fire

Article

Enhancing Fire Safety: Real-Scale Experimental Analysis of External Thermal Insulation Composite System Façades' Behavior in Fire

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Abstract: In the unfortunate event of a fire, within the context of the evolution of façade fires, with a specific focus on the utilization of polystyrene thermal insulation (external thermal insulation composite system façades—ETICS façades), this study delves into the investigation of fires ignited by containers containing plastic bottles. Through an examination of the fluctuating temperatures within the affected room and its adjacent areas, as well as an assessment of the fire's impact on polystyrene thermal insulation, this paper underscores the significance of incorporating non-combustible barriers into the building's thermal insulation system. The tests conducted revealed that the temperature inside the room reached a maximum of 1100 °C, subsequently decreasing to 800 °C at a height of 2.5 m and approximately 400 °C at a height of 5 m. For this research, two 1100-L containers of household waste were employed, each weighing 45.5 kg and possessing a gross calorific value of 46.97 MJ/kg, with 10.7 kg of PET bottles inside, characterized by a higher calorific value of 23.90 MJ/kg as the source of the fire. Heat release rate highest values were obtained between 11 and 17 min, with a maximum value of 4919 kW. Thus, even in the absence of specific legislation, this study emphasizes the imperative need to establish safety distances for the storage of household waste away from the building's façade to mitigate the risk of fire propagation, particularly in relation to materials such as polystyrene thermal insulation. Furthermore, in certain situations, extensive fire experiments on a grand scale, like the one undertaken in this research, hold a crucial position in confirming numerical findings for global researchers. This process assures the reliability and real-world usefulness of fire safety studies through the experimental outcomes presented in this investigation.

Keywords: exterior fire; ETICS façades; building façades; fire barriers; experimental measurements; heat release rate

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1. Introduction

Fire safety has been and will continue to be a top priority for all parties involved in the building industry, whether we are talking about controlled or uncontrolled burning. Researchers are making significant efforts to comprehend the complexities of the phenomena, and for this goal, both experimental data and numerical modeling can be used. Because real-scale testing is a destructive phenomenon, it is extremely difficult to replicate most of the time. For this reason, modeling in various software using Pyrosim/Fire Dynamic Simulator, Ansys, or others [1,2], has gained an increased popularity recently, because the results are realistic and provide an extremely close picture of the evolution of the combustion and all the parameters involved.

In the assessment of uncontrolled fire-type combustion, the primary objectives encompass a range of critical issues. These objectives revolve around understanding how construction materials react when exposed to flames, the duration over which fire propagates across their surfaces, and the time required for the complete consumption of available material. While experiments on a smaller scale are feasible and practical, the landscape changes dramatically when considering fires occurring within larger structures such as garages, expansive buildings, or warehouses. In such instances, conducting experimental trials becomes prohibitively expensive due to their destructive nature. Consequently, the most viable option entails the utilization of process modeling within specialized computer software.

Nevertheless, in specific circumstances, larger-scale fires like the one conducted in this present study become indispensable for obtaining experimental results that can subsequently serve as critical benchmarks for validating numerical outcomes. These full-scale fire experiments provide the foundational authenticity required to substantiate the findings of computational simulations, lending substantial credibility to such studies. The extensive data garnered from these comprehensive fire tests not only enhance the reliability of numerical models but also lay the groundwork for advancing fire safety research and ensuring the effectiveness of safety measures in practical, real-world scenarios.

Full-scale experiments concerning the behavior of external thermal insulation composite systems (ETICS) during exterior building-generated fires are exceedingly rare on an international scale (distinct from experiments based on compartment fire scenarios). Furthermore, there are currently no national or international real-scale testing methods available for this type of fire scenario. On the other hand, there is a virtually limitless array of fire scenarios originating from the exterior of a building that can be subjects of research and are plausible. After reviewing the specialized literature, we have not encountered an experimental test of similar scale, based on the scenario of igniting a ground-floor room of a building from two trash containers, as well as assessing the fire propagation originating from these two containers into the interior and, subsequently, onto the combustible façade of the building.

Throughout the world, there are various approaches and methods for assessing the fire performance of external cladding elements. These approaches range from full-scale tests, technical requirements, and certification rules, to specific standards and national regulations. Currently, we aim to highlight some of these methods and standards used in different countries to evaluate the behavior of materials and external cladding systems in case of fire. Through this analysis, we will emphasize the significant variations in addressing this crucial aspect of building safety and performance.

In the United Kingdom, requirements for the fire performance of external cladding elements are closely tied to the property limits of buildings and their height regime. Based on the results of full-scale tests described in the technical specification BS 8414-1/2 [3,4], the use of thermally insulated systems with fire-resistant polystyrene is permitted without restrictions. In France, technical instruction IT 249 [5] imposes a series of construction provisions for thermal rehabilitation solutions. There is also a full-scale testing method known as LEPIR II, used solely for research and development. Croatia has adopted testing methods described in the BS 8414-1/2 [3,4] standards used in the United Kingdom. These methods simulate the scenario of exposure to a compartment fire and exposure to flames originating from the window opening located at the base of the wall. In Germany, a certification system called Ü-mark, mandated by national regulations (in parallel with European product classification standards based on fire reaction tests), is used. The DIN E 4102-20 testing method [6] is also employed to evaluate the performance of external cladding systems in a compartment fire situation. This testing method is similar to the one described in BS 8414 [3,4]. Sweden is the only country among the Nordic countries that requires full-scale testing of external cladding elements for buildings with more than three levels (testing standard SP Fire 105 [7]) The fire source is created using a gas burner.

In Hungary, a full-scale testing method, MSZ 14800-6 [8], is used for external cladding systems.

The testing method for external cladding elements in Japan is similar to laboratory tests conducted in the United Kingdom [9]. China uses the GB/T 29416 testing method [10] to determine the fire performance of external cladding elements, which is similar in dimensions and measurements to BS 8414-1/2 [3,4]. The fire source can be created using wood piles or gas burners.

There is a significant interest in fires involving dumpster containers that have an impact on buildings. This has led to the development of European guidelines for establishing safety distances between buildings and dumpster containers [11]. The NFPA has created the EFFECT^{TM} software (External Façade Fire Evaluation And Comparison Tool) [12], which includes scenarios involving fires originating from trash containers [13]. Importantly, it is worth noting that the frequency of such fires is particularly high in cases of deliberate arson [14]. We can see that this fire scenario is relevant and highly plausible. Furthermore, according to a report by firefighters in Bucharest, the façade of a residential building was completely consumed by a fire that originated from combustible waste placed near the building and ignited by a cigarette butt [15], and in recent years, other similar incidents were documented where the façades of buildings caught fire [16].

The most severe façade fire (resulting in six casualties) that originated from dumpster containers occurred at a hostel in France in 2010 [17]. According to German fire statistics spanning from 2001 to 2017 [18], the majority of façade fires (involving ETICS with EPS insulation) were traced back to dumpster containers (approximately 35%). Consequently, German construction authorities opted to conduct tests simulating façade ignition from external sources, emulating dumpster containers, and using wood as the primary fuel source (200 kg wood crib) [19].

The study detailed in reference [20] focuses on incidents of fires in school buildings within the context of Sweden. The primary ignition factor in these cases is arson, encompassing intentional burning of dry vegetation, refuse, or other flammable materials near the building's exterior. Notably, the most severe fires tend to initiate externally, typically originating near the building's façade, and then spreading upwards through the façade itself and infiltrating the attic via ventilation openings. Another study [21] discusses a façade fire in Dijon, France, during which the external thermal insulation composite system (ETICS) caught fire, resulting in seven fatalities and 130 injuries due to toxic smoke. The fire originated from waste containers located adjacent to the building's façade. In 2015 on the Rue Richard Coudenhove-Kalergi in Kirchberg, Luxembourg, two garbage containers near the side wall of a building on the site were on fire. The flames extended to the façade, causing significant material damage. The heat severely damaged the windows [22].

Within the realm of construction, real-world experiments often center on specific segments of abandoned structures, purpose-built components designed exclusively for testing, or even the fire testing of materials intended for use in the construction of buildings. This encompasses a wide spectrum, ranging from façade systems to interior coverings, all of which require meticulous examination to ensure safety and efficacy in the face of potential fire hazards.

The various support systems, including curtain walls, that are required to maintain the façades' systems' integrity, were discussed by Lugaresi et al. [23]. The mechanical and thermal qualities that influence the failure of noncombustible components, such as stone, concrete, metal, and glass panels, as well as the behavior of common connections, was investigated. An investigation of relevant scenarios for building façade fire inspections conducted by Li et al. [24] highlighted that the heat flux and temperature profile in the plume rise roughly linearly in proportion to the outdoor fire heat release rate (HRR).

In addition to the elements related to the building's structure and the thermal insulation system used, external parameters such as temperature, solar radiation intensity, and wind speed also have a very important contribution to the production and spread of fire on the façade. Abu-Zidan et al. [25] approached the impact of the velocity and direction of the wind on the spread of a façade fire in an independent square building. External wind has been observed to stave off the initial development of façade fires, but it can dramatically worsen fire spread once the fire has fully ignited.

Schabowicz et al. [26] targeted the ascertainment of intrinsic changes in the microstructure of fiber-cement boards following fire exposure. In order to evaluate the microstructure, the degraded samples were compared to reference samples. A scanning electron microscope was used to analyze images of backscattered electrons and maps acquired using energy dispersive X-ray spectroscopy allowing conclusions to be derived. In [27], the authors experimentally approached a façade structure that is more and more common, namely, the ventilated façade, from the point of view of fire safety. One of the main conclusions was that the standards for the falling-off of elements from vented façades during a fire are not properly defined due to a lack of clearly set requirements and testing. This has a substantial impact on the safety of evacuation during a fire emergency. Experiments were conducted on a large-scale façade model with two types of external-façade cladding for the objectives of this article. The installation of different kinds of mechanical protection to keep external cladding elements in place increases the degree of protection but does not totally remove the problem of parts of the façade sliding off.

Nonetheless, the vast majority of the study conducted includes the use of computer process modeling tools [28–30], theoretical methods for façade systems' evaluation based on existing criteria in different states [31–33] and small-scale models, like in the case of Zhang or Zhou experiments [34,35]. While the results obtained are significant, the need for real-scale experiments is emphasized once more. Real-scale tests are difficult to carry out as they are of a destructive type and involve either the use of an old disused building or an actual construction of a small building whose façade system is to be investigated in terms of reaction to fire in different scenarios. Hajdukovic et al. [36] made experimental studies targeting the external thermal insulation composite system (ETICS) façades with expanded polystyrene (EPS) insulation fire performance on a large-scale experimental stand. Fire tests on two large-scale façades, without fire barriers, were conducted to investigate the incident heat flux upon the façade's surface and structural damage.

Currently, legislation at the European Union and, in particular, in Romania must be updated to meet new market demands in order to increase the safety of residents of buildings with ETICS façades. The future trend is to use non-combustible insulating materials such as mineral wool, which is currently only used to create non-combustible barriers between different levels of buildings.

In national norms, in order to prevent the spread of flames on the façades that used only board-type polystyrene as an insulating system, non-combustible barriers such as mineral wool are recommended; this solution was also used in the experimental stand. In Romania, only fire protection barriers with a height of 0.30 m are applied near the floors or the windows of the enclosures on all exterior sides with non-combustible materials on structures with a height of up to 28 m. These guidelines are not legally enforceable and are outlined in the paper "Framework solutions for the thermal-hygro-energetic rehabilitation of the envelope of existing residential buildings", Indicative SC 007-2013 [37].

Across the globe, there exists a diverse array of full-scale façade tests, and these have been the subject of scrutiny in the preparation of this report. It is worth noting that these tests exhibit significant variation in terms of their geometry, the nature of the fire source employed, the specific details of specimen support, the extent of exposure severity, and the criteria for acceptance. Research to date has brought to light the observation that the exposure to exterior wall systems generally faces heightened severity when subjected to an internal post-flash-over fire, where flames emerge from windows, as opposed to external fire sources. This distinction is the primary reason behind the fact that the majority of full-scale façade fire tests are designed to simulate an internal post-flash-over fire scenario. However, it is important to recognize that there are situations where external fires, particularly those at ground level involving fuel loads such as back-of-house storage areas or large vehicle fires, can equal or even surpass the severity of internal post-flash-over fires. Consequently, while many of these full-scale façade tests focus on replicating internal post-flash-over fires, they may also establish a performance standard applicable to external fire events [38].

In recent years, fires affecting the façades of buildings, whether they have thermal insulation or not, have received significant attention [39,40]. This increased focus is due to incidents resulting in either loss of human lives or purely material losses [39]. Special consideration has been given to external thermal insulation composite systems (ETICS) façades in experimental [41] and numerical [42] studies.

Annually, in Finland there are approximately 10 incidents involving external ignition [43]. These ignition events encompass various situations, such as deliberate acts of arson targeting waste containers or structures near a building. In the specific building under consideration, the absence of waste containers, shelters, or other potential ignition sources in close proximity, along with strict regulations prohibiting parking adjacent to the façade, mitigates the risk of external ignition. The scenario in which external ignition takes place, other than on a balcony, leading to fire spreading inside the apartments on the first floor and posing a threat to occupants' lives, is quite rare. It typically requires a substantial accumulation of flammable materials to be intentionally ignited in close proximity to the façade, directly beneath the windows on the first floor. In a technical context, the role of the combustible façade in facilitating fire spread during such an incident is akin to situations where external flames emanate from a room with a flashed-over fire. When external ignition occurs, it may result in fire spreading upwards along the façade. However, the hazards to life in this specific fire scenario are relatively low. This is due to the fact that fire propagation along the wooden façade tends to be slow, and it does not significantly impede the safety of building evacuation. This remains true even in extreme cases where evacuation necessitates the assistance of the fire services, potentially involving window escapes. The flames on the façade are typically weak, making them manageable for firefighters to extinguish promptly [43].

The background study on façade fires is indeed a critical aspect of this research. The ever-increasing utilization of combustible insulations with varying thicknesses in façades is a trend that deserves substantial attention. In contemporary building practices, the application of polystyrene thermal insulation, such as external thermal insulation composite system façades (ETICS façades), has become widespread. These insulation materials offer energy efficiency benefits but also introduce new fire safety challenges due to their combustible nature.

The research presented in this paper is motivated by the pressing need to comprehensively investigate the fire risks associated with the use of combustible insulation materials in façades, with a particular focus on polystyrene thermal insulation. By examining the scenario of fires ignited by containers containing plastic bottles, we aimed to shed light on a specific yet plausible fire hazard that can occur near the building's façade.

It is worth emphasizing that as the thickness and combustibility of insulation materials increase, so does the potential for fire propagation and hazards. This study underscores the importance of considering not only the energy efficiency aspects of insulation materials but also their fire performance, especially in real-world scenarios where fires can be initiated externally, as demonstrated in this research.

The purpose of the article is to investigate the behavior of construction materials, particularly the reaction of materials like polystyrene thermal insulation when exposed to flames. It aims to examine key aspects of uncontrolled fire-type combustion, including how materials respond to flame contact, the rate at which fire spreads across their surfaces, and the time it takes for the fire to consume the material completely.

Additionally, the article explores the challenges and limitations of conducting experiments on a larger scale, such as in garages or large buildings, and highlights the importance of using computer modeling when full-scale experimental testing is impractical. In the realm of construction, the article emphasizes the significance of real-world testing, which may involve abandoned structures, purpose-built components, or the examination of materials used in building construction, including façade systems and interior coverings, all with the overarching goal of enhancing fire safety.

This article contributes significantly to the façade fire phenomena evaluation by presenting a real-scale experiment, namely, how a fire evolves as a result of a container that caught fire, on the base of main parameters variation.

2. Materials and Methods

2.1. Materials

The ETICS system was composed of the following components: expanded polystyrene boards, adhesive mortar, plastic dowels, primer, silicone-based decorative plaster, and fiberglass mesh, all these being described below.

Expanded polystyrene boards were of type EPS 80 with an identification code according to SR EN 13163+A1:2015 [44], EPS80+ EN 13163-T1-L2-W1-Sb1-P3-BS150-CS(10)80-DS(N)2-DLT(1)5-TR150-WL(T)3-DS [45]. They had the following characteristics: board dimensions 1000 mm $\times$ 500 mm $\times$ 100 mm, a calculated density of 20.5 kg/m^3, compression strength at 10% deformation CS(10)80 (CS $\geq$ 80 kPa), bending strength BS150 (BS $\geq$ 150 kPa), perpendicular tensile strength TR150 (TR $\geq$ 150 kPa), and a declared thermal conductivity λ_D of 0.038 W/mK. The fire reaction class of the polystyrene in the thermal insulation system was class E.

Adhesive mortar used was a spackling compound for bonding and leveling the expanded polystyrene boards. It exhibited the following characteristics: a density of 1430 kg/m^3, adhesion to polystyrene exceeding 0.08 N/mm^2, bending strength of at least 4.9 N/mm^2, and an estimated consumption of 4.0 kg/m^2 for fixing the polystyrene board (the adhesive mortar was used as a spackling compound for embedding the fiberglass mesh and exterior leveling of the expanded polystyrene boards with a stainless steel trowel).

Plastic dowels were used for the mechanical fastening of the expanded polystyrene boards, which were made of thermoplastic polymers and had dimensions of 10 $\times$ 120 mm. One dowel was installed in each corner of the polystyrene boards, as is common practice.

Primer for synthetic resin-based plaster, filler material, and quartz were used for priming the exterior surface as a base coat before applying decorative plaster, with a density of 1.75 $\pm$ 0.05 g/mL and specific consumption of 1 kg/4.8 m^2/1 coat depending on the surface's porosity and preparation level.

Silicone-based decorative plaster with resin, pigments, and marble granules with the following characteristics was used: density 2.0 $\pm$ 0.1 g/mL, specific consumption of 2.4 kg/m^2, granulation 1.5 mm, non-volatile content 88.5 $\pm$ 1%, and pH 8.5–9.0.

Fiberglass mesh was used for exterior reinforcement of the expanded polystyrene with the following characteristics: specific weight of 160 g/m^2, mesh size: 5 $\times$ 5 mm, and roll width 1 m.

The considered ETICS system was fire tested in the INCERC laboratory in Bucharest, Romania, in accordance with the provisions of the testing method standard SR EN 13823+A1:2014 [46], as seen in Table 1.

The fire reaction classification of the ETICS system was carried out in accordance with SR EN 13501-1+A1/2010 [47] and the product composite external thermal insulation system (ETICS) based on expanded polystyrene and silicone decorative plaster in relation to its reaction to fire, according to smoke emission and according to burning droplets/particles, was classified B-s2 d0.

Table 1. Specific reaction to fire test parameters of the ETICS system.

Evaluated Parameters	Test 1	Test 2	Test 3	Mean Value
FIGRA0.2 MJ [W/s]	94.2	89.2	96.6	93.3
FIGRA0.4 MJ [W/s]	94.2	89.2	96.6	93.3
THR600 s [MJ]	3.3	3.6	3.4	3.5
SMOGRA [m^2/s^2]	7.3	8.8	8.8	8.3
TSP600 s [m^2]	48.1	54.3	51.3	51.2
		Visual observations		
Visual parameters				
Burning drops ≤ 10 s	No	No	No	No
Burning drops >10 s	No	No	No	No
Static fracture limit > specimen edge	No	No	No	No
Intermittent ignition on specimen surface	Yes	Yes	Yes	Yes
Detachment of components from the specimen	Yes	Yes	Yes	Yes
Specimen collapse	No	No	No	No

2.2. Actual Experiment and Method

The experimental test carried out at a large scale, reproduced a fire that started and propagated outside a building enveloped with an ETICS system made of 10 cm thick expanded polystyrene. The experimental stand was built according to BS 8414-1:2020 [3,4,48]. The difference between our analysis and the standard is how the fire started.

Whereas the standard fire started from a stack of wooden materials inside the room, our analysis started from two containers with pets at a very close distance of the building and studied how the fire can spread inside the room and also the effects it has on the façade. The floors of the building are protected on the outside by fire barriers made of mineral wool and the rest of the thermal insulation system consists of cladding with expanded polystyrene plates.

Non-combustible insulation materials, such as basalt mineral wool, play a crucial role in enhancing the fire resistance of buildings while simultaneously improving thermal efficiency. These materials contribute to limiting the spread of fires and create a safe environment for all occupants. Basalt wool barriers, each measuring 100 mm in thickness and 300 mm in width, were strategically placed around the room's perimeter (bordering the window area). Additionally, basalt wool barriers were also installed at the level of the floors above the first and second stories, spanning their entire lengths.

The basalt mineral wool used in the construction of non-combustible barriers underwent fire reaction testing at the INCERC Laboratory in Bucharest, Romania, following the testing methodology outlined in EN ISO 1182:2020 [49]. It received a fire reaction classification according to EN 13501-1:2019 [47] and it falls within the A2 fire reaction class.

The source of the fire was represented by two containers of household waste, each with a capacity of 1100 L and a mass of 45.5 kg (see Figure 1). These containers were made of high-density plastic material with a higher calorific value of 46.97 MJ/kg, as determined using a calorimetric bomb in the laboratory for fire reaction. The dimensions of each container are as follows: length (L) = 1370 mm, width (l) = 1070 mm, and height (h) = 1344 mm. The containers were each filled with 10.7 Kg of PET bottles that have a higher calorific value of 23.90 MJ/kg.


(a)


(b)

Figure 1. (**a**) Fire source; (**b**) placement zone.

The dumpsters had their lids open intentionally to analyze an unfavorable yet plausible scenario. In this way, air could enter, aiding combustion. There are numerous real-world cases where a larger volume of waste is deposited inside the dumpsters than the containers can accommodate, and the lid remains partially open or even fully open, allowing natural ventilation of air into the dumpster in the event of a fire.

The investigation aims to assess not only how the fire interacts with the building's façade, but also how the fire spreads within the interior space. To test the most challenging scenario, the two containers were deliberately positioned next to the glazed surface. The containers were positioned 45 cm from the window and 10 cm from the opposite wing covered with the ETICS system.

One of the containers was placed on top of a 600 kg tare industrial scale with an accuracy of ±0.5%, that had been insulated against fire using ceramic mineral wool. Measuring the real-time mass loss of the container allowed us to determine the time evolution of the heat release rate (HRR) parameter.

Inside the test room, the following were installed: an 8 mm thick HDF laminated parquet was put over the entire floor area, with a carpet placed on top of it. The room also contained a wooden desk, two wooden chairs, and curtains with drapes near the window, to make the fire scenario as realistic as possible (see Figure 2).

Figure 2. Experimental setup—object placement inside the room.

To assess the fire load in the considered room, the weights of the room's furnishings were measured as follows: each chair, 4 kg; the desk, 12 kg; and totaling 20 kg of hardwood. On the floor, there was an 8 mm thick laminate parquet covering an area of 2 square meters, with a layer of expanded polyethylene with a thickness of 3 mm beneath the parquet (covering 2 square meters). Additionally, there were two polyester curtains (5.6 square meters in total at 50 g/square meter) and two opaque polyester drapes (8.4 square meters in total at 300 g/square meter) at the window.

The window frames were constructed from PVC with three casements (one fixed and two casement windows) measuring L = 2000 mm, H = 1400 mm, and featuring a PVC profile with 6 chambers. The weight of the PVC window assembly was 15 kg.

Before performing the test, atmospheric parameters were monitored and they were as follows: temperature 20.1 °C, humidity 39.7%, and wind speed less than 2 m/s.

In the context of temperature measurement in this real fire scenario, we employed K-type thermocouples with a refractory steel sheath and a diameter range spanning from 1.5 to 4.5 mm. These thermocouples can record temperatures within the broad range from 0 to 1200 °C. The choice of thermocouple diameter was made with careful consideration, taking into account the anticipated temperature conditions in the respective measurement zones. This deliberate selection aimed to strike a balance between sensitivity and durability. It is widely recognized that thermocouples with smaller diameters tend to be more sensitive to rapid temperature changes but are generally less robust. On the other hand, thermocouples with larger diameters tend to be more resilient but may exhibit reduced sensitivity to quick fluctuations in temperature. In our specific case, we made use of 4.5 mm diameter thermocouples for the sensors located within the room (Figure 3), as these were well-suited to handle the temperature variations encountered. For the thermocouples placed in the ETICS system's first row, ranging from T1.1 to T1.8 (as illustrated in Figure 4a), we opted for a 3 mm diameter, taking into account the thermal conditions in this particular context. In the second row of the ETICS system, encompassing T2.1 to T2.8 (as shown in Figure 4a), we utilized thermocouples with a 1.5 mm diameter, again aligning our choice with the expected temperature dynamics.

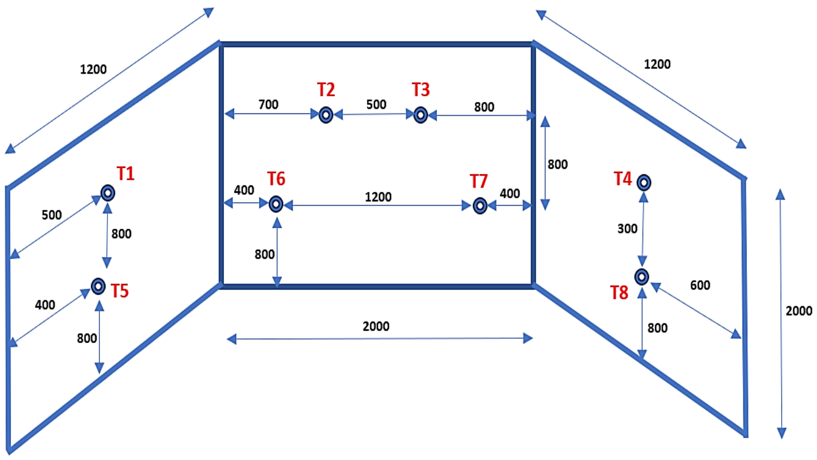
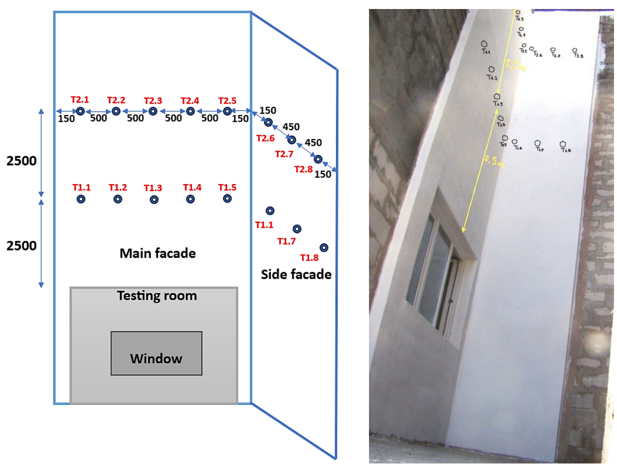


Figure 3. Thermocouples positioning on side walls of testing room (T1–T8 sensors; dimensions in mm) (source: own elaboration).



(**a**) (**b**)

Figure 4. (**a**) Thermocouples positioning on façade (dimensions in mm) (source: own elaboration, inspired by BS 8414) [3,4]; (**b**) photo of the experiment location.

The sensors were positioned according to the standard as follows: 8 were mounted in the walls of the test room presented in Figure 2 as follows: 2 sensors on the left wall, 4 sensors on the back wall, and 2 sensors on the right wall, as presented in Figure 3.

In order to monitor the temperature both in the simulated living room and on the tested building's façade, 24 type K thermocouples with an accuracy of ±0.5 K were installed.

On the exterior wall (see Figure 1), 8 sensors were placed at a height of 2.5 m from it and 8 at a height of 5 m on the façade (Figure 4) [48].

The level of accuracy was selected based on other relevant studies involving combustion processes, where temperatures change rapidly, requiring high-performance measurement sensors [50,51].

Within the INCERC Fire Safety Research and Testing Laboratory [52], an experimental test of a fire generated from the outside of a building was carried out, with the aim of determining the flame propagation mechanisms on a façade made of the ETICS system, under natural ventilation conditions.

The fire scenario was as follows: an external heat load of 4800 MJ and a heat load inside a living room (compartment) of 800 MJ. The heat load density was 1200 MJ/m^2 on the outside and 400 MJ/m^2 on the inside.

Estimating the heat release rate (HRR) from mass loss data is a common practice in fire research. However, it presents several challenges, one of which is dealing with the combustion of three different types of fuels: plastic from the plastic bottles, plastic from the container, and 1 L of diesel fuel. Each of these fuels burns differently, with varying combustion characteristics. In our case, the calorific values ranged from 23.9 MJ/kg (plastic bottles) to 46.97 MJ/kg (container), and diesel fuel had a calorific value of 45.5 MJ/kg. This variability makes generalizing HRR calculations across different fire scenarios challenging. In our study, we assumed that the fuel was uniformly mixed.

Another difficulty is related to the measurement errors of the mass loss during a fire. For this, we used a 600 kg tare industrial scale with an accuracy of ±0.5%.

The test geometry deviates from the British standard BS 8414 [3,4] in terms of the glazed area of the room, which is no longer 2 × 2 = 4 square meters, as specified in the BS 8414 construction details. Instead, it is 2 × 1.4 square meters (the window area). Furthermore, the test area at INCERC Bucharest has a U-shape, as opposed to the L-shape of the fire reaction test stand in the BS 8414 standard [3,4]. This difference arises because, 2.5 m in front of the room (opposite the long wing), there is a reinforced concrete wall (a diaphragm) with a height matching the test stand's height.

All the parameters were meticulously monitored throughout the entire duration of the fire. Following the conclusion of the experimental test, a comprehensive set of observations was conducted to assess the effects of the externally generated fire on a building enveloped with external thermal insulation composite systems (ETICS). This comprehensive monitoring and observation process allowed for a thorough examination of how the fire, originating from an external source, had an impact on a structure protected by ETICS.

The researchers did not aim to replicate the experimental test because the thermal load considered is theoretically unique in its content. While the possibility of such a fire is plausible based on the fire scenarios taken into account during the experimental test, considering all the conditions that underlie the occurrence of such a fire makes it practically impossible to repeat this experimental test. For this reason, as well as due to the relatively high costs involved, researchers have contemplated leaving open the possibility of continuing this research in the future through the use of validation techniques for the experimental test using numerical simulations.

3. Results and Discussions

In order to initiate and sustain the initial combustion, 1 L of diesel fuel was used to saturate the contents of the two containers. The ignition of both sources commenced using a torch.

After the initiation of the sources, for about 5 min, the PET in the containers that had the caps tightened, suffered mechanical explosions. After this period, the fire manifested itself for approximately 2–3 min with reduced intensity inside the containers, maintaining the burning of the melted plastic mass—Figure 5. After the 8th minute, the fire began to develop rapidly and encompassed the entire mass of the containers, so that in the 8:30th minute a generalized fire (similar with a flash-over) of the two containers was reached.

Figure 5. Initial phase followed by the flash-over in minute 8:30.

Within 1 min after the flash-over, the containers' cover gave way under the influence of the fire and began to deform and melt. Because of this, the containers lost their balance and overturned in the direction opposite the camera, as depicted in Figure 6.

Figure 6. Containers start melting after 9:30 min.

By the 9:30 min mark, the fire had not spread inside the room or on the ETICS system. Approximately one minute later (min 10:30), the fire began to affect the PVC profile around the room's window. At 11:30 min from the start of the fire, the burning of the window frame became extensive, leading to the windows breaking. This, in turn, allowed the fire to start spreading inside the room, as depicted in Figure 7.

Figure 7. Fire penetration inside the room, after 14 min.

At 14 min, the fire began to spread inside the room, and by 16 min, the fire entered the regression phase. By 21 min, the fire inside the room had been extinguished, and the fire outside entered the phase of strong regression, as shown in Figure 8. It is worth noting that the ETICS system sporadically ignited on the 1st floor, above the basaltic mineral wool barrier, but the fire did not spread higher.

Figure 8. Fire regression phase, after 16 min.

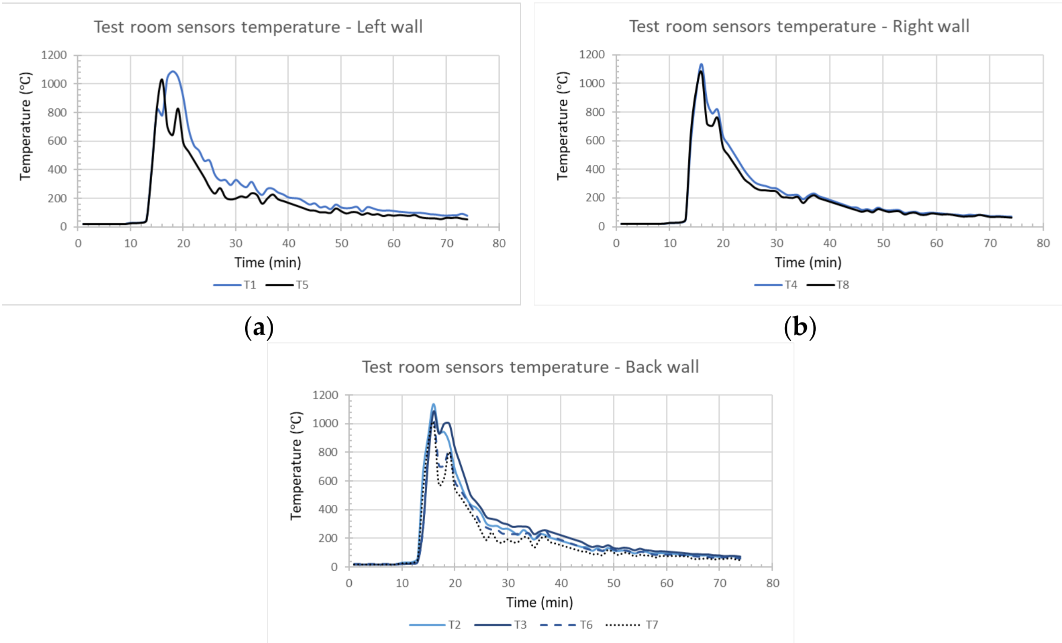
At min 37, the fire generated from the outside of the building was still burning and continued to burn at a reduced intensity until after the 60th minute from the ignition of the fire, when it was completely extinguished.

The ETICS system was completely damaged in the area of direct flame action (the space from the ground level to the first basalt mineral wool barrier placed 2.5 m above the living room) as a result of the fire's action on it. Within 60 min of the fire igniting, the containers and their contents were totally consumed. Basalt mineral wool barriers were resistant to fire and did not detach from the support surface. The materials in the living room were completely consumed by fire. The PVC carpentry window with double glazing had been entirely burned, and the glass that had fallen as a result of the glass breaking had melted. The upper half of the ETICS system was fumigated heavily. Figure 9 shows the fire effect on the room and on the façade, respectively.

(**a**) (**b**)

Figure 9. Fire effect (**a**) in the room and (**b**) on the façade.

In order to monitor the temperature variation in the living room, 8 thermocouples of type K were mounted on the four side walls of the room as stated earlier. The indoor temperature profile for each wall is presented in Figure 10.

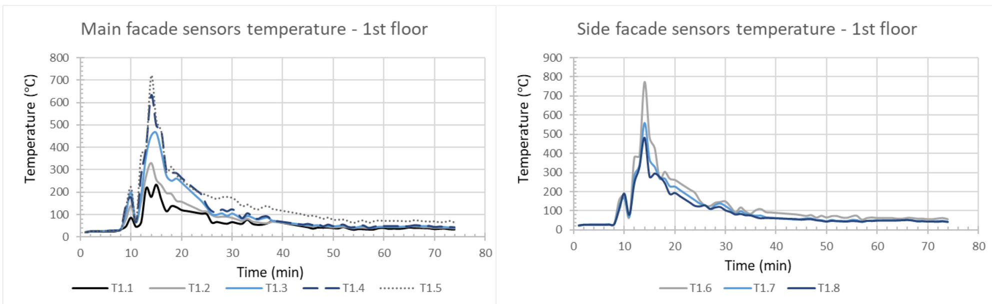


(**a**) (**b**)

(**c**)

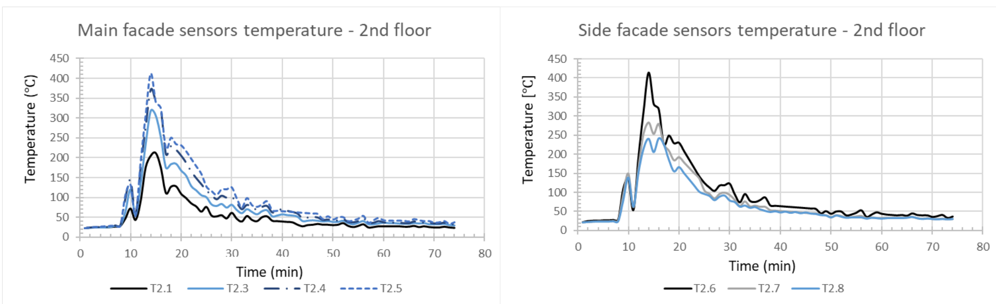
Figure 10. Temperature profile inside the tested room: (**a**) left wall, (**b**) right wall, (**c**) and back wall.

The temperature variation on the façades can be seen in Figure 11 for the thermocouples placed at a height of 2.5 m, and Figure 12 for the thermocouples placed at a height of 5 m above the room.



(**a**) (**b**)

Figure 11. Temperature profile at 2.5 m above the room: (**a**) main façade and (**b**) side façade.



(**a**) (**b**)

Figure 12. Temperature profile at 5 m above the room: (**a**) main façade and (**b**) side façade.

During the fire, the temperature reached a maximum value of approximately 1100 °C in the 19th minute, and this maximum temperature was sustained for a brief period (2–3 min) after which the graphic variation highlights the regression of the fire until it was extinguished.

The maximum temperature values inside the room and at the height of the façade were recorded starting from the 31st minute, following the sudden ignition of materials throughout the room (flash-over). These values were 1140 degrees Celsius inside the room, 772 degrees Celsius at 2.5 m above the room, and 414 degrees Celsius at 5.0 m above the room.

In terms of the façade's response to the thermal effects of the fire, temperatures were monitored at a height of 2.5 m above the living room and also at a height of 5 m. In each case, 8 thermocouples were used, as shown in Figure 4.

As indicated in the graphs presented in Figures 11 and 12, as the distance from the room increases, the temperature values decrease, reaching a maximum of approximately 800 °C at a height of 2.5 m facing the room and approximately 400 °C at 5 m above the living room.

Another important aspect monitored during the experiment was the heat flux released by the burning containers (HRR). This was determined based on the containers' mass loss and their heat load, as shown in Figure 13. As expected, at moments when the transferred heat flow reached its peak values, particularly during the flash-over phenomenon, the temperatures recorded by the sensors also reached their maximum values.

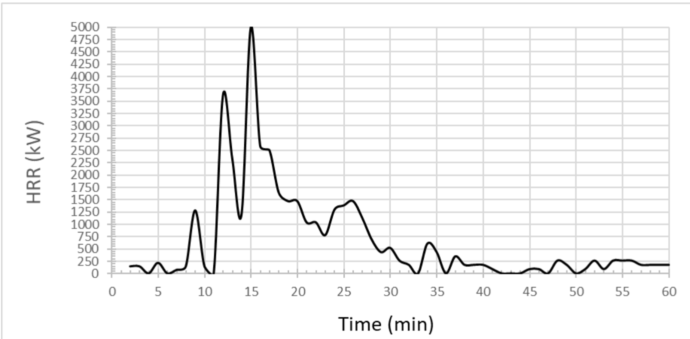


Figure 13. Heat release rate during fire for one container.

The maximum HRR values for a single container were recorded between the 11th and 17th minutes, reaching a peak value of 4919 kW.

Determining these values and graphically representing them is a valuable tool, as when this experiment is translated into computer modeling software, one of the input data is the variation of HRR. Understanding how the heat flux transferred per square meter of surface varies provides valuable data, enabling simulations of fires starting from similar containers positioned at different distances from buildings or in various configurations. This allows for an evaluation of the adverse effects of such fires on adjacent façades without the consumption of material resources that would be required for real-scale experiments.

Because the variation curves may be transferred into fire-dedicated software such as Pyrosim, plotting the heat release rate per unit area (HRRPUA) variation profile constitutes an important addition to the current scientific level (Figure 14).

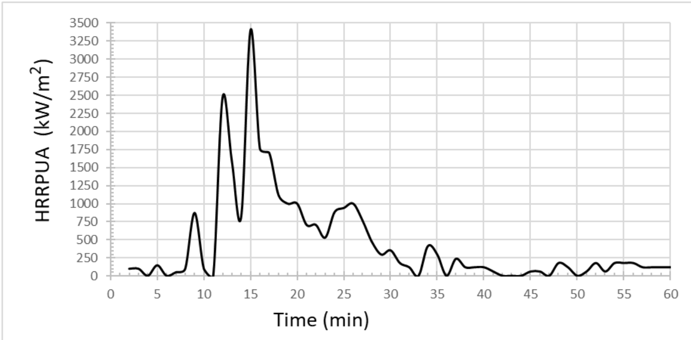


Figure 14. Heat release rate per unit area (HRRPUA) variation profile during fire.

In addition to the inherent challenges of conducting large-scale fire experiments, it is crucial to address two significant concerns: the substantial financial costs involved, and the environmental impact associated with such endeavors. The sheer magnitude of resources required for these experiments, especially in the case of expansive structures like garages or large buildings, places a considerable strain on research budgets. These costs encompass not only materials, equipment, and personnel but also the expenses related to safety measures, post-experiment cleanup, and facility maintenance. Furthermore, it is essential to recognize the environmental toll that large-scale fire experiments can impose. These experiments often involve the controlled ignition of substantial amounts of materials, leading to the release of pollutants, particulate matter, and greenhouse gases into the atmosphere. The disposal of debris and remnants from these experiments also poses environmental challenges, particularly when hazardous or non-recyclable materials are involved.

In light of these concerns, researchers and institutions have increasingly sought alternatives that are both cost-effective and environmentally responsible. One such solution is the utilization of computer modeling. By reducing the need for live fire tests, computer simulations significantly curtail the consumption of resources and the release of pollutants. These models operate in a controlled digital environment, sparing the environment from the pollution associated with large-scale fire experiments. The adoption of computer modeling not only aligns with sustainable research practices but also underscores a commitment to environmentally responsible research methodologies. It allows researchers to mitigate the financial burden while simultaneously reducing the environmental impact of fire safety research.

While computational fluid dynamics (CFD) programs have become invaluable tools in fire safety research, it is important to underscore the indispensable role of experimental results in the validation process. CFD simulations provide a powerful means of predicting fire behavior, temperature distributions, and smoke propagation within structures, offering researchers valuable insights into complex fire scenarios. However, these numerical models are only as reliable as the data used to calibrate and validate them.

This is where experimental results come into play as a critical component of the validation process. Real-world fire experiments serve as the benchmark against which CFD simulations are compared, ensuring that the digital predictions align with physical reality. The synergy between experimental findings and numerical simulations fosters a robust and reliable understanding of fire dynamics, strengthening the foundation of fire safety research and enhancing our ability to develop effective safety measures for diverse architectural settings.

4. Conclusions

Façade fires are a real problem in the built environment, and one of the reasons for this is the use of combustible materials in the building's thermal insulation system, which, once ignited from a specific source, spread extremely quickly with large flames all over the façade but also inside the living rooms. The research that is provided in the paper is significant since it is conducted on a large scale and replicates a façade fire with flame penetration into the living room.

The experimental data obtained clearly underline the importance of non-combustible barriers within buildings by observing a clear temperature difference from inside the room where a maximum of 1100 °C was reached to 2.5 m above with a maximum of approximately 800 °C and then to 5 m above the room with a maximum of about 400 °C. The analysis of the final appearance of the burned space reveals that the flames only spread to the immediately upper level, as the flames were strong enough to pass over the combustible barrier, but the façade structure of the wall was not harmed starting from the second level.

As a fire source, two 1100 L containers of domestic waste with a mass of 45.5 kg and a gross calorific value of 46.97 MJ/kg each were filled with 10.7 kg of PET bottles with a gross calorific value of 23.90 MJ/kg. Thus, although they are not particularly mentioned in the regulations, safety distances must be maintained when storing household waste from the building's façade so that the fire does not spread to the façade in the case of a fire of the stored materials.

Heat release rate (HRR) values were highest between 11 and 17 min, with a maximum of 4919 kW. Because the variation curves may be transferred into fire-dedicated software such as Pyrosim, plotting the heat release rate per unit area (HRRPUA) variation profile constitutes an important addition to the current scientific level. All this information can be used in computer simulations to follow the effects of a similar fire on other building constructions without the material consumption that would have occurred in an actual test. To the best of the authors' knowledge, no profiles for the burning of garbage containers are currently available, emphasizing the necessity of the research.

The study underscores the challenges and financial constraints associated with conducting large-scale fire experiments, particularly in environments like garages or expansive buildings. These limitations necessitate the utilization of cost-effective alternatives, such as computer modeling, to simulate fire scenarios and assess safety measures comprehensively.

The article emphasizes the practical value of real-world testing within the construction domain. These tests encompass a wide spectrum, ranging from investigations conducted within abandoned structures to the examination of materials used in building construction, including façade systems and interior coverings. Such real-world experiments provide invaluable insights into fire safety measures, allowing for the development of effective fire prevention and mitigation strategies.

The results of the experimental study align with the typical outcomes characterizing experimental studies of this nature. The added value of this study lies in the fact that the researchers considered two fire scenarios during the experimental test, and the subsequent results obtained were conclusive and valuable. For example, a plausible and highly unfavorable (borderline) exterior fire action scenario on the façade of an insulated building with an ETICS system, as well as in a ground-level room, was presented. The propagation of an exterior fire into a ground-level living room within a building was evaluated. Researchers assessed the stages of fire action inside a living room (fire initiation, fire development, fire generalization—flash-over, and fire regression). During the experimental test, phenomena resulting from the burning of the two containers were observed, affecting the building's façade. The fire resistance response time of a PVC window under the influence of a thermal load composed of two containers filled with PET bottles was evaluated. The loss of mass of the thermal load was measured during the experimental test to determine HRR (heat release rate). The results obtained from the experimental test are valuable in that they can serve as a starting point for further scientific research that validates these experimental results through computer-based numerical simulations. Last, but not least, the researchers identified a time gap required for firefighters' intervention until the moment an exterior fire spreads inside a building.

One of the most significant contributions of this article lies in its potential to facilitate future research by allowing other investigators to use the experimental results for the validation of numerical findings. This eliminates the need for repetitive, costly, and environmentally taxing large-scale experiments. By making these experimental data accessible to the broader scientific community, we pave the way for a more sustainable and collaborative approach to fire safety research. Researchers can confidently rely on these validated datasets, sparing both human and environmental resources while advancing our collective understanding of fire dynamics and safety measures. This not only enhances the efficiency of future research endeavors but also aligns with responsible and environmentally conscious scientific practices.

The authors want to continue testing in the future by investigating the influence of external elements on fire propagation in real-world situations, particularly how it evolves as wind speed increases.

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