Journal of Safety Science and Resilience 6 (2025) 100189

Contents lists available at ScienceDirect

Journal of Safety Science and Resilience

journal homepage: www.keaipublishing.com/en/journals/journal-of-safety-science-and-resilience/



Heat penetration and thermal response due to firebrand accumulation on the exterior walls of dwellings☆

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ARTICLE INFO

Keywords:
Heat penetration
Thermal response
Firebrand accumulation
Ignition and fire reaction
Layer insulation

ABSTRACT

This paper presents an extensive experimental investigation campaign concerning the thermal fire reaction of firebrands, as they accumulate on the exterior walls of dwellings, a common occurrence in southern Europe. Three types of wall core layers were studied: bricks, designed according to the Exterior Thermal Insulation Composite Systems (ETICS) methodology, cross-laminated timber (CLT) and normal wood (NW), both utilizing the sandwich methodology. The wall specimens are made of a combination of materials such as three types of mortar (Tria, Sika, and Weber), and various thermal insulation materials, such as agglomerates of composite cork, impermeable membranes, rigid rock wool, fireproof paint, and extruded polystyrene rigid foam (XPS), which are recommended for their good performance against fire and high temperatures. Firebrands are then deposited on the localized surfaces of the wall specimens, and the temperature is recorded in each layer. This study aims to precisely verify the firebrand reaction to fire, including the type of ignition, smoke and droplet production. The insulation capabilities of each insulation and wall system will also be analyzed.

1. Introduction

Firebrands play a pivotal role in the progression of wildfires, initiating spot fires ahead of the main fire front and particularly threatening the wildland-urban interface [1]. Propelled by the wind with minimal lofting, these firebrands accelerate fire front propagation [2] and pose a significant risk to dwellings close to the interface [3]. This problem has been largely recently studied, and mitigation [4] is a recommended approach to reduce structural damage from firebrand accumulation. At a small scale, this type of damage may seem small, but at a larger scale, the effect is overwhelming, taking many years to reinstate the infrastructure and economy in impacted zones [5].

During severe wildfires, the interplay of fire and weather gives rise to a firestorm, extensive spotting of large firebrands, vigorous pyrogenic winds, and robust pyro-convection. Firebrands, often called embers, play a crucial role in the rapid spread of fires during extreme fire events. The movement of burning materials such as wood chips, bark, twigs, leaves, or nuts ahead of the primary fire front not only accelerates the rate of fire spread but also can initiate new fire fronts separated from the central fire front [6].

Given this context, there has been a growing focus on investigating the deposition and accumulation of firebrands, which are recognized as a paramount factor contributing to localized ignition. The heightened attention to this aspect arises from the understanding that the build-up of firebrands, coupled with prolonged contact with flammable materials, often leads to fires, particularly in wooden structures [7].

According to findings and reports from experts [8–10], the ignition during the 2017 Great Fires in Portugal was predominantly attributed to firebrands. The potent influence of the wind facilitated the transport of firebrands to residential areas, where they remained glowing for extended periods.

Recent research has established that firebrands generated during wildfires possess the capability to transport considerable distances, thereby initiating additional fires [7,11,12], in which the estimated distances from active wildfire locations range from 500 m [13] to 2.0 km [14]. In certain instances, these firebrands descend onto construction elements, where combustible materials may have accumulated. Upon contact with firebrands, energy transfer occurs, potentially leading to the ignition of these accumulated elements [6].

Various studies indicate that ignited firebrands typically result in

☆ Peer review under the responsibility of China Science Publishing & Media Group Ltd.

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https://doi.org/10.1016/j.jnlssr.2024.12.003
Received 18 August 2024; Received in revised form 19 December 2024; Accepted 24 December 2024
Available online 15 February 2025
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ignition [15]. However, in specific cases, unignited firebrands deposited on a house can induce heat transfer contingent upon the firebrand size and airflow. This can lead to igniting construction elements, even hours after the wildfire has subsided. While numerous studies have focused on numerical and experimental predictions of firebrand transportation [16–19] and firebrand characterization [19], their impact on understanding the thermal effects on construction elements remains limited.

1.1. Objectives

The main objective of this study is to investigate the thermal fire reaction of walls under firebrand accumulation. Furthermore, this study aims to assess the influence of various thermal insulation materials with different mortar types when an exterior wall is subjected to firebrand deposition. The observed fire reactions are reported, and smouldering penetration due to the firebrand and the insulation capacity of each chosen construction solution is assessed.

A set of materials for the wall core layers commonly used in the construction industry in southern Europe, a world region that normally experiences large wildfires during the summer, is selected. Normal brick masonry walls and even wood base walls with normal timber and cross-laminated timber (CLT) were tested for the construction elements. These two types of dwellings have also recently become popular for new dwellings in the European construction industry because they are carbon deposits, promoting a negative carbon footprint. To comply with the new thermal European standards, in this work, for brick walls, the thermal insulation is preferably inserted in the exterior surface of the wall and has a similar layer distribution according to the exterior thermal insulation composite system (ETICS), which is a standard widely adopted construction method in Europe. In ETICS systems, thermal insulation materials are applied directly to the exterior surface of a wall, typically secured with adhesive, mechanical fasteners, or a combination of both. A reinforced base coat and protective top coat are applied, providing weather resistance, impact durability, and aesthetic finish options. For wood-based walls, the sandwich methodology, which is also quite popular in the industry of composite wood panels where multiple layers of materials are combined to create a single, insulated, and highly durable wall structure, has also been used. Typically, this method involves an inner and outer structural layer with a thermal insulation core layer sandwiched between them.

1.2. Research significance

The scientific community has mostly focused on firebrand transportation, giving precedence over firebrand creation and fuel ignition. However, limited attention has been given to the direct ignition of construction elements when in contact with firebrands, with few studies addressing the specific issue of firebrands initiating combustion in various layers of external walls.

A thorough literature review has highlighted a notable gap in existing knowledge, particularly the scarcity of studies examining fire reaction tests for the thermal effects of firebrand accumulation in external walls. Although Arruda et al. [20] extensively studied the thermal effects of firebrand accumulation in specimens of construction materials, they did not consider the influence of multiple material layers. The comprehensive exploration of these materials alongside various secondary components in construction elements such as walls, along with their thermal response to firebrand accumulation, is largely lacking. This research aims to fill this critical knowledge gap and contribute valuable insights.

1.3. Extension in wildfire protection research

The same authors of this paper recently recommended new fireproof construction recommendations [21] for wildfire-resistant houses. However, they may not be cost-effective because these parameters are based on an indoor 60-minute standard nominal fire curve, which is more severe than an external wildfire. Furthermore, the same authors presented new wildfire standard curves to recreate the thermal heat flux of a tree or bush burning near an isolated residence in a forest environment [22]. To simulate the indirect effects of firebrand accumulation in dwellings, the authors proposed a revised standard temperature curve [23], the product of an intensive laboratory fire trial program. These scientists have also recently conducted a comprehensive experimental campaign to investigate the firebrand reaction in popular material specimens utilized in the construction industry due to firebrand accumulation [24].

2. Previous studies on construction elements

In light of the annual recurrence of wildfires in the Wildland-Urban Interface (WUI) and the significant material, human, and animal losses they entail, it is essential to recognize that firebrand accumulation is a primary contributor to the spread of fires. Therefore, numerous studies have been conducted to address firebrand mechanisms [25] and their effects on various materials [26], as well as construction elements in dwellings [27].

The experimental study of firebrand accumulation and transportation into external walls has been performed previously by other researchers but with different objectives from this work. For example, in the work of Suzuki et al. [28], ignition was created on re-entrant corners constructed from wood studs/OSB but fitted with actual siding treatments to analyze the impact of siding treatments on indirect firebrand propagation from external walls to neighbouring dwellings.

An experimental campaign investigated the vulnerability of siding treatments, walls with eaves, and glazing systems to firebrand transportation and later deposition. This was performed using a Dragon Firebrand Generator in the NIST laboratory [29]. This study was carried out to find out whether firebrands might ignite fine fuels placed next to the wall assembly and whether the wall assembly itself could ignite due to the fine fuels' subsequent ignition.

The effect of natural weathering (external ambient agents) on intumescent-type fire-retardant coatings that could be applied in external walls was examined by Bahrani et al. [30]. It highlighted the coatings' ability to contribute to fire propagation and decreased ignition resistance, even in flammable materials. Using a cone calorimeter, three coatings were evaluated over a year at different heat flux levels. The results showed that the coatings did not act as extra fuels during weathering; rather, their effectiveness in preventing fires diminished. Statistics showed that weathering time, heat flow, and coating type effects on combustion properties were more significant than weathering orientation, which had no effect. To measure the amount of firebrands produced during combustion under different wind speeds.

Another important construction element susceptible to ignition due to firebrand accumulation is the roof, especially in old dwellings [8]. This type of construction element has already been studied in the scientific community. One of the first experimental studies was conducted by Manzello et al. [31] to assess roofing material vulnerability to firebrand attack, and their findings highlighted behaviours like smoldering ignition and melting of asphalt shingles, particularly in roofs with gutters.

These studies were subsequently followed by [32], which conducted a comprehensive study using a firebrand generator to simulate firebrand attacks. It examined the influence of an applied wind field to investigate the ignition susceptibility of curved ceramic tile roofing assemblies. Their findings revealed that ceramic tile roofing assemblies are indeed vulnerable to ignition during a firebrand attack. Therefore, they recommended that the first layer of insulation material should be fireproof.

Vulnerabilities of roofing, siding, attic vents, decking, mulches, and associated decks were systematically evaluated [33]. Most of the test findings were in the form of photographs and videos, which could be incorporated into the evaluation tool to establish the importance of

window components and screening. The findings highlighted the vulnerability of glass as the most critical component, with window screens reducing radiant heat transmission into the building. Furthermore, results supported heat flux calculations, indicating that curtains behind closed windows with annealed or tempered glass ignite only after the glass breaks. Notably, the dual-pane tempered glass window did not break under the 35 kW/m^2 exposure in this test series.

An experimental investigation was carried out by Manzello et al. [34] to investigate whether tile assemblies allow firebrands to penetrate and melt the underlying sarking. Their findings revealed that firebrands successfully penetrated the tile gaps, subsequently melting the sarking material in both types of concrete tile roofing assemblies (flat and profiled tiles), as well as in the profiled tile terracotta roofing assembly when exposed to wind-driven firebrand showers.

This research was later complemented by carrying out an experimental protocol to ignite full-scale roofing assemblies [35]. They found that when orientated strand board is the only material used for sheathing, a significant portion of the firebrands collected from roofing assemblies were <1 gram and 10 cm^2.

Through wind tunnel tests, Nguyen et al. [36] examined rooftop ember retention during wildfires. The building geometry, wind flow, and roof slope were discovered to have an impact on ember removal. Greater ember retention zones were produced by increasing the roof's slope in specific wind directions. High ember stability was seen in internal corners, such as those surrounding dormers.

An experimental study was carried out by Arruda et al. [20] to examine the reaction of different construction materials against firebrand accumulation. Their research revealed the dangers of bituminous tiles, PVC's poor fire resistance, and cork's long-lasting, >200-minute ability to withstand combustion. It was observed that inflexible rock wool and aluminium showed the best reactions to firebrands, but pine or CLT wood required protective paint. However, it was discovered that XPS was useless in this situation, and it was advised that metal mesh in air vents have gaps smaller than 2.5 mm to prevent flame ignition.

3. Experimental campaign

This section provides detailed information about the wall specimens, including the constituent materials, compositions, dimensions, and geometric characteristics, as well as a thorough explanation of the test setup methodologies used to assess their thermal reactions to firebrand accumulation. A concave exterior wall geometry in L shape was chosen since this shape may provide the most severe case and is often found in classical main entry architectural paths in dwellings.

3.1. Chosen construction materials

The materials selected for the experimental campaign encompass three structural materials for the wall core layer: bricks, CLT, and structural wood (timber).

The chosen bricks are made from clay or shale and fired in a kiln. They are the most commonly used in walls due to their high compressive strength and durability. They offer good thermal mass and fire resistance, making them a reliable and long-lasting construction material. These were assembled via classical masonry techniques with standard mortar between bricks.

CLT consists of layers of wood glued together at perpendicular angles, providing a high strength-to-weight ratio and excellent thermal insulation. It is used in walls, floors, and roofs, particularly in sustainable and tall timber buildings.

Timber, sourced from natural lumber, is extensively used in structural framing, flooring, roofing, and decorative elements in construction. It offers good tensile strength and workability and is a renewable resource.

Additionally, various thermal insulation materials were employed, including cork agglomerate composites (from Corticeira Amorin), impermeable membranes, rigid rockwool, and polystyrene foam (XPS), alongside three types of mortar commercial providers: Sika, Weber, and Tria. Tria mortar was mainly designed for fire protection of structural and non-structural construction elements, but Sika and Weber are standard materials found in industry. The specific characteristics of these structural and thermal insulation materials are outlined in Table 1, while details regarding the mortars are provided in Table 2. The properties of Sika mortar are identical to Webber in terms of thermal performance.

In addition, Tria Coating Protective paint, along with secondary materials such as a net for reinforcing the mortar and paint, are used to simulate real exposure conditions. All these materials were chosen for this study because they are commonly used in Portugal for the external facade walls of dwellings in wildland areas, making them more prone to wildland fires.

3.2. Chosen construction wall types and layers

To assess the fire reaction against firebrand accumulation of the various combinations of materials forming walls, the specimens in this study are divided into three groups:

The first group contains ten brick wall specimens, where each specimen consists of four layers arranged as follows: brick, mortar, insulation material, reinforcement net, and paint, as illustrated in Fig. 1 (a). Detailed information regarding the composition of the brick wall specimens is provided in Table 3.

The second group contains seven timber (normal wood, NW) wall specimens, and the third group contains seven CLT wall specimens. The NW and CLT wall specimen groups contain the same method arrangement layers, as shown in Fig. 1(b). Among the variables in the NW and CLT wall specimens are the type of thermal insulation. For this type of external wall, Tria coating protective insulation was used, along with the use of Tria mortar, with the installation method described in Table 4.

Each wall consists of two plates forming a right angle (L shape), which are supported by a square concrete plate with a total test geometry of around 500 × 600 × 400 mm^3. The depth of the L shape varies between the corresponding types of materials being used. The total height of the test varied between 400 mm and 600 mm depending on the core layer material being tested. The thickness of the mortar was fixed at 9.0 mm (Fig. 1(c)).

3.3. Test setup

This test setup aligns with the guidelines outlined in the California Building Code Chapter 7A-4 [37], stipulating the deposition of 1.0 kg of firebrands in construction element specimens. The selected construction elements are equipped with RS PRO-Type K thermocouples, measuring 2.0 m in length and 1/0.3 mm in diameter. These thermocouples were strategically positioned on each layer to monitor temperature transmission from the firebrands to the elements. The temperature data are meticulously recorded at a frequency of 1.0 Hz for a maximum period of 200 min, providing comprehensive data on their behaviour during the cooling stage. In light of findings from multiple studies [38–41] indicating that compressed wood pellets generate more severe firebrand

Table 1
Thickness of the core layers and thermal insulation materials.

Material	Fire Reaction Rating	Thermal conductivity (W/m·K)	Thickness (mm)
Cork	E or F	0.04	30.0
Membrane	A or C	0.05	2.0
Rockwool	A1	0.04	60.0
XPS	C or even B.	0.04	50.0
Brick	A1	0.70	85.0
Timber	D or E	0.12	38.0
CLT	B or C	0.12	60.0

Table 2
Details of the characteristics of the mortars.

Property	Fire Reaction Rating	Thermal Conductivity (W/m·K)	Apparent Density (kg/m³)	Density of Cured Mortar (kg/m³)
Weber/Sika	A2-s1, d0	0.450	1400	1200–1300
Tria	A1	0.122	600–760	850–900

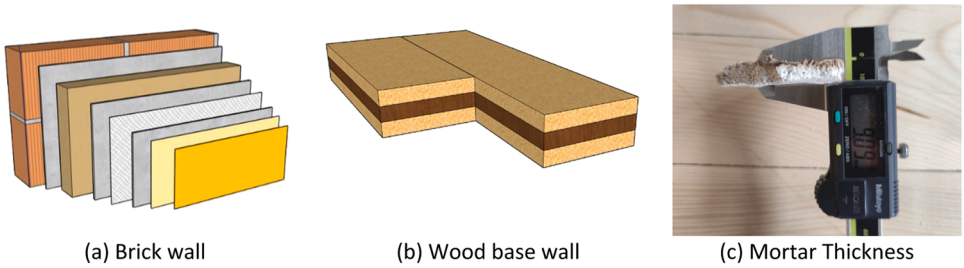


Fig. 1. Composition details of the walls.

temperatures, they were chosen to simulate the thermal action of firebrands. The process begins by placing 1.0 kg of firebrands in the metal cup, and undergoing a pyrolysis process until achieving full ignition, as illustrated in Fig. 2(a) and (b).

The firebrands are then placed in the corner, as shown in Fig. 2(c), and are exposed to an industrial wind blower to simulate the action of the wind at a speed of 1.31±0.13 m/s. In each layer, a set of thermocouples is placed using different placement methods for each specimen. The number and position of the thermocouples depended on the adopted core wall layer and insulation combination. Still, a general case representation of the test setup is presented in Fig. 3 for the brick walls and Fig. 4 for the wood base walls.

The duration of each test varied from 100 to 200 min, with differences driven primarily by safety considerations. Specifically, wood-based walls exhibited signs of uncontrolled combustion during testing, necessitating an early termination in some cases. Uncontrolled combustion was identified by the rapid escalation of surface flames, increased heat release, and excessive smoke, all of which indicated a transition from smouldering to active flaming, exceeding the safe operating conditions of the test setup. In contrast, for the brick walls, the test duration exceeded 150 min and was stopped only once the thermal insulation was compromised.

An example of the wall specimen with mortar applied in the thermal insulation is depicted in Fig. 5(a), in which the coating is applied above the insulation thickness to prevent any unexpected flame propagation at the top. This is necessary to prevent direct transmission of heat flux into the interior insulation layers. A concrete slab was also used as base support to simulate the connection of the walls to the foundations. The mortar was also continually applied between the wall and slab to prevent heat flux transmission at the bottom of the test (Fig. 5(b)).

Table 3
Details of the Brik wall specimens.

Walls designation	Type of mortar	Thermal insulation
B	Without	Without
B-W-R	Weber	Rockwool
B-S-R	Sika	Rockwool
B-W-X	Weber	XPS
B-S-X	Sika	XPS
B-T-X	Tria	XPS
B-W-C	Weber	Cork
B-S-C	Sika	Cork
B-W-M	Weber	Membrane
B-S-M	Sika	Membrane

Table 4
Details of the wood wall specimens.

Walls designation	Structural materials	Setting method	Coating protective	Thermal insulation materials	Mortar
NW-N-TP	Normal Wood	Normal	Tria Paint	Without	Without
NW-S-R-TM	Normal Wood	Sandwich	Without	Rockwool	Tria Mortar
NW-S-R	Normal Wood	Normal	Without	Rockwool	Without
NW-S-TP-R	Normal Wood	Sandwich	Tria Paint	Rockwool	Without
NW-S-C	Normal Wood	Sandwich	Without	Cork	Without
NW-S-C-TM	Normal Wood	Sandwich	Without	Cork	Tria Mortar
NW-S-TP-C	Normal Wood	Sandwich	Tria Paint	Cork	Without
CLT-N	CLT	Normal	Without	Without	Without
CLT-S-R	CLT	Sandwich	Without	Rockwool	Without
CLT-N-TM	CLT	Normal	Without	Without	Tria Mortar
CLT-N-R-TM	CLT	Normal	Without	Rockwool	Tria Mortar
CLT-N-TP	CLT	Normal	Tria Paint	Without	Without
CLT-S-TP-R	CLT	Sandwich	Tria Paint	Rockwool	Without
CLT-S-C	CLT	Sandwich	Without	Cork	Without

4. Experimental outputs and observations

4.1. Measured temperatures

During the firebrand accumulation tests, the temperature evolution within the layers of each wall specimen was recorded and plotted as a function of time (Figs. 6, 8 and 10). Additionally, the average maximum temperatures reached in each layer for each specimen (Figs. 7, 9 and 11), to produce outputs to analyze the thermal performance of each wall solution. There was a noticeable difference in temperature between the firebrand accumulation and the first layers of specimens attributed to varying non-deterministic external climatic conditions.

From Figs. 6 and 7, it can be noted that the performance of the first group of wall specimens varied considerably based on the type of thermal insulation and mortar used. All specimens performed well during firebrand accumulation tests, including the reference specimen containing only brick, in which the temperatures in the last inner layer did not exceed the ambient temperature of 30 °C in all specimens for the entire test duration.

Compared with those containing Weber mortar, the brick wall specimens containing Sika mortar exhibited a faster temperature increase, which was attributed to the higher density of Sika mortar. In



Fig. 2. (a) Pellets used, (b) Illustration of firebrand ignition and (c) Placement of firebrand accumulation in the wall specimens.

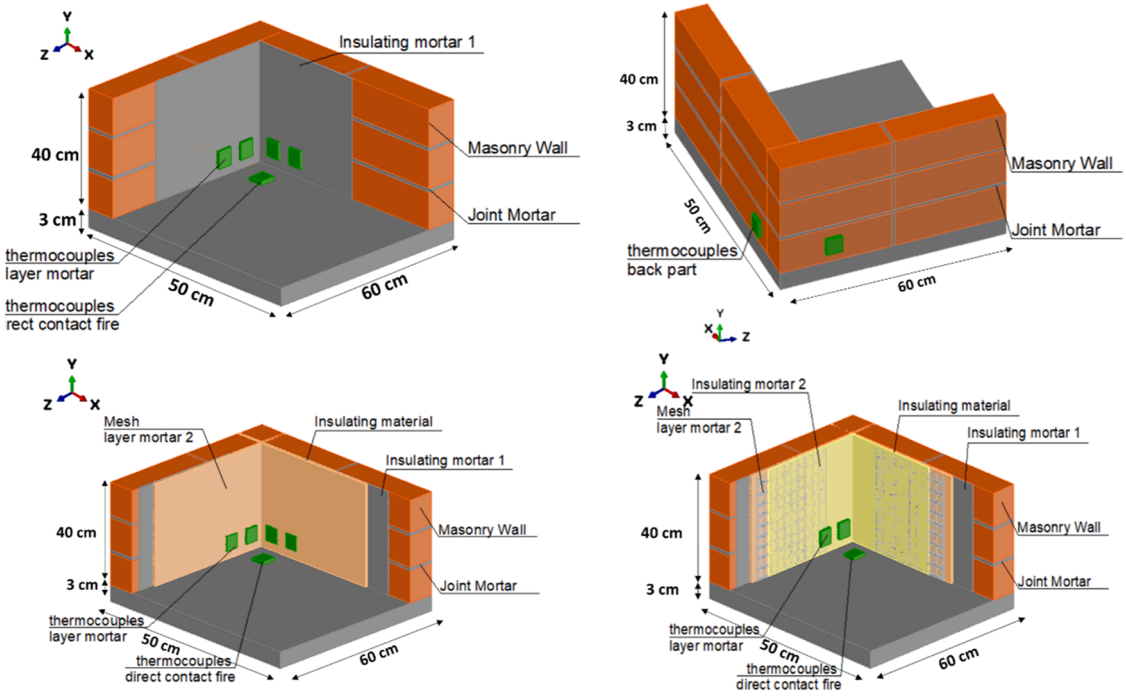


Fig. 3. Test setup details of the brick walls.

addition, compared to B-W-X and B-S-X, the B-T-X specimen with Tria mortar showed the most rapid temperature increase in the exposed layer, reaching a peak average maximum temperature of 834.87 °C. However, subsequent layers experienced a significant drop in temperature, falling below those observed in the B-W-X and the B-S-X specimens. Tria mortar might have a higher capacity for thermal mass, allowing it to absorb and dissipate heat more effectively than Sika and Weber mortars. This was expected since the Tria mortar was designed to withstand high temperatures.

Regarding the effect of XPS on the performance of these three brick wall specimens based on the temperature-time curves, it is impossible to accurately assess due to XPS melting at temperatures above 75 °C, as demonstrated by many studies [20,42]. This phenomenon is discussed in detail in Section 4.2.

Despite high temperatures on the exposed layers of the brick wall specimens containing Rockwool insulation (B-W-R and B-S-R), with average maximums reaching 458.18 °C and 654.70 °C, respectively, these specimens maintained stable performance throughout the test. Inner layer temperatures showed a gradual decrease. This can be attributed to the principal role of Rockwool, which has low thermal conductivity and substantial thickness. These findings align with published research [20].

Similarly, the B-W-C and B-S-C specimens, which contained cork as thermal insulation, maintained their insulation performance despite exceeding the average maximum of 400 °C in some exposed layers. The cork played a pivotal role in reducing temperature penetration to the inner layers due to its low thermal conductivity and favourable combustion properties. These results are consistent with published research [20].

Specimens with membrane insulation, such as B-W-M and B-X-M, showed good performance, as mentioned above. However, the membrane had a limited effect on reducing temperature. This is evident from the significant temperature penetration observed from the second to the third layers, which can be attributed to the membrane's minimal thickness. These findings align with previously published research [20].

Figs. 8 and 9, which show the results of the second group specimens, indicate that the timber (NW) specimens performed well during the firebrand accumulation test. Except for the NW-N-TP specimen, which is considered the reference for this group, the average maximum temperatures in the last inner layer did not exceed 30 °C, whereas in the reference specimen, temperatures reached 33.68 °C and 42 °C in the right and left inner layers, respectively.

The effectiveness of using thermal insulation such as rockwool or cork in timber specimens is evident in NW-S-R and NW-S-C, where a

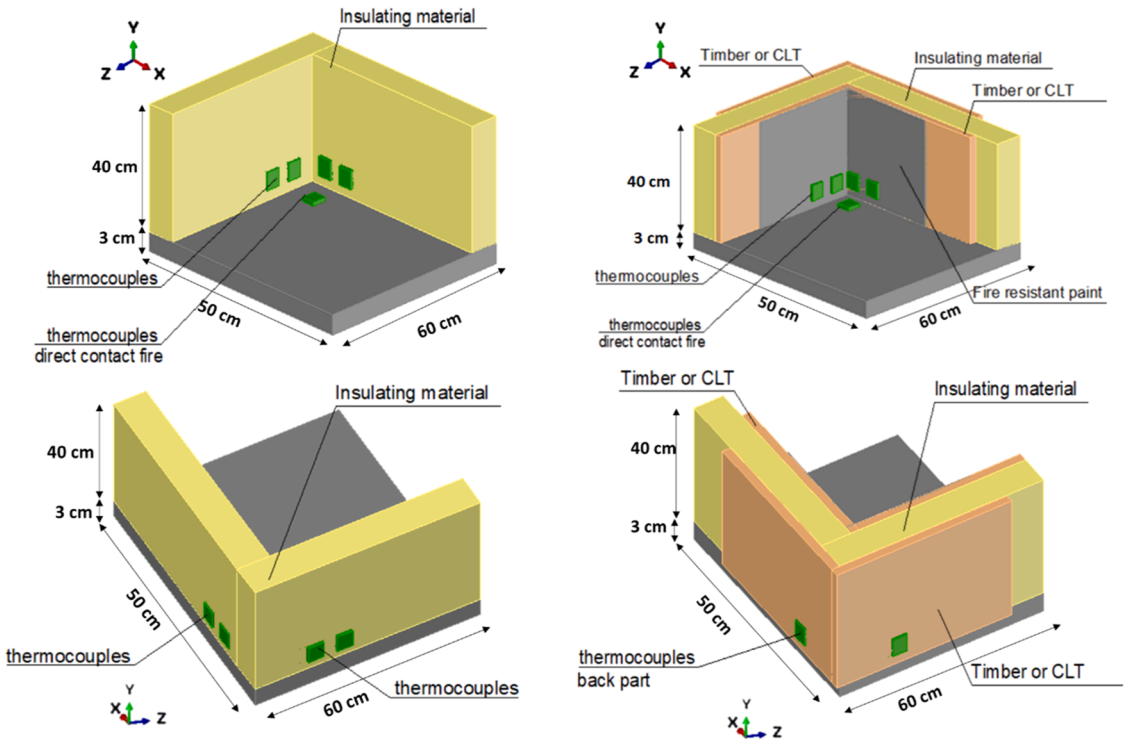


Fig. 4. Test setup details for the wood base walls.

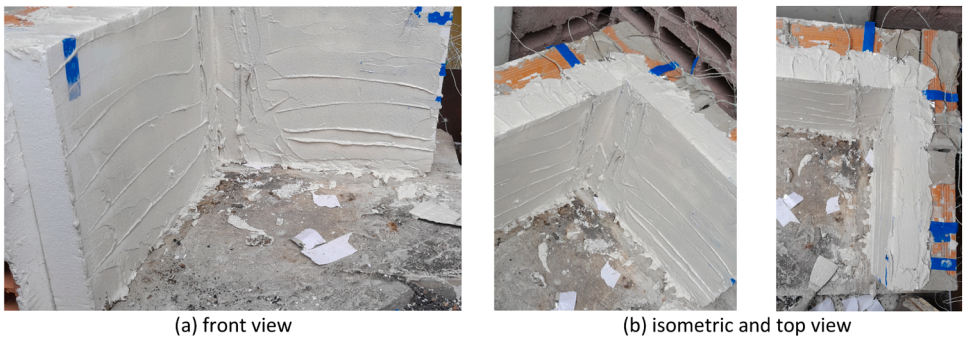


Fig. 5. Brick wall specimen after applying mortar in the insulation material.

noticeable reduction in temperature can be observed from layers 2 to layers 3 in both specimens, showing equivalent effectiveness.

Through specimens NW-S-R-TM and NW-S-C-TM, the role of the Tria mortar in enhancing the resistance of the timber wall specimens against firebrand accumulation can be observed. These specimens demonstrate a significant reduction in temperature from the exposed layer to the inner layers.

The contribution of Tria paint to firebrand accumulation is evident in specimens NW-S-TP-R and NW-S-TP-C, where significant protection is observed from the exposed layer to the inner layers.

Figs. 10 and 11 revealed that the specimens CLT-N-TP, CLT-S-TP-R, and CLT-S-C performed well in the third group against firebrand accumulation. As anticipated, the reference specimen CLT-N presented the worst performance, with the average maximum temperature in the last inner layer on the right side reaching 170.38 °C. This means that wood-based walls in dwellings, without any type of insulation, may not present the necessary conditions for shelter, according to [43], since the interior temperature is above 70 °C.

For the specimens with thermal insulation in a sandwich setting, namely, CLT-S-R and CLT-S-C, those containing cork insulation exhibited superior performance compared to the rockwool specimen. CLT-S-R experienced significant heating on the exposed layer. This effect is due to the windy conditions during testing, which could have intensified heat transfer and elevated temperatures in the inner layers. Furthermore, the CLT-S-R specimen experienced uncontrolled combustion within the wood core, which exacerbated the temperature rise and compromised the thermal protection offered by the rockwool layer.

The CLT-N-TM and CLT-N-R-TM specimens demonstrate the enhanced performance of CLT against firebrand accumulation by applying Tria mortar, as evidenced by a noticeable temperature drop from the exposed layer to the inner layers in both specimens.

The performance of Tria paint in CLT specimens is notable in NW-S-TP-R and NW-S-TP-C, where it prevents firebrand accumulation and provides significant protection to the exposed layer.

By comparing B, NW-N-TP, CLT-N, and CLT-N-TP, it can be observed that the B specimen demonstrates the best behaviour against firebrand accumulation. This is because bricks have a high density and thermal mass, which help them absorb and dissipate heat, thereby delaying fire spread. Additionally, bricks are considered non-combustible. The CLT-N specimen performs the worst during the firebrand accumulation tests because it experiences direct contact between the flame and the CLT surface, which is considered a combustible material. The NW-N-TP and

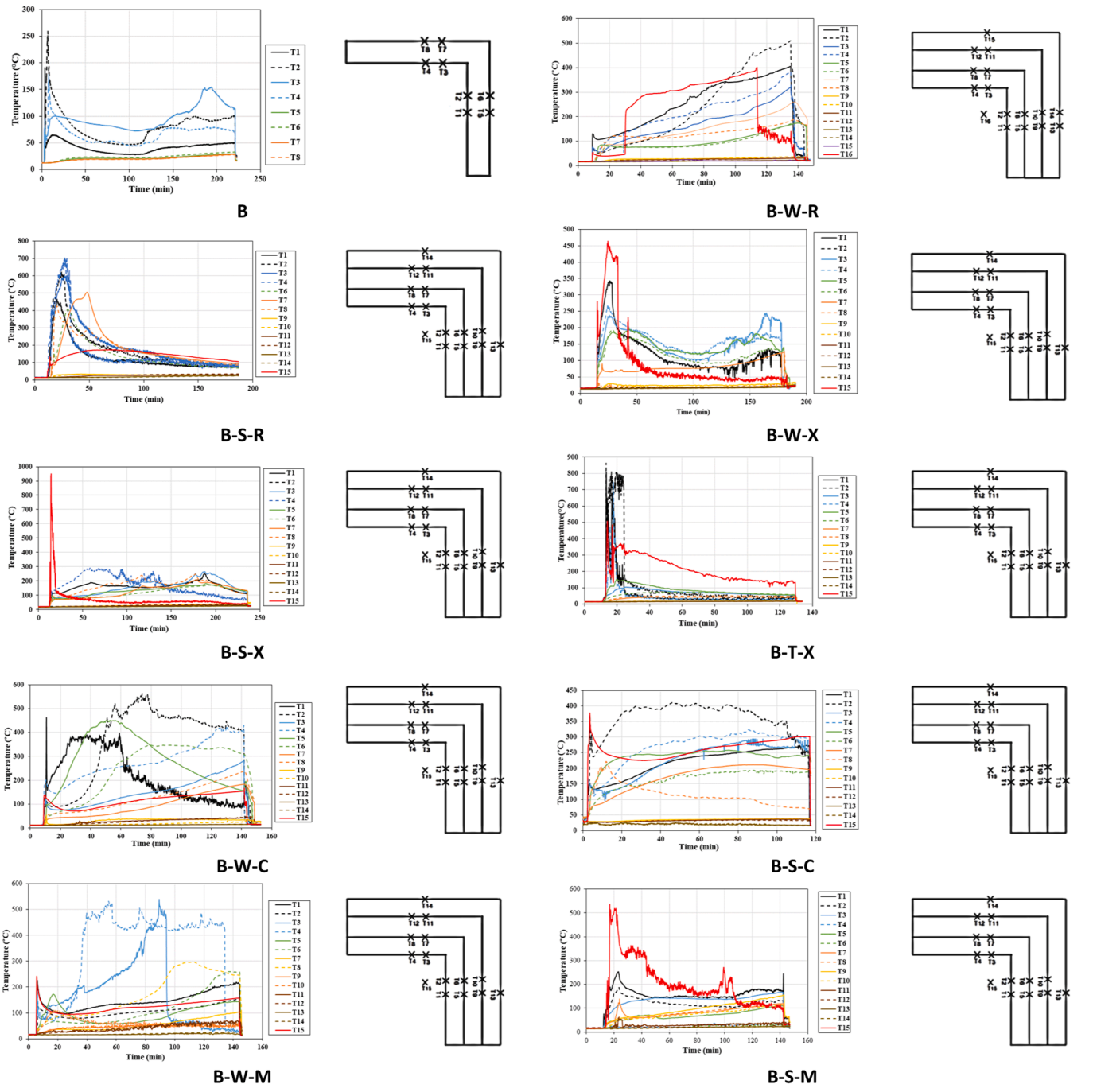


Fig. 6. Temperature vs. time curves of the first group of specimens (brick walls) during the firebrand accumulation tests.

CLT-N-TP specimens exhibited moderate performance during the firebrand accumulation tests due to the application of Tria Paint. This protective coating is a barrier between the flame and combustible materials, such as timber and CLT.

4.2. Heat flux

The heat flux curves for the wall specimens, which recorded temperatures in each layer and performed well during the firebrand accumulation tests, are presented in Fig. 12. These curves were derived based on Fourier's law of heat conduction, which is given by the following equation:

$$q = k(T_{ave}) \times \frac{(T_{outer} - T_{inner})}{d} \quad (1)$$

where q is the heat flux (W/m^2), k is the thermal conductivity of the wall material (W/m·K), T_{outer} and T_{inner} are the temperatures on the outer and inner sides of the wall, respectively, and d is the thickness of the wall (m). The adopted value for the thermal conductivity $k(T_{ave})$ uses the average temperature equivalent to the midpoint layer temperature.

From Fig. 12, the comparison of heat flux in the first layer of each wall specimen shows that Weber mortar exhibited significantly higher heat flux than NW and CLT. This difference is due to the higher thermal conductivity and thinner layer of Weber mortar. In the second layer, cork demonstrated higher heat flux than rockwool in several instances, except in the CLT-S-R specimen, which experienced uncontrolled combustion in the wood layer. This result is attributed to cork's thinner layer compared to rockwool and aligns well with the findings of Arruda et al. [20]. In the third layer, the brick specimen exhibited higher heat flux

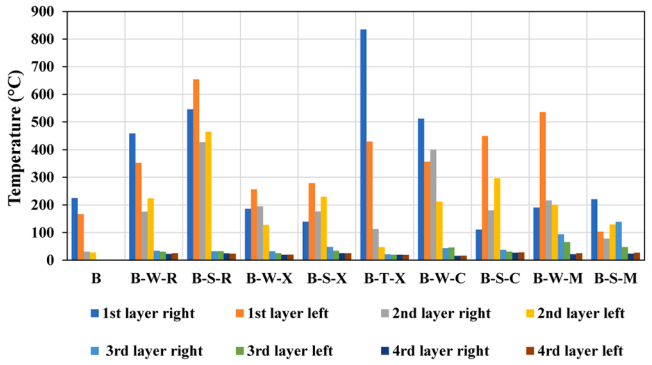


Fig. 7. Average maximum temperature in layers of each specimen of the first group (brick walls).

than both NW and CLT, except the CLT-S-R specimen, which was exposed to uncontrolled combustion. This elevated heat flux in the brick layer is due to its higher thermal conductivity.

4.3. Observed fire reaction and ignition

The reactions of the wall specimens against firebrand accumulation were monitored, and several findings were obtained. Figs. 13–15 show situational pictures of the components in each wall specimen following testing.

In the first group specimens (Brick walls), as shown in Fig. 13, the reference wall specimen with only bricks was not greatly affected by firebrand accumulation, as there was no ignition, smoke, or droplet production. This was expected since the reaction to fire for standard brick is A1; therefore, it is not expected that the firebrand thermal flux will produce any thermal damage.

Notably, the mortars in all specimens did not ignite against firebrand accumulation, with no smoke or droplet production, because they were primarily composed of non-combustible substances. However, some cracking can be observed on the mortars due to thermal stress. Regarding the thermal insulation reaction during the firebrand accumulation tests, the rockwool and cork in the specimen with Sika mortar experienced smouldering ignition accompanied by significant smoke production, whereas the rockwool and cork in the specimens with Weber mortar exhibited only low-impact smouldering with minimal smoke production. The XPS insulation in specimens B-W-X, B-S-X, and B-T-X melted and evaporated at low temperatures across all three specimens, with the B-T-X specimen containing Tria Mortar, showing less severe degradation. The impermeable membranes in specimens B-W-M and B-S-M underwent smouldering ignition.

In the second group of specimens (NW specimen), based on Fig. 14

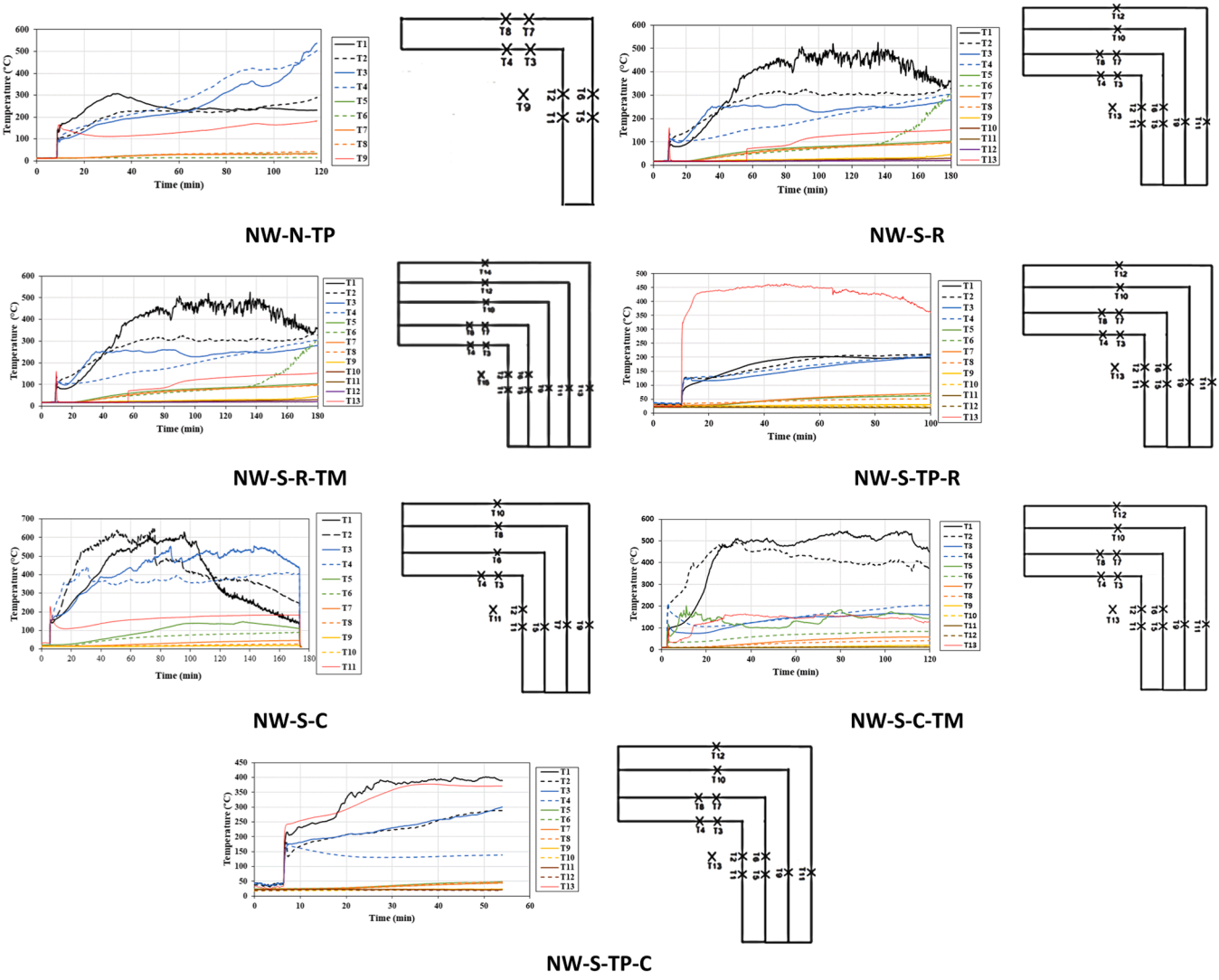


Fig. 8. Temperature vs. time curves of the second group of specimens (timber walls) during the firebrand accumulation tests.

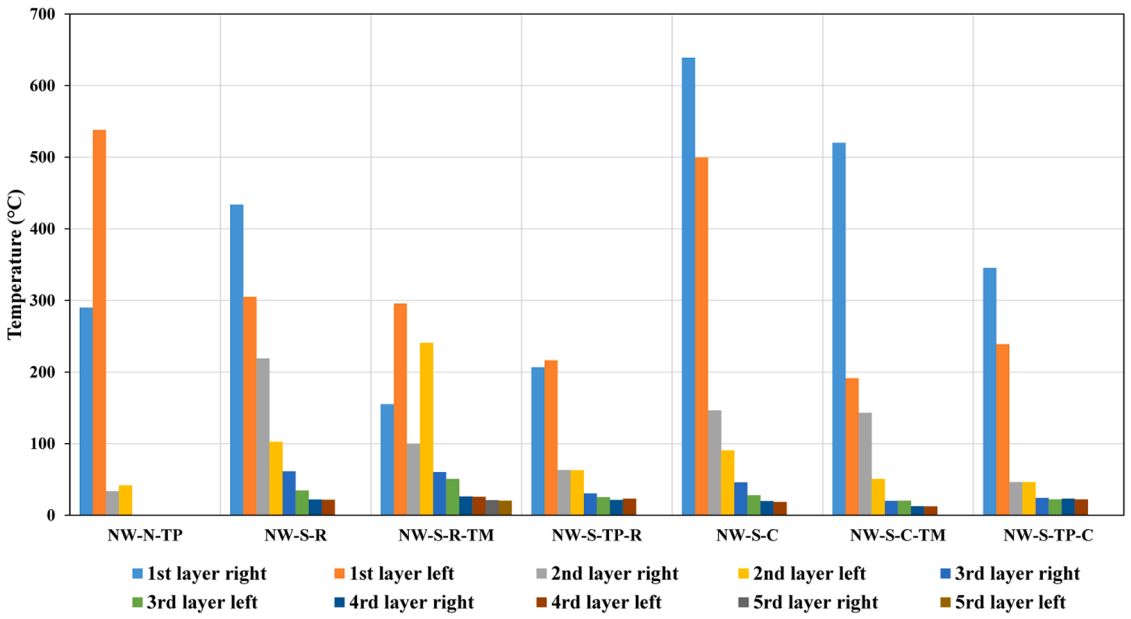


Fig. 9. Average maximum temperature in layers of each specimen of the second group (timber walls).

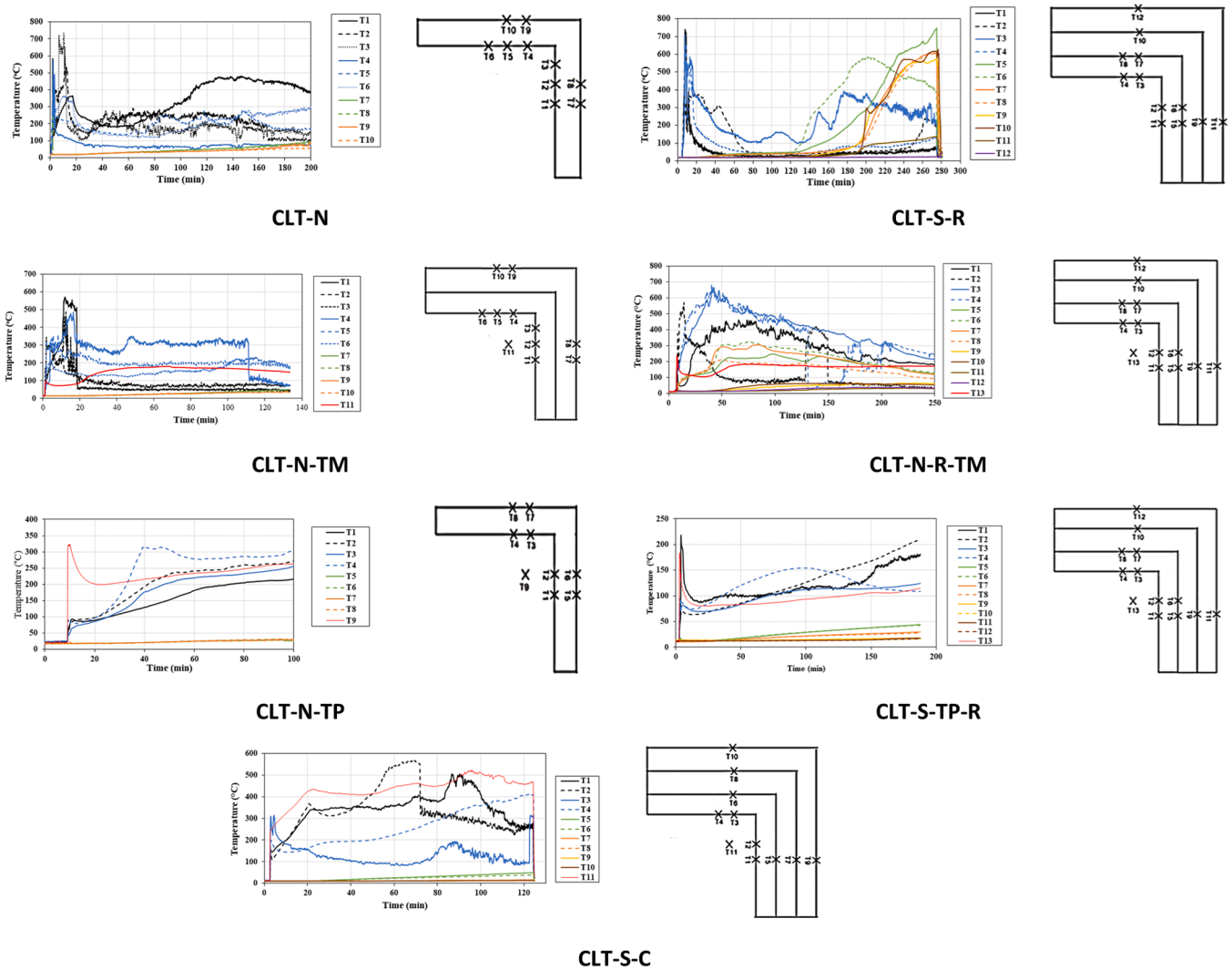


Fig. 10. Temperature vs. time curves of the third group of specimens (CLT walls) during the firebrand accumulation tests.

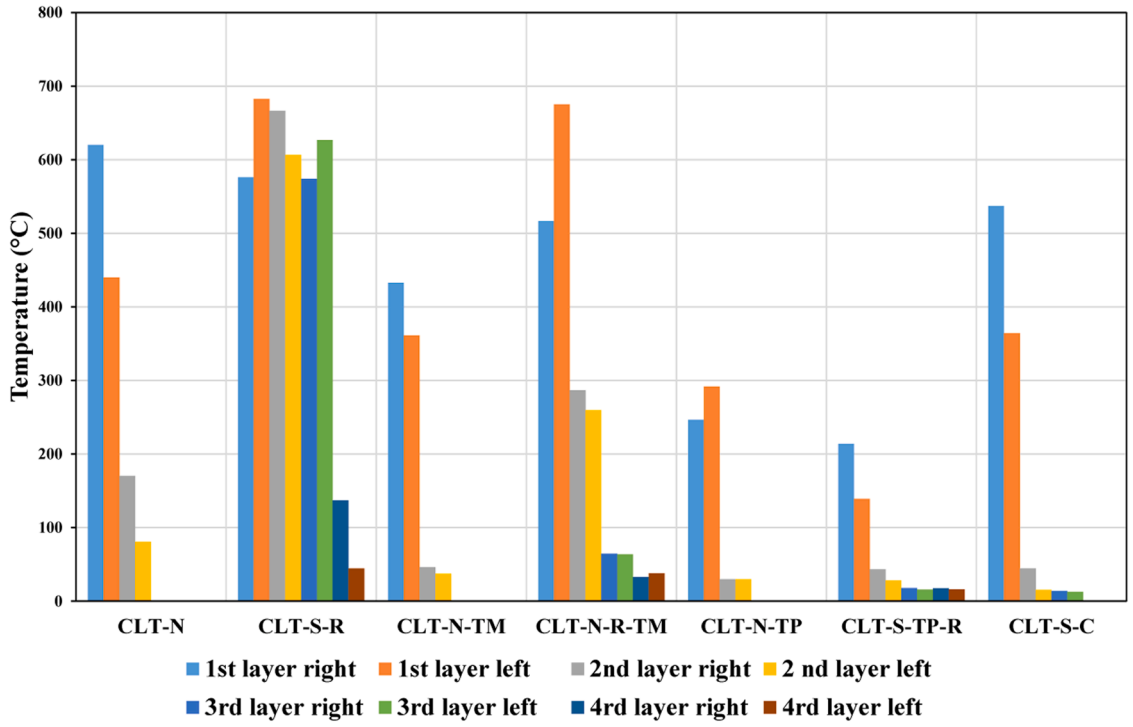


Fig. 11. Average maximum temperature in layers of each specimen of the third group (CLT walls).

and observations from the firebrand accumulation tests, it is evident that the specimens NW-S-R and NW-S-C, containing unprotected NW, were clearly exposed to flame ignition, resulting in significant droplets and smoke production in a short period on the exposed surface. The specimens containing Tria paint NW-N-TP, NW-S-TP-R, and NW-S-TP-C experienced smouldering ignition with minimal droplet and smoke production on the exposed surface. In contrast, the specimens NW-S-R-TM and NW-S-C-TM, containing Tria mortar, did not ignite on the exposed surface, except for some cracks observed at the bottom of the NW-S-C-TM specimen. Regarding the thermal insulation reaction during the firebrand accumulation test, it was observed that the rockwool in specimen NW-S-R underwent smouldering ignition, followed by small smoke production. In specimens NW-S-R-TM and NW-S-TP-R, no ignition was observed in the rockwool. No ignition was recorded for the corks used as insulation materials in the NW-S-C, NW-S-C-TM, and NW-S-TP-C specimens.

For the performance of the third group specimens (CLT walls) against firebrand accumulation, as shown in Fig. 15, unprotected CLT specimens NW-S-R and NW-S-C exhibited rapid flame ignition and droplet formation accompanied by smoke production on the exposed surface. Conversely, CLT specimens treated with Tria paint CLT-N-TP and CLT-S-TP-R displayed smouldering ignition and droplet formation with smoke generation on the exposed face. CLT specimens protected with Tria mortar (CLT-N-TM and CLT-N-R-TM) experienced localized spalling after the tests. For thermal insulation, the rockwool in specimen CLT-N-R exhibited smouldering ignition and subsequent smoke production during the firebrand accumulation test. Conversely, the rockwool in specimens CLT-N-R-TM and CLT-S-TP-R remained unaffected by ignition. Additionally, no ignition was observed in the cork in the CLT-S-C specimen.

4.4. Firebrand heat penetration in the layers

The effect of heat penetration due to firebrand accumulation on wall specimens was evaluated by analyzing the traces remaining in each layer. For the first group of specimens, as illustrated in Fig. 13, the extent of heat penetration varies with the type of mortar and fire insulation employed. Specifically, the heat reached the thermal insulation in all specimens. Notably, specimens containing Weber Mortar demonstrated less widespread heat penetration than those with Sika Mortar. However, exceptions were observed in specimens with XPS thermal insulation, whereas those with Tria mortar exhibited less widespread heat penetration. Additionally, the impact of thermal insulation was significant: heat penetrated more deeply into the specimens containing XPS, even reaching the brick wall layer, as indicated by the surface mortar of the brick in specimen B-W-X (see Fig. 16). Importantly, in all the brick specimens, heat did not penetrate the final layer.

In the second group of specimens, as depicted in Fig. 14, specimen NW-S-R allowed substantial heat penetration, resulting in a significant spread on the surface of NW and into the Rockwool. The specimens containing Tria paint exhibited reduced heat penetration, with heat not reaching the thermal insulation, and only a minimal effect was observed on the NW surface after the Tria paint was removed. Similarly, the specimens with Tria mortar did not allow heat to reach the thermal insulation, showing only minimal surface effects. For specimen NW-S-C, significant heat impact on NW was evident, but the cork remained unaffected, with less heat penetration in the interior layer of the wood for the sandwich specimen.

For the third group of specimens, as shown in Fig. 15, substantial heat penetration and spread were observed in CLT for unprotected specimens, with a notable effect on the Rockwool in specimen CLT-S-R. In contrast, the cork in specimen CLT-S-C was not affected, with almost no heat penetration observed in the interior wood layer in this last solution when using cork as insulation. The specimens containing Tria paint exhibited only minimal heat penetration, which did not reach the Rockwool in specimen CLT-S-TP-R. Likewise, the specimens with Tria mortar showed minimal heat penetration and did not impact the Rockwool insulation in specimen CLT-N-R-TM.

5. Conclusions

In this work, the thermal effect due to firebrand accumulation in external walls was studied via a combination of insulation materials, with an assembly process present in the classical European ETICS

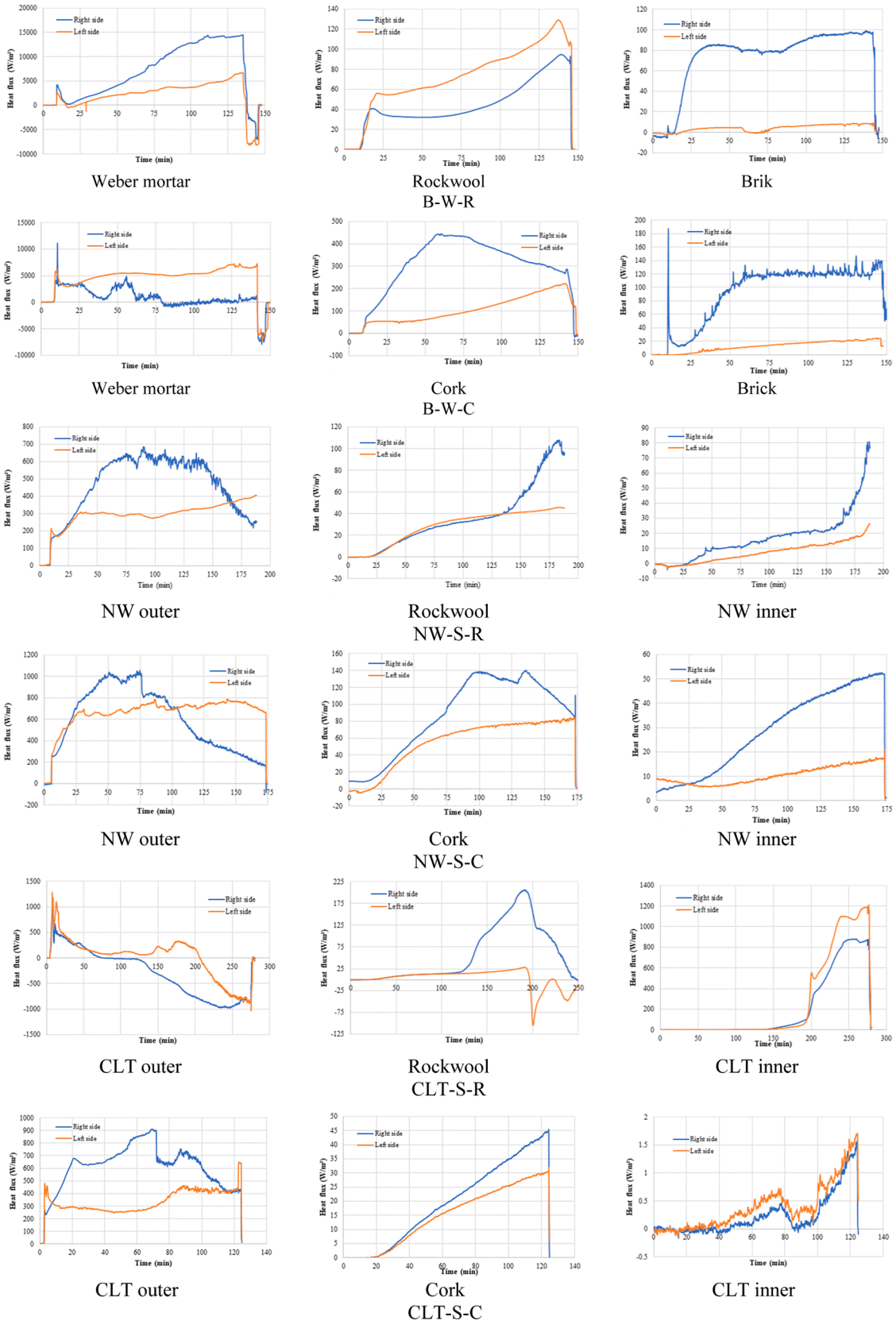


Fig. 12. Heat flux curves for each layer in the wall specimens.

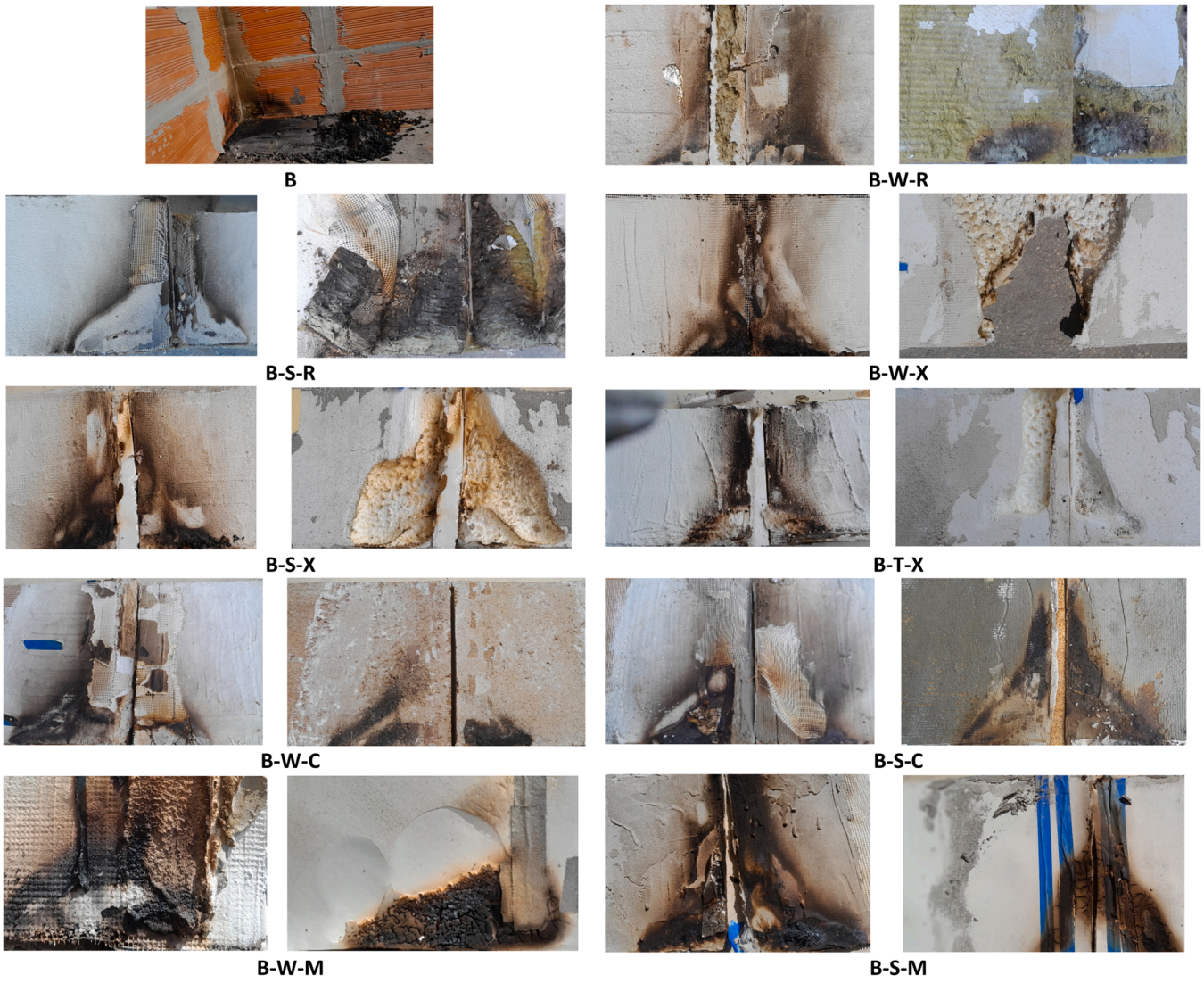


Fig. 13. Effects of firebrand accumulation on heat penetration within the first group specimens (brick wall).

standards. Three different core layer elements were used for the wall, in which these were subjected to high temperatures that were recorded via thermocouples data.

For the wood wall base specimens, it was possible to conclude that:

- As expected, these performed poorly due to being flammable, although the CLT presented a higher temperature in some thermocouples of the inner layers.
- Tria mortar was able to prevent high flammability, although some smouldering still occurred, and damage was transmitted to the thermal insulation material.
- With the Tria coating, no flame occurred, and small smouldering occurred. No thermal damage was observed in the thermal insulation material.
- For the insulation with the cork composite, some temperature reduction was observed, and no smouldering of the cork was still observed. This was observed for both the normal wood wall and the sandwich model.
- Even in the sandwich model for the wood wall, some smouldering is observed in the rockwool when it is used as a thermal insulation material.
- Compared directly with the brick wall specimens, the heat penetration due to firebrand accumulation was more severe in the wood base wall specimens when using the same thermal insulation.
- All wood specimens without any protection for the exterior surface presented interior temperatures above 70 °C, meaning that even if they did not experience flame ignition, they were not admissible as materials for shelter against wildfires.

These findings indicate that the best protection for a wood base wall is either a coating or fireproof painting. This 1st solution is expensive and non-pleasing in terms of aesthetics since it covers the wood. The 2nd solution is more aesthetic since when dry, it becomes transparent, but it is still very expensive. Additionally, both solutions may still need some repair because of the small amount of damage observed during the post wildfire event.

Even solutions with rockwool present some thermal damage due to smouldering in the interior insulation. This type of smouldering damage was prevented only in the insulation material if cork was used. In any case, all exterior surfaces without protection for the wood wall base specimens observed either flame or smouldering ignition due to firebrand accumulation, which may compromise the shelter possibility of a dwelling when it is hit by a wildfire.

For the brick wall specimens, it was possible to conclude that:

- In general, the heat penetration that caused thermal damage in the insulation material was smaller when compared with the wood-based wall specimens. This was not true only when XPS was used.

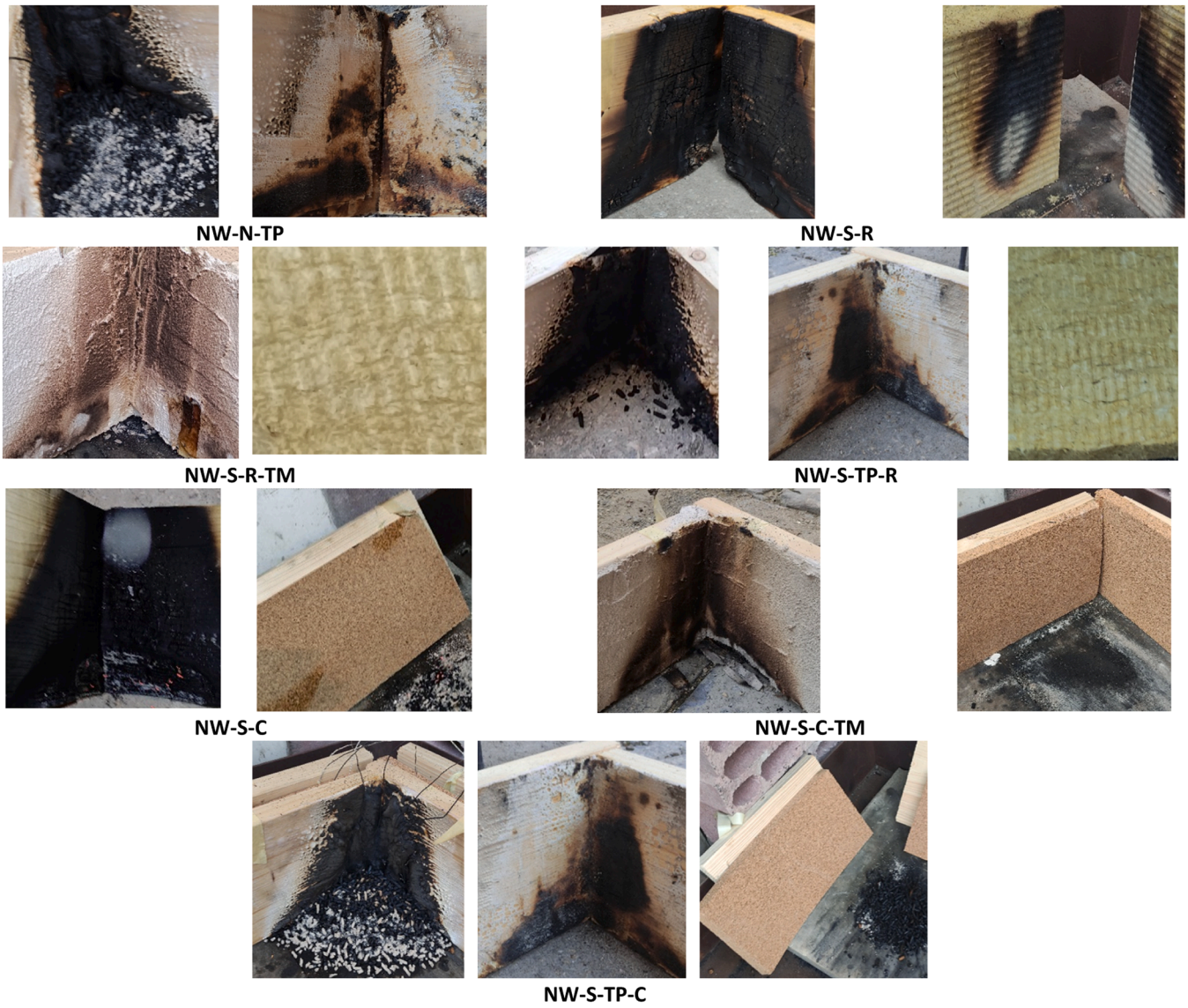


Fig. 14. Effects of firebrand accumulation on heat penetration within the second group specimens (timber wall).

- When XPS was used as thermal insulation, all tests presented extensive thermal damage due to heat penetration, even with the Tria coating. This was due to the low allowed service temperature of 75 °C.
- Similar to the case for the wood specimens, when cork was used as an insulation material, less thermal damage occurred, with almost no observable smouldering.
- Although the impermeable membrane exhibited smouldering ignition, it performed well overall, except for its limited effect in reducing temperature due to its minimal thickness.
- Tria mortar presented the best thermal performance when compared with standard mortars in terms of measured interior temperature and thermal damage in the insulation material due to heat penetration.
- For all the brick wall test solutions, the interior measured temperature was <30 °C.

These results are in accordance with previous research [20,42], in which the use of materials such as EPS and XPS as external insulation may be compromised for high temperatures. Therefore, using these as insulators in ETICs systems should be avoided and cannot be admitted to a dwelling with a function of shelter during wildfires.

When comparing cork and rockwool as external insulators, the former presented lower thermal damage. Importantly, both methods presented significant fire resilience against firebrand accumulation and heat penetration, indicating that they are recommended for use in shelters against wildfires.

5.1. Limitations of the study

This work investigated a concave exterior wall, which may be more severe than a classical plane wall surface when it is in contact with firebrand accumulation. The adopted firebrand accumulation is according to the needs of California Building Code Chapter 7A-4, which may also be more severe than classical firebrand deposition using an ember generator. It does not take into account extra elements in walls, such as windows, doors, and air vents, which may change the outcome of the general results.

5.2. Future developments

New wall geometries using a double brick layer are expected to be tested and presented to the scientific community. Additionally, new

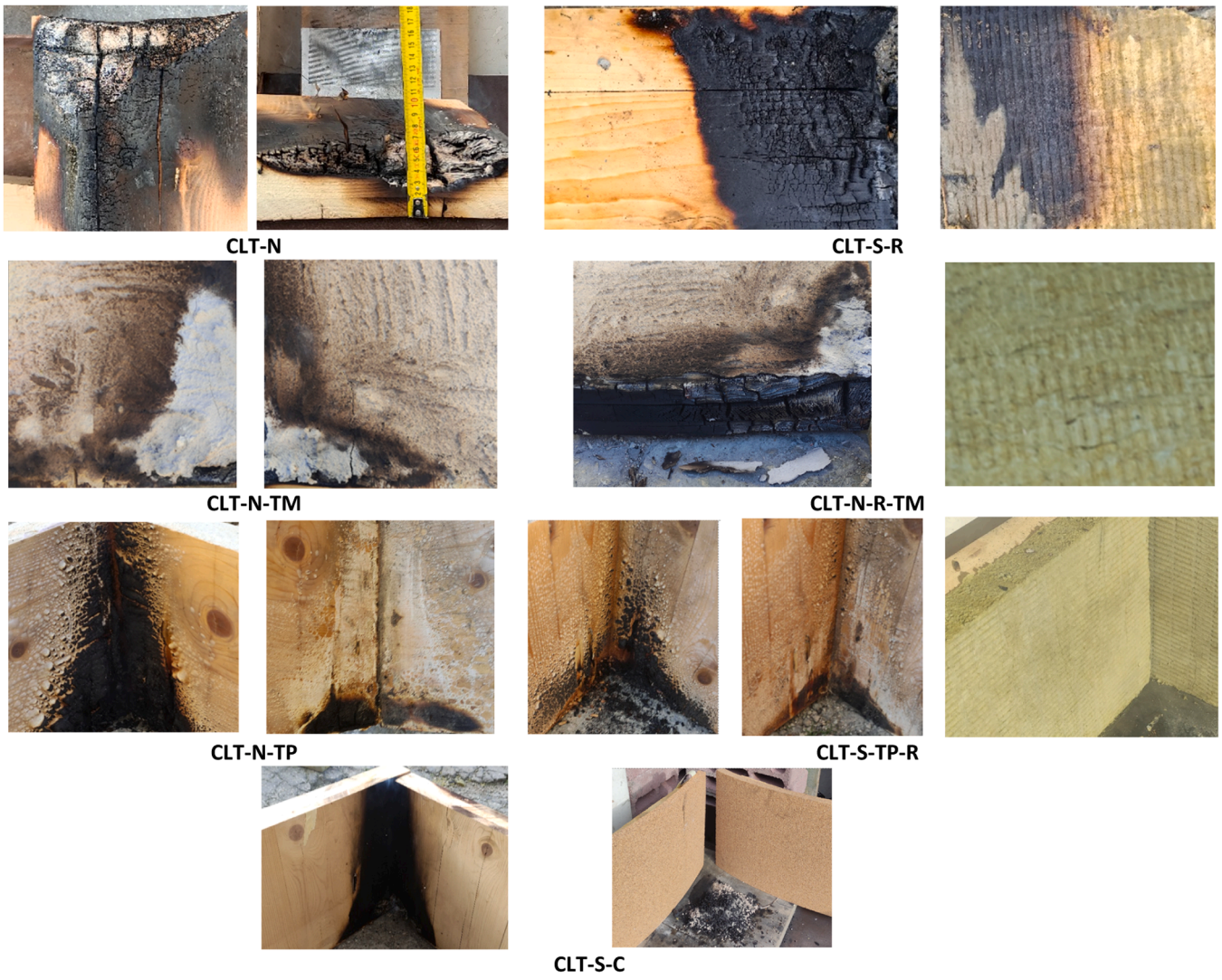


Fig. 15. Effects of firebrand accumulation on heat penetration within the third group specimens (CLT wall).



Fig. 16. Heat spread in the mortar of the brick in specimen B-W-X.

materials for the main layer, such as concrete blocks and cellular concrete, can also be tested for firebrand accumulation. Reaction protective solutions for external walls using external protective elements can also undergo testing for firebrand accumulation. It is also planned a similar fire experimental campaign for classical ceramic roofs, with different insulation layers.

Ethics statements

Not applicable because this work does not involve the use of animal or human subjects.

CRediT authorship contribution statement

M. Zitouni: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **M.R.T. Arruda:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **P. Cantor:** Resources, Methodology, Investigation, Formal analysis, Data curation. **F. Branco:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the Foundation for Science and Technology (FCT), Portugal, for the Project "New Fireproof Dwellings for Wildfire PTDC/ECI-CON/2240/2020″ (DOI: 10.54499/PTDC/ECI-CON/2240/2020). The authors are also grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS (DOI: 10.54499/UIDB/04625/

2020). The authors would also like to acknowledge FCT for the financing of the doctoral grants SFRH/BD/03935/2023 (DOI: 10.54499/2023.03935.BD) and SFRH/BD/04011/2023 (DOI: 10.54499/2023.04011.BD).

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