. In general, a good correlation between the numerical and the experimental results was obtained, mainly at the final stage of the experiments.

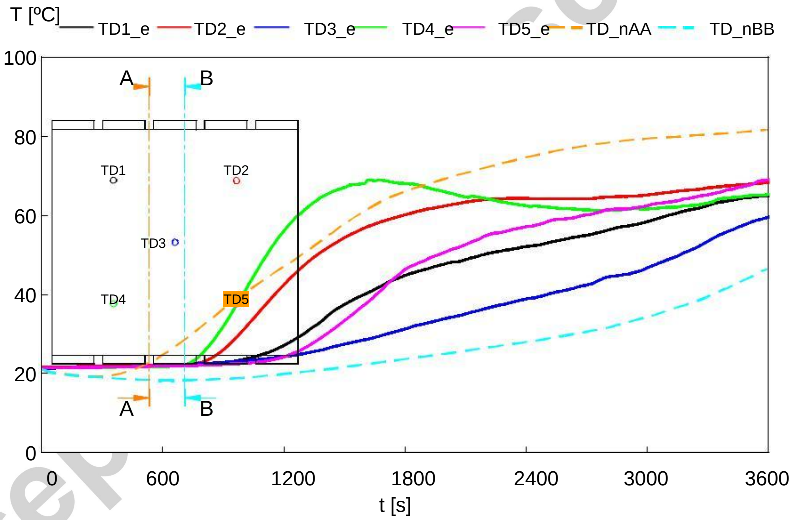
5.4 Thermocouples applied in the unexposed surface

Fig. 34 shows the temperatures recorded by the thermocouples applied in the unexposed surface of the *tabique* wall panels.

a)



b)



c)

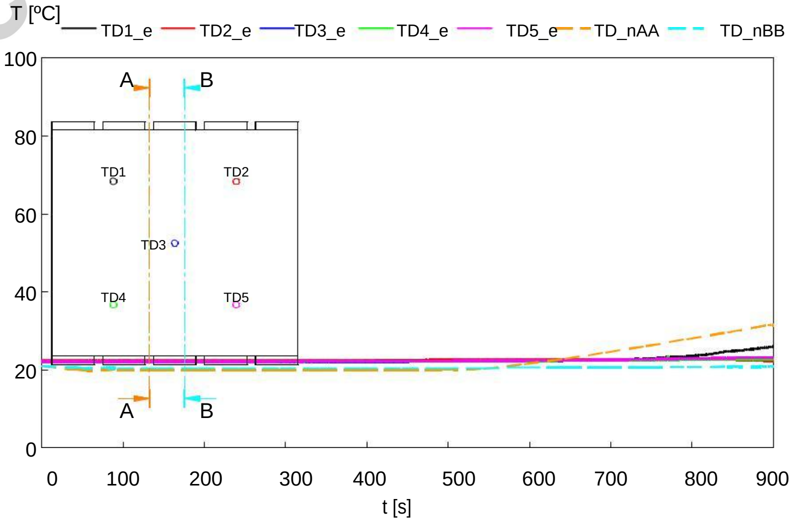


Fig. 34 Time-temperature evolution measured by TD thermocouples placed in the unexposed surface, for: a) th = 15 mm; b) th = 10 mm; c) th = 5 mm.

From Fig. 34 it is noticed that the temperatures of the unexposed surface remained practically unchanged at around 21ºC until t = 900 s. According to EN 1363-1 [10], the insulation criterion was verified.

5.5 Global damage comparison

A comparison between numerical and experimental fire damage modelling is done in Fig. 35 and for the last stage of the test.

Tabique panel with th = 15 mm *Tabique* panel with th = 10 mm *Tabique* panel with th = 5 mm

Fig. 35 Final results of material damages: numerical and experimental modelling.

It can be seen in Fig. 35 that the numerical simulation predicted that approximately half of the laths existing in the surface subjected to fire action burned for *tabique* wall panel with th = 15 mm. This fire scenario was confirmed experimentally proving that there is a good agreement between the numerical modelling and the experimental test regarding the final result.

For the *tabique* wall panel with th = 10 mm, the numerical prediction corresponded to the damage that actually occurred in the structure. As it can be seen in Fig. 35, the laths were completely burned. The vertical boards were slight affected because they showed a reduced rate of carbonization. There was also a good relation between numerical and experimental simulations despite some small differences.

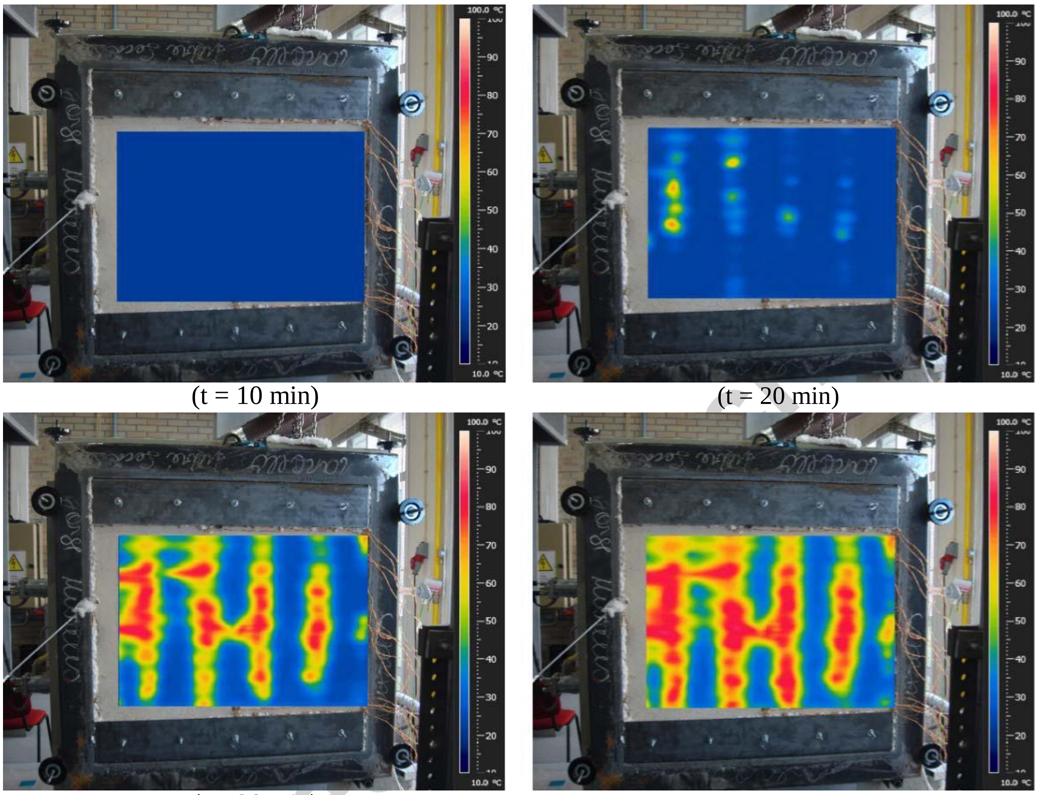
Regarding the *tabique* wall panel with th = 5 mm, the numerical simulation shows that approximate 1/3 of the thickness of laths suffered burning. In fact, a partial carbonization of laths occurred experimentally. The numerical model captured quite accurately again the experimental behaviour.

6 Infrared (IR) thermography

In the following figures we can see the infrared (IR) thermography diagrams at different testing stages. The IR thermography is very helpful in this study because it allows us verifying the effect of isolating the timber with an earth-based render and also the non-uniform thermal behaviour across the wall, for instance. The results of the IR thermography complement the above ones because the surface temperatures of the entire unexposed surface of the panel can be assessed. In contrast, thermocouples measure temperatures locally. This field measurement is of great importance to define the position of thermocouples used to find maximum temperature events in future tests.

6.1 *Tabique* panel with th = 15 mm of earth-based render

Fig. 36 shows the temperature evolution for the *tabique* panel with 15 mm of earth-based render thickness.



(t = 10 min) (t = 20 min)

(t = 30 min) (t = 35 min)

Fig. 36 Infrared thermography of the *tabique* wall panel with th = 15 mm.

The minimum temperature recorded throughout the test is 22.6°C. The average temperature at the end of the test was 52°C. According to IR thermography, the temperature of the outer face of the panel began to increase at 20 min approximately, and ranged to a maximum of 85°C. In this panel, the highest experimental temperature of 55ºC was recorded by the TD3 thermocouple (refer to Fig. 34).

6.2 *Tabique* panel with th = 10 mm of earth-based render

Fig. 37 shows the evolution of the temperature of the outer face of the *tabique* wall panel with a 10 mm thick earth-based render.

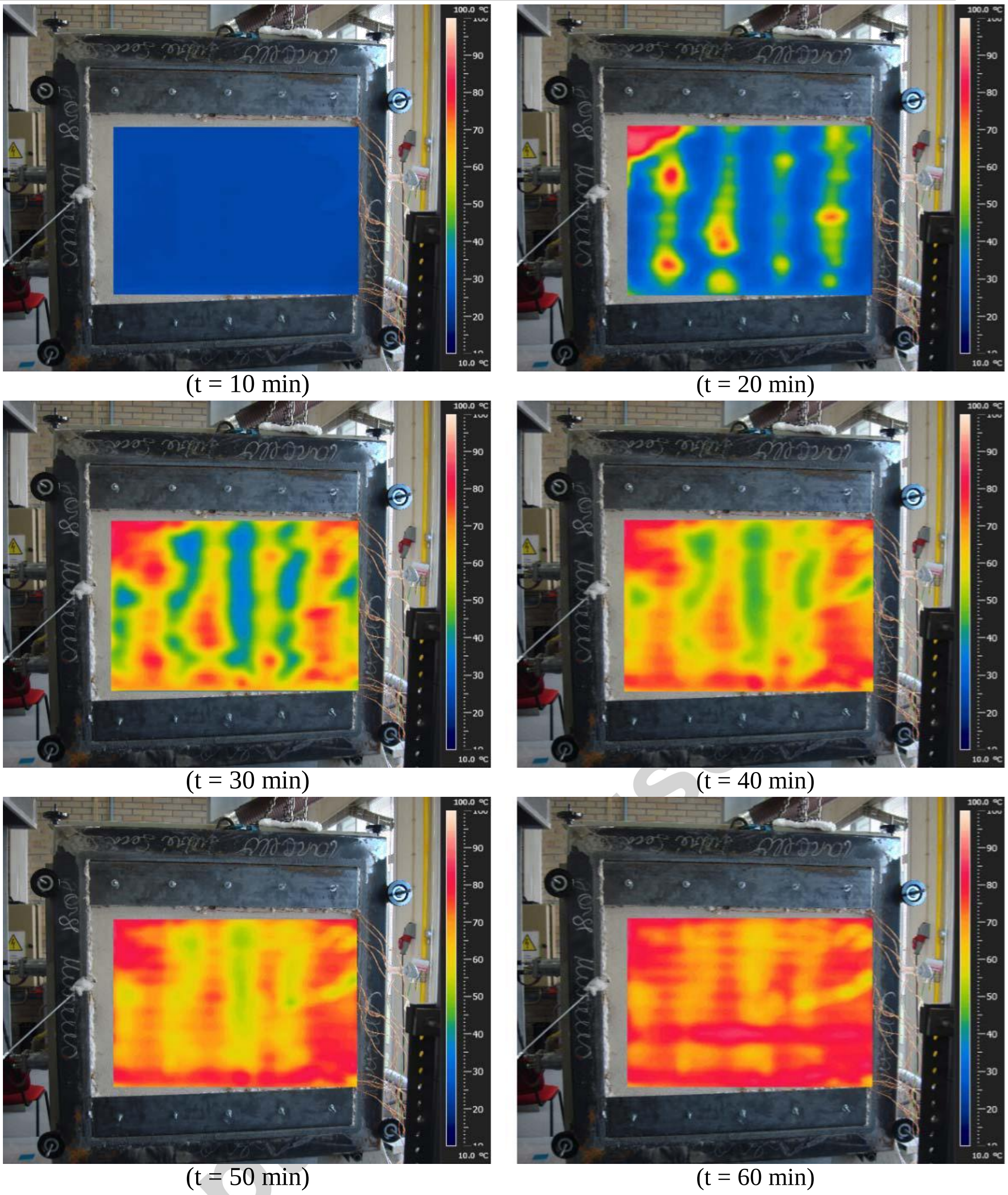
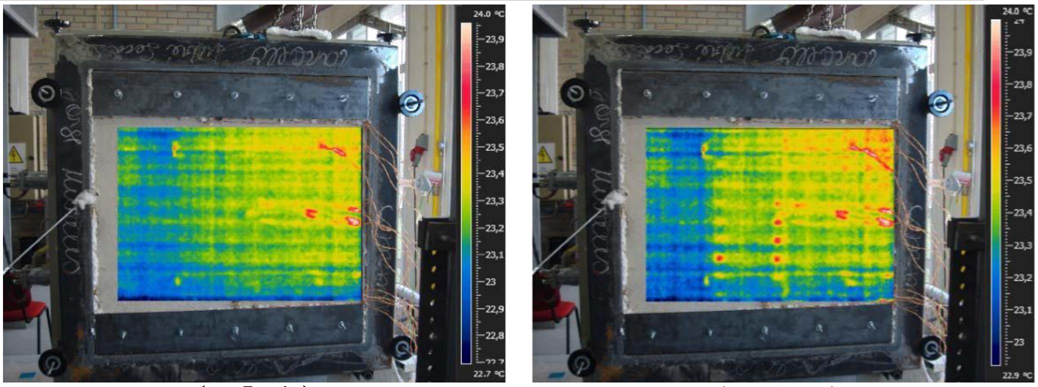


Fig. 37 Infrared thermography of the *tabique* wall panel with th = 10 mm.

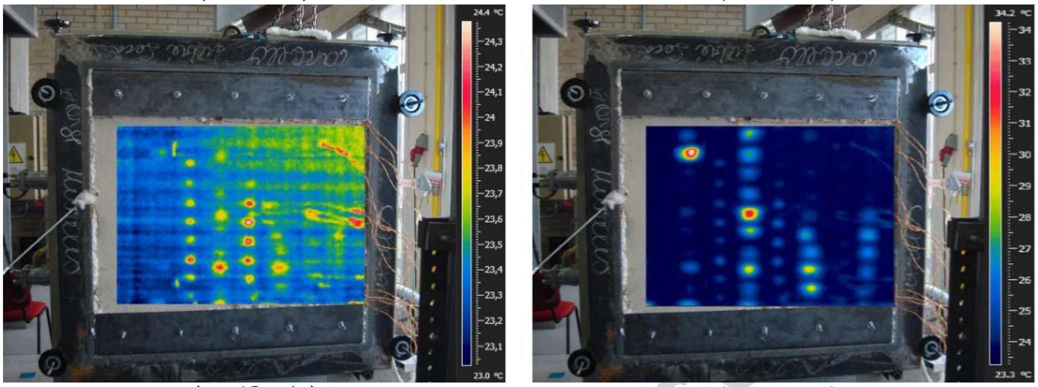
In this case, the minimum temperature recorded throughout the test is 58°C. The average temperature at the end of the test was 76°C, as shown in Fig. 37. According to the IR thermography, the increasing of temperature was noticed after 10 min and ranged to a maximum of 90°C. For current test, the highest experimental temperature of 70ºC was recorded by the TD5 thermocouple (refer to Fig. 34). In this case there is a sharp increase of the temperature because the panel has a lower render thickness.

6.3 *Tabique* panel with th = 5 mm of earth-based render

Fig. 38 shows the temperature evolution of the *tabique* panel with 5 mm of earth-based render thickness.



(t = 5 min) (t = 10 min)



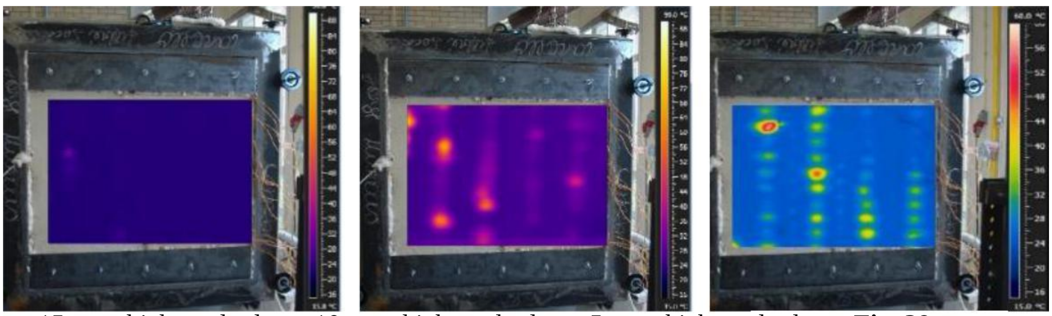
(t = 12 min) (t = 15 min)

Fig. 38 Infrared thermography of the *tabique* wall panel with th = 5 mm.

In this case, the minimum temperature recorded throughout the test is 21°C. The average temperature at the end of the test was 28°C. According to IR thermography, the increasing of temperature of the outer face of the panel was noticed after 5 min and it reached the maximum value of 35°C. At the same time, the highest experimental temperature of 26ºC was recorded by TD1 thermocouple (see Fig. 34). The temperature evolution was more pronounced in this panel because its render layer is thinner.

6.4 Comparison between *tabique* panels with different earth-based render thicknesses

Fig. 39 presents the IR thermography diagrams obtained at t = 900 s for each tested panel. Fig. 40 shows the time-temperature evolution of the unexposed surface.



15 mm thick render layer 10 mm thick render layer 5 mm thick render layer **Fig. 39** Infrared thermograph diagrams of *tabique* wall panels (t = 900 s).

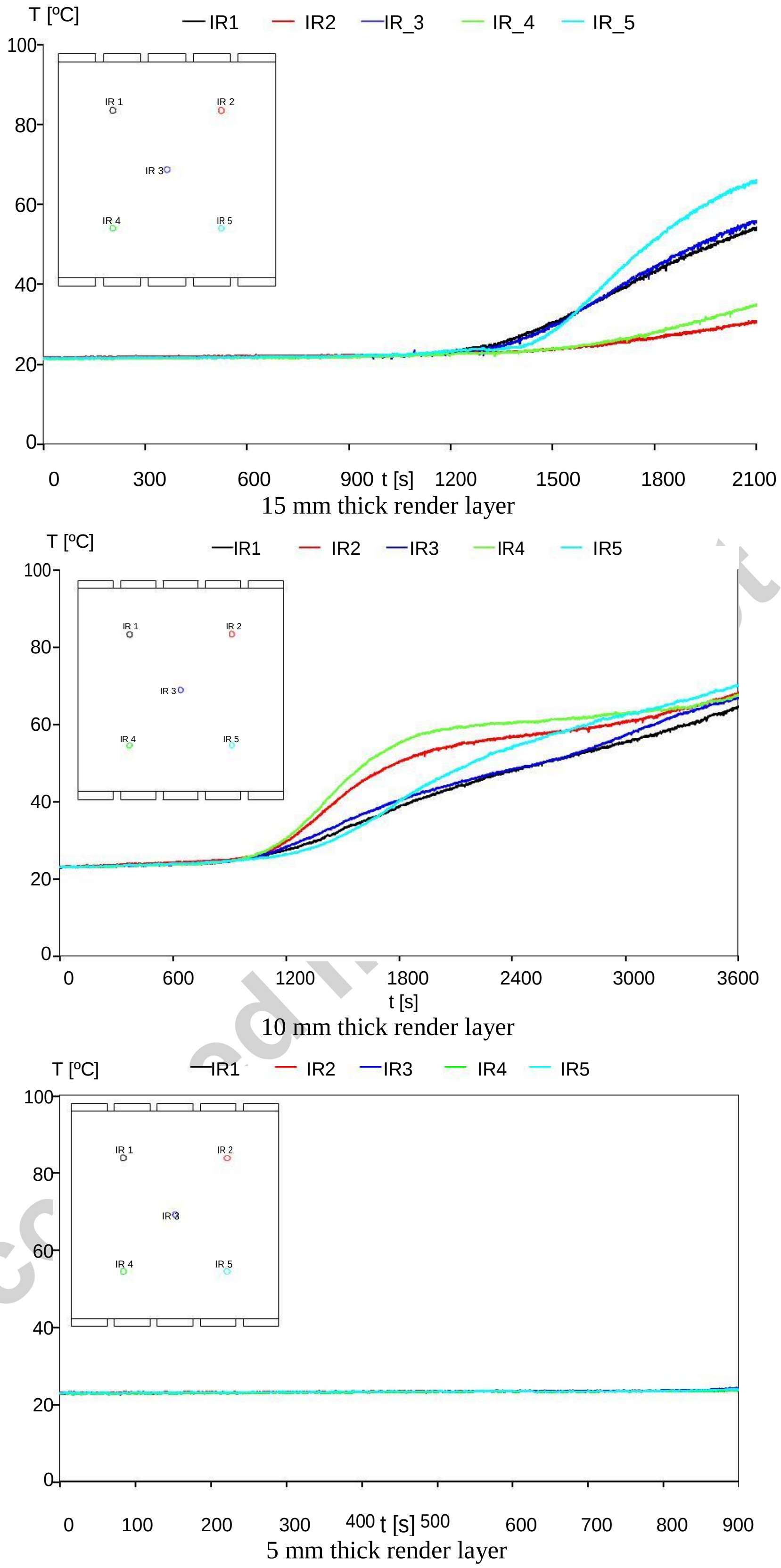


Fig. 40 Time-temperature evolution of the *tabique* wall panels by IR thermography (unexposed surface).

From Fig. 36 to Fig. 39 the wood insulation effect is noticed as well as the insulation effect of the different earth-based render thicknesses considered. At t = 3600 s, the surface temperature increased up to 80ºC, which means that the insulation criterion was fully verified because the average temperature increase did not exceed 140°C in relation to the initial average temperature. Moreover, the maximum temperature at any point of the unexposed surface did not exceed the final temperature of 180°C. Therefore, it can be concluded that the earth-based render acted as a fire exposure protecting layer for the wooden structure improving the overall fire performance of this type of building element.

Fig. 40 shows the time-temperature evolution of the points of the unexposed surface in where the thermocouples were placed and using infrared thermography (see Fig. 3). Comparing the respective time-temperature evolution obtained by these two data acquisition procedures it is possible to figure out that there is adequate accordance.

7 Conclusions

This paper presents the first research study related to fire behaviour of *tabique* walls, concerning its fire resistance. An experimental program including *tabique* panels manufactured in laboratory was developed. The *tabique* panel represents a portion of a real-scale wall, and all the dimensions are real ones, like the *tabique* panels that can be met in real buildings. Experimental results allowed the authors to verify that both criteria (insulation and integrity) defined in the European standard for fire resistance tests [10, 11] were fulfilled by the three tested *tabique* wall panels for the whole test duration.

The insulation criterion verification was conducted according to the relation between the average temperature increase and the average initial temperature, which was not higher than 140°C. Moreover, the maximum temperature at any point of the unexposed surface of the *tabique* panel did not exceed the final temperature of 180°C, above the initial average.

The integrity criterion was observed throughout the experiments by employing a cotton wool pads saturated in ethyl alcohol. No flame or ignitions of the cotton have been identified. However, a significant amount of smoke release from burning wood was noticed at the final stage of the test.

The earth-based render acted as a fire protection layer to the wooden structure improving significantly the fire resistance of this building construction element.

The *tabique* walls behaviour was similar in all experimental tests. It can be seen that the highest temperatures were recorded near to the exposed surface, as it was expected. The temperature evolution was more pronounced in *tabique* panel with thinner render layer. Concerning the temperatures recorded at 1/5 depth from the unexposed surface, the temperature remained almost unchanged at the ambient value.

The time-temperature evolution shows that the first part of the graphics remains unchanged because a covering layer isolated the heat coming from the furnace during a period of 120 s at 200 s approximately until it reached the laths existing in the fire exposed face. At that moment, the temperature near to the exposed surface rose linearly until the wood moisture evaporation plateau was reached. Afterwards, the temperatures of the unexposed surface began to increase. In this process, both materials accumulate energy in an endothermic process. When the water evaporation ended, the measured temperatures increased again, following the same evolution slope than the initial behaviour.

Temperature measurements were recorded through earth-based render thickness.

Comparing the three *tabique* wall panels for t = 900 s, the maximum imposed temperature in the furnace was of 737ºC, while the corresponding temperature recorded near the exposed surface was of 100ºC, which represent a temperature reduction of 85%.

The numerical temperatures show good agreement with the experimental results (temperature and position of the char layer). The numerical models were validated experimentally, allowing calibrating and adjusting the material properties used in the *tabique* wall panels.

The obtained results may be valuable because they allow improving the knowledge and simulation on *tabique* walls behaviour subjected to fire conditions. In particular, they contribute to predict the failure criteria due to fire, increasing the safety of people and property.

References

[1] ISO, ISO 834-1 - Fire-resistance tests - Elements of building construction – Part 1: general requirements, 1999.
[2] A. Cepeda, A. Murta, J. Lousada, J. Pinto, L. Fernandes, P. Tavares, P. Silva, H. Varum, Tabique construction in Alto Tâmega, Structures and Architecture (2010).
[3] J. Pinto, G. Gulay, J. Vieira, V. Meltem, H. Varum, I. Bal, A. Costa, Save the Tabique Construction, Structures and Architecture (2014).
[4] J. Pinto, H. Varum, D. Cruz, D. Sousa, P. Morais, P. Tavares, J. Lousada, P. Silva, J. Vieira, Tabique Construction Characterization in Douro North Valley, Portugal: A First Step to Preserve this Architectural Heritage, 2nd WSEAS International Conference on Urban Rehabilitation and Sustainability (URES'09). Environmental Science and Sustainability, WSEAS Press, Baltimore, USA, 2009, pp. 48-53.
[5] J. Pinto, H. Varum, A. Cepeda, P. Tavares, J. Lousada, P. Silva, J. Vieira, Study Of The Traditional Tabique Constructions In The Alto Tâmega Region, Wessex Institute of Technology, UK, 2010, pp. 299-307.
[6] S. Cunha, J. Pinto, A. Paiva, A. Briga-Sá, N. Soares, H. Varum, D. Ferreira, A contribution for the improvement in thermal insulation of tabique walls coated with metal corrugated sheets, Journal of Building Services Engineering Research & Technology 36(4) (2015) 439-454.
[7] P. Kuklík, M. Charvátová, The behavior of OSB board´s fire protection coating under the nominal fire, M2D 2015 - 6th International Conference on Mechanics and Materials in Design, P. Delgada/Azores, Portugal, 2015, pp. 2409-2414.
[8] M. Drdácký, M. Kloiber, Considerate SDT methods for safety assessment of historic timber, M2D 2015 - 6th International Conference on Mechanics and Materials in Design, P. Delgada/Azores, Portugal, 2015, pp. 2349-2350.
[9] A. Araújo, E. Fonseca, D. Ferreira, P. Piloto, J. Pinto, Fire behaviour of tabique walls, IFireSS - International Fire Safety Symposium, Coimbra, Portugal, 2015, pp. 109-110.
[10] CEN, EN 1363-1 - Fire resistance tests - Part 1: General requirements, Central Secretariat, Brussels, 1999.
[11] CEN, EN 1364-1 - Fire resistance tests for non-loadbearing elements - Part 1: Walls, Central Secretariat, Brussels, 2015.
[12] D. Ferreira, A. Araújo, E. Fonseca, P. Piloto, Fire behaviour of tabique wall - experimental and numerical study, M2D 2015 - 6th International Conference on Mechanics and Materials in Design, P. Delgada/Azores, Portugal, 2015, pp. 2331-2340.
[13] CEN, EN 1995-1-2 - Eurocode 5: Design of timber structures - Part 1-2: General – Structural fire design, Central Secretariat, Brussels, 2004.
[14] CEN, EN 1996-1-2 - Eurocode 6: Design of masonry structures - Part 1-2: General rules – Structural fire design, Central Secretariat, Brussels, 2005.
[15] D. Thê-Nguyen, F. Mefath, Behaviour of hollow clay brick masonry walls during fire. Part2: 3D finite element modeling and spalling assessment, Fire Safety Journal 66 (2014) 35-45.

Highlights

- First research related to fire behaviour of *tabique* wall.
- The insulation criterion was verified on *tabique* wall exposed to fire.
- The integrity criterion was verified as no flame or ignitions have been identified.
- The earth-based render significantly improved the fire resistance.
- The numerical model show good agreement with the experimental results.