



Numerical study of the fire behaviour of external walls in light steel framing

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ARTICLE INFO

Keywords:

Light steel framing
External walls
Numerical simulation
Fire resistance
Fire behaviour

ABSTRACT

This study focuses on the fire behaviour of external walls in Light Steel Frame (LSF) structures. Previous investigations have primarily addressed the fire behaviour of internal wall configurations, however, the increasing number of fires affecting external walls shows that their behaviour must also be understood.

Therefore, this work investigates the fire behaviour of these elements, presenting a numerical study of six different typologies usually found in LSF practice by analysing the temperature evolution across the wall and in the steel profiles. The results show that the temperature evolution is slower when the fire is impacting the outer side of the wall but, in these cases, the recommended critical temperature of 350 °C is reached earlier in the steel profiles. Finally, this work shows that more studies are necessary to describe the fire resistance of external walls, in particular when these elements have a loadbearing function.

1. Introduction

The fire behaviour of wall panels in Light Steel Framing (LSF) has been studied by different researchers in the last three decades, and the use of cold-formed steel products in the construction sector has expanded to new markets around the world. Cold-formed steel profiles can be assembled in various combinations to provide structural load-bearing systems for buildings of up to five floors or more, or used as supplementary systems, along with the more traditional steel or concrete structural systems.

The cold-formed light steel structural system, also known as Light Steel Framing (LSF), is a self-supporting steel solution and dry construction system [1] that is widely adopted in industrial and commercial buildings. In addition, it is being increasingly used in the residential building sector, replacing traditional structures made with concrete, masonry, and wood, which are widely used in Europe, Australia, and North America. The LSF system offers numerous advantages for construction and maintenance, such as:

- Cold-formed steel structures have high quality, in addition to the stability of shape they can be machined, are non-combustible and do not require protection from pests. [2];

- LSF structures are available in a variety of shapes and sizes and for that reason can accommodate flexible and economical structural designs;
- The cold-formed sections - CFS of the LSF system are formed by folding, in roll forming machines, of cut strips of plates or coils, or by continuous forming in a set of rotating dies, from coils cold-rolled or hot-rolled, both operations being carried out with steel at room temperature [1];
- The light weight of the structures in LSF requires smaller foundations and provides a high level of seismic resistance, because it is a self-supporting structure, in which all walls have a structural performance.
- They are sustainable and can speed up the construction time.

The fire behaviour is affected by the resistance of the cold-formed steel profiles that heat rapidly and with the increase in the steel temperature, there is a degradation of the mechanical properties and, consequently, a reduction in the structural load-bearing capacity [3,4]. To decrease the heat transfer and improve their fire resistance, LSF structures are usually protected by gypsum boards or other materials forming the wall panels in light steel framing [5].

Two of the most basic and versatile materials used in the light steel framing system and, consequently, in the manufacture of wall panels in

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<https://doi.org/10.1016/j.firesaf.2023.103946>

Received 21 November 2022; Received in revised form 6 July 2023; Accepted 29 August 2023

Available online 2 September 2023

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LSF, are gypsum board and OBS “Oriented Strand Board”. Used in almost all environments in different forms and typologies, respecting the technical needs of the built project. OSB can be used in the LSF System, on floors, slabs and external walls or internal walls with structural needs, having different thicknesses and classifications according to the type of use in the manufacturers’ manuals and the guidance of the EN 300 [6] standard. OSB, when exposed to fire, is susceptible to burning, in turn increasing the temperature in the LSF profiles. This complex behaviour has not been modelled and should be addressed in the future preferably through physical tests. Light Steel Framing (LSF) wall panels are fire rated for integrity (E), insulation (I) and bearing capacity criteria (R).

For this first numerical study of exterior walls in LSF, 6 (six) typologies were chosen, composed of the referred basic materials most used also in the Portuguese market (see Fig. 1), with different types of insulation in their cavity. For this numerical study, two types of insulation were defined in the cavities of the typologies studied (rockwool and superwool), these being the most used in previous numerical studies [7], with well-defined thermal properties (see section 3.2) and a third type of insulation configuration, without any material (air).

Rock wool has much higher insulation levels due to its formation based on basalt or iron ore blast furnace slag [8], providing greater density, which, consequently, becomes an excellent insulation option. The choice to use superwool was due to the properties of its main components, including silica-alumina arrangements, which provide low density, high melting point, lightness and low thermal conductivity. Thus, although its use as a thermal insulator in the cavity walls in LSF is still a novelty, the properties of superwool make it attractive in terms of the thermal performance of structures in LSF [9], which includes the types of external walls in LSF, an object of this study.

The fire behaviour of interior wall panels in LSF has been extensively investigated, especially in the last three decades [7,11–15], a context in which to increase the fire resistance, different insulation materials, placed in the cavity of the LSF walls, were investigated. Other techniques have been investigated, such as modifying the characteristics of the walls, increasing the thickness and the number of layers of gypsum plates, or adopting composite layers. In some studies, internal insulation improved the fire resistance criteria (I) of LSF wall panels [16], while others [17,18] revealed that wall assemblies without cavity insulation provided greater fire resistance than cavity insulated assemblies. In general, these studies evaluated the effects of these parameters through large-scale fire tests [19,20] or numerical simulations [21–32] exposed to the ISO 834 standard fire curve.

The ISO 834 curve, commonly applied in some studies [33,34], is frequently used in experimental and numerical tests when seeking to evaluate the fire resistance of internal wall construction elements. In what concerns the use of the external fire curve, defined in EN 1991-1-2 [35] since it reaches a maximum temperature of up to 660 °C, some studies consider it inadequate or of lesser importance to determine the fire resistance of building elements of external walls. In addition, although this fire curve is intended for the outside of separating external walls which can be exposed to fire from different parts of the façade, i.e. directly from the inside of the respective fire compartment, it does not

result from an external fire but rather from a fire outbreaking from inside a building. Therefore, researchers prefer to use the ISO 834 standard fire curve, even in external wall typologies, for reasons of universal use in research evaluating fire resistance, in addition to having more severe exposures and allowing comparison with results from previous studies [34]. This study also investigates the impact of using ISO 834 to determine the fire resistance (I) of external walls exposed in the inner layer, compared to a fire exposure in the outer layer.

Finally, the global trend suggests that the use of LSF systems will increase since it provides a sustainable solution for the construction market, aligned with the policies seen in Europe. However, given the unique functional requirements of buildings located in southern Europe, in terms of thermal and acoustic behaviour, when compared to those in North and Central Europe, North America or Australia/New Zealand regions that lead the research and development of LSF technology [2], the direct generalization of this technology to other geographic locations may not be the best solution and requires further investigation [36]. This is especially relevant in the context of fire resistance since the impact of different LSF wall configurations remains unknown. On the other hand, since previous studies have focused on the fire behaviour of interior walls, the fire behaviour of external walls has yet to be thoroughly explored despite being a relevant scenario due to the **continuous increase** in urban and forest fires affecting the exterior walls of buildings, as observed in the recent forest fires in Portugal.

2. Literature review

2.1. Chronological research of experimental and numerical tests of LSF walls in fire situation

One of the first experimental studies of LSF wall fire, reported in the literature, was developed in 1973 [32], presenting two fire resistance tests in double wall assemblies. Fire resistance tests were performed on two wall panels with cold-formed steel profiles with fibreglass insulation. Each model consisted of a double-module gypsum board and cold-formed steel profiles. The external gypsum plates were 15,9 mm thick gypsum, while the internal ones facing the cavity between the walls were 12.7 mm thick. The cold-formed steel profiles used in the research had sections of $76.2 \times 44.5 \times 12.7 \times 1.21$ mm. The fibreglass insulation used in set two was thicker than that used in set one. A uniformly distributed load of 15 kN/m was applied to each wall. The structural failure of the wall exposed to fire in model 1 occurred in 42 min, and in model 2 the structural failure occurred in 67 min. In both models, structural failure occurred only after the collapse of the exposed gypsum board. It was also observed in this work that, compared to model 1, heat propagation in model 2 was much slower. This was attributed to the thicker insulation used in the model 2. As a final result of the trials, the researchers recommended the use of two layers of gypsum boards with staggered joints to eliminate direct heat transfer toward the cold-formed steel profiles [37].

Klippstein, in 1978, performed tests on ten wall panels exposed to fire defined by ASTM E119. The purpose of these tests was to empirically determine the temperature variation in the cold-formed steel profile and



Fig. 1. Example of use of external walls in light steel framing with the use of OSB plates in the region of Coimbra – Portugal (adapted from Ref. [10]).

its lateral deformation during the test until the moment of wall collapse, which would serve as an input in predicting the structural behaviour of the profiles when exposed to the ASTM E119 fire curve or similar fires. All panels were made with “C” shaped cold-formed steel profiles, with varying thickness and dimensions, spaced every 600 mm. One to three layers of 12.7 mm or 15.9 mm gypsum board were fixed on the fire exposed side. A gypsum board was applied to the unexposed side of the panels. In four of the wall specimens, fibreglass insulation was placed between studs and cladding, the other six tests were performed without insulation. The average load per stud ranged from 15.12 kN to 44.7 kN. The cold-formed steel profiles closer to the ends of the wall were identified with lower temperatures than the central ones, possibly due to the flow of cold air from the outside into the furnace, caused by the negative pressure inside it, or eventually by the fixations to the frame of the furnace. The central studs were submitted to higher temperature than the end studs of the wall, suffered more thermal expansion and consequently were submitted to more load during the initial phase of the fire test. In the later phase of the test, the load was redistributed to the studs farthest from the centres. The collapse time of the wall panels ranged from 37 min to 127 min, with the highest collapse times generally associated with a greater number of gypsum plates on the fire exposed side and lower load levels on the wall [12].

In 1985, Schwartz and Lie [31], analysed the effect of heat transmission to avoid burning the materials in contact with the unexposed side of the walls, evaluating the temperature criteria for the unexposed side defined in the ASTM E119 standard. They suggested that an average temperature increase of 222 °C and a maximum temperature increase of 250 °C at any point should be considered in the revision of the criteria of the ASTM E 119 standard.

Sultan and Lougheed [38], in 1994, performed several small-scale fire resistance tests on wall models consisting of cold-formed steel profiles, constructed with gypsum boards and using glass fibres, rockwool, and cellulose for the cavity insulation. The geometry of the test models was 914 mm high and 914 mm wide. It was observed that the insulation of the cavity using rockwool and cellulose fibres improved the fire behaviour, increasing the resistance (I) by approximately 30 min when compared to the non-insulated wall models, while only a small benefit was observed for the case of samples using glass fibres. The cavity side of the exposed plaster heated up faster reaching a temperature of 700 °C, much earlier when compared to the non-insulated wall. After the calcination of the exposed plate, that is, after its burning, with the partial loss of its chemical properties, the exposed side to the cavity registered much higher temperatures when compared to that of non-insulated wall assemblies. Small-scale wall assemblies were constructed using two types of gypsum boards (regular and fire resistant gypsum board). The authors observed that, in the case of fire resistant gypsum board, the temperature increase is mainly due to the burning of combustible material used in the insulation, while in the regular gypsum boards the temperatures on the exposed side of the cavity were comparable to the furnace temperatures, which implies a rapid and extensive failure of the gypsum board. The advantage obtained from the use of cavity insulation was that, the plate on the unexposed side remained at a much lower temperature for a longer period of time, compared to the plate in the experimental model of the wall without insulation in the cavity [38]. Upon failure of the gypsum board on the exposed side, the insulation of the cavity helped to provide some initial fire protection to the gypsum board on the unexposed side. This protection lasted about 5–10 min with glass fibres, 10–15 min with rock fibres and 25–30 min with cellulose fibre insulation. It was found that the temperature rise of the unexposed gypsum board, after the initial protection period, was faster in the case of fibreglass insulation in the cavity. On the other hand, it was observed that the temperature in the cavity even exceeded the measurements in the experimental model without insulation, thus giving a neutral effect on the fire resistance of sets constructed with type X gypsum board. For the regular models of gypsum boards, this temperature increase led to an earlier failure of the boards, thus decreasing the fire resistance (I) rating

of the wall below that of the non-insulated counterpart. The authors observed that the insulation of the cavities using rock and cellulose fibres provided approximately 30 min of improved fire resistance (I) [38].

In 1995, Sultan [39] conducted large-scale fire resistance testing on load-bearing and non load-bearing LSF walls and found that when rockwool was used as cavity insulation, the insulation fire resistance of the system increased by 54% compared to void cavities, while the addition of 90 mm thick wet sprayed cellulose fibre insulation did not affect the fire rating, when compared to the void cavity.

In 1996, Gerlich and, Buchanam [40] investigated the parameters that were affecting the performance of load-bearing LSF walls under fire and presented a new design method based on the temperature field determined by the finite element method. This design method considered the studs subjected to a combination of axial loading and bending, assuming the reduction of stiffness and strength at elevated temperature, predicting the deflection resulting from temperature gradients and second order effects. Gerlich in 1995 [11] performed three fire tests on large-scale LSF load-bearing walls with gypsum board, using standard and real fire scenarios. The failure was initiated by the structural collapse of the LSF, followed by integrity failure of the unexposed lining due to excessive deformations at the locations of stud buckling. The structural failure was identified by the reversal in vertical displacement, reaching a very high rate of displacement.

Kwon [41], in 1998, conducted four fire tests on two types of load-bearing external walls. The experimental wall models were full scale. The walls were made with cold-formed steel profiles using rockwool insulation in the cavity region. Another 10 mm thick of unspecified insulation material was used as the basecoat layer on the outside of the wall samples. The researchers observed that the fire-resistant properties of the walls of the cold-formed steel profiles mainly depended on the fire reaction properties of the gypsum boards. At least two layers of 12.5 mm thick X-type gypsum boards would be required on both sides of the wall with additional rockwool in the cavity region to certify the wall by R60. On the contrary to USA or other countries, one layer of 12.5 mm gypsum board on one side is impossible to endure 60 min for load bearing wall using a domestic fire resistance test with load and without load.

The review article presented in 1999 by Alfawakhiri et al. [22] regarding cold-formed steel profile walls under fire, summarizes the information about the fire resistance of load-bearing LSF walls. The experimental tests, the analytical studies and the material properties are discussed. Important considerations on the failure of gypsum boards, effect of bolt spacing, the orientation of gypsum board joints and spacing of profiles were also presented and pointed out as to have a very strong effect on the fire performance of the LSF systems.

In the same year, Kodur et al. [42] studied the behaviour of the sets of walls classified in W1, W2 and W3 exposed to the ISO 834 standard fire curve, using fibreglass, rock fibre and cellulose as the insulation material of the cavity. The profiles used were of type “C” with dimensions 92.1 × 41.3 × 12.7 mm, spaced at 406 mm, 610 mm and 406 mm in the three samples, W1, W2 and W3. The researchers observed that structural failure of the samples occurred before heat penetration of the unexposed side could occur, further noting that gypsum boards on the fire-exposed side fell several minutes before structural failure. Visual inspection of the insulation material from the cavity after testing revealed that the fibreglass insulation had suffered only limited damage in certain areas; the rock fibre insulation was in good condition, but the cellulose insulation was fully charred. The researchers realized that structural failure before integrity failure in all tests indicated that much higher fire resistance ratings would be possible for similar LSF assemblies without applied loads. The time and temperature curves of the assays indicated that the two plate layers on the exposed face provided about 40 min of delay in increasing the temperature of the LSF wall profiles. The temperature rise in the cold-formed steel profiles after this initial period was the fastest on the W1 wall with fibreglass insulation and the slowest on the W3 wall with cellulose fibre insulation. The structural collapse times of the specimens W1, W2 and W3 were

observed at 55, 73 and 70 min, respectively. The authors also observed that the higher fire resistance of the wall W2, compared to W3, probably occurred due to a greater spacing between the stud and, therefore, lower total load in sample W2, compared to sample W3 [42].

Alfawakhiri and Sultan [43] in 2000, presented an analytical thermo-structural model for load-bearing LSF walls. Temperatures were predicted by the 1D numerical model called TRACE and the out-of-plane displacement is determined by the effect of the thermal bowing and by the action of the eccentric vertical load. The results were compared with six experimental results. The experimental observations revealed that heat penetration failure was not detected in any of the tests (no insulation failure). All specimens failed by losing their ability to sustain the applied load. The insulation placed in the cavity region reduced the ability to sustain the load in the LSF walls. The heating regime of studs with insulation in cavity features high temperature gradients across the steel section, while for non-insulated walls temperature is rather close to uniform heating. The deformed failure mode shape was flexural buckling towards the furnace for non-insulated walls and away from the furnace for insulated walls. In the due course of the PhD thesis, Alfawakhiri in 2001 [18], presented these experimental tests with more numerical comparisons. The same results were observed in the experimental investigation carried out in 2001 by Kodur and Sultan [17], concluding that: wall assemblies without cavity insulation provide higher structural fire resistance when compared to insulated assemblies; Increasing the stud spacing also increases the fire resistance; replacing a gypsum board layer with OSB shear resulted in a significant decrease of the fire resistance; and finally, a specimen with double row steel stud wall presented higher fire resistance compared to single row steel stud wall.

The experimental and numerical study presented in 2003 by Feng et al. [16] was used to evaluate the thermal performance of different configurations on LSF walls. Eight reduced scale fire tests were carried out on LSF panels, considering different types of steel sections, different numbers of gypsum boards, and the existence of cavity insulation. These authors concluded that the thermal performance of these panels was not significantly affected by the type of internal insulation, nor by the shape of the thin-walled cold formed steel cross section, but rather by the insulation panels on the fire exposed side. They have also tested a special cassette stud type, in which the narrow flange of the cassette sections should be facing the fire exposed surface, reducing the area of steel to conduct the heat.

In 2003, an experimental investigation carried out by Sakumoto et al. [44], evaluated the fire resistance of LSF walls and concluded the importance of thermal shielding of gypsum boards coupled with the protective layers of plywood, gypsum board and other materials. With the experimental test, it became clear that the fall prevention of gypsum boards is important to improve fire resistance, and that the increase in the number and thickness of gypsum boards to be applied, as well as the use of reinforced gypsum board of cement and fibre are effective in fire protection.

In 2010, Kolarkar [19] evaluated the structural (R) and thermal (I) performance of LSF wall systems under fire conditions. Of the various tests performed in the studies, a full-scale test, also performed at room temperature, showed that the proposed cold-formed steel stud wall systems with external insulation in a composite panel provided a considerably higher fire resistance with less lateral deformations than conventional cavity insulated stud wall systems. The composite panel was developed by joining two gypsum boards with thermal insulation between them.

In 2013, Shahbazian and Wang [45] proposed a simple method with 1D heat flux analysis, to calculate the temperature distribution in the cold form sections when the wall panel is exposed to fire. The results are in agreement with those obtained through 2D analysis using the finite element method in ABAQUS.

In the same year, Keerthan and Mahendran [46] developed a numerical study with SAFIR to determine the thermal performance of

gypsum board and cold-formed steel structure, made by two gypsum plates with an insulation layer between them, proposing new simple formulas to estimate the evolution of temperature on the unexposed side. More recently, the same authors [47] presented a comparison between the numerical and experimental results obtained for the thermal performance of cold-formed steel walls with load in fire situation, showing good agreement between them and proving that finite element models can be used to simulate the thermal behaviour of LSF walls with load and with varied configurations of insulation and gypsum plates.

In the aforementioned work [47], the authors showed that cavity insulation impairs the fire classification of LSF walls, while the use of external insulation improved fire performance.

Recently, in 2020, an experimental study on the fire resistance of walls with the unladen LSF system with variable cavity depth was carried out [5]. The results identified that increasing the cavity depth of LSF walls from 76 to 150 mm single-layer gypsum board, significantly improves the insulation fire performance.

In the same year, seven small-scale LSF wall models were subjected to numerical simulations and experimental tests, evaluating their fire resistance according to their properties and physical characteristics. All tests were validated using two-dimensional numerical models, based on the finite element method, finite volume method and the hybrid finite element method. The results indicate that the fire resistance increases with the number of profiles and also with the thickness of the protection layers [7].

In 2021, researchers performed several numerical and experimental studies on internal and external LSF light steel frame walls. Some of these studies, carried out with internal double stud walls, have shown that a cavity of larger dimensions delays the heat transfer through its cross section, which consequently delays the temperature increase on unexposed surfaces [9]. Still, others have shown that LSF walls insulated with silica aerogel blanket cause an increase in fire resistance, delaying the temperature level in the profiles [48]. Other studies [49] evaluated the same type of external insulation, this time applying walls with PCM (phase change material) incorporated cellulose insulation, presenting similar results, in which externally insulated LSF walls have higher levels of fire resistance (I) than cavity insulated LSF walls. In the same year, an investigation into the external wall typology resulted in one of the first studies on the fire behaviour of walls covered with autoclaved cellular concrete panels [33], pointing to the maintenance of low temperatures for 160 min, and to the achievement of a level of fire resistance of 204 min under load-bearing conditions.

2.2. Data from the chronological literature review

Over the years, numerous experimental and numerical tests have been carried out [5,7,14,15,22–24,28,31,43–45,47,50–79] analysing the behaviour of LSF walls of different protection typologies for cold-formed profile structures. With the increasing enhancement of technology in the construction industry, and the further development of new products worldwide, developed mainly for the LSF system, the number of investigations for these new products submitted to fire tests has increased in recent years (see Fig. 2).

In the bibliographic survey, the number of articles published between 1995 and 2021 and the respective countries where the research took place were identified. The largest number of investigations about the behaviour of LSF walls under fire was carried out in Australia (see Fig. 3), associated with the research developed by the Mahendran research group, one of the responsible for the largest number of studies carried out during this period. This group held several numerical and experimental tests, analysing the behaviour of different types of LSF walls of the different types of protective materials to cold-formed steel profiles.

It was also identified among the tests performed that researchers chose to test and study the behaviour of the internal LSF walls, with very few studies on the behaviour of the external LSF walls being identified

Research evolution over the years
Behavior of LSF walls in fire situation

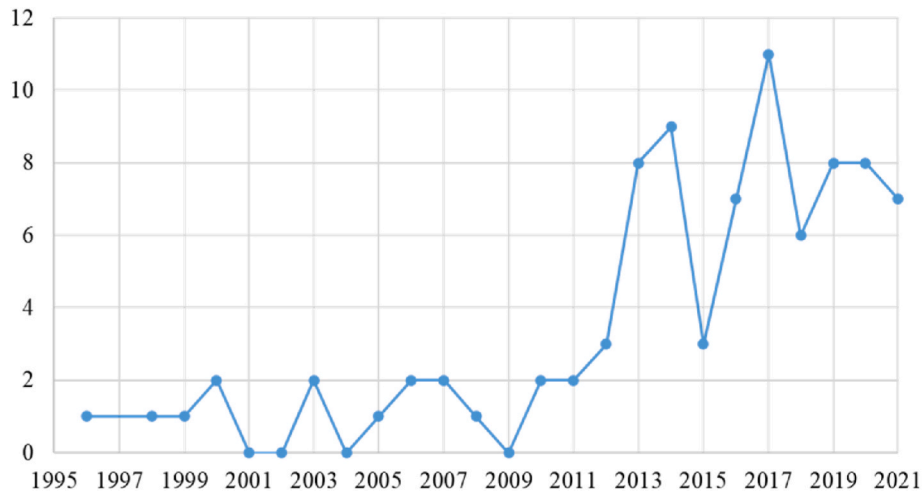


Fig. 2. Surveys carried out between 1995 and 2021.

Articles published by countries: behavior of LSF walls in fire

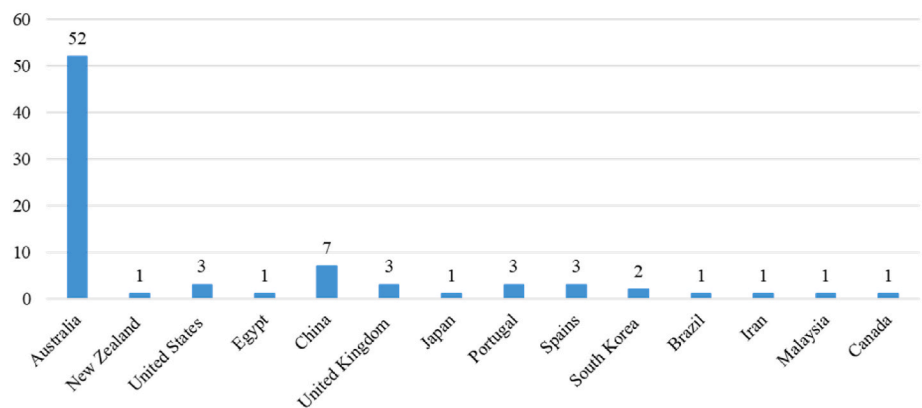


Fig. 3. Some Articles published by Countries between 1995 and 2021.

The walls here named external represent the periphery of a building, which can also be classified as external façades of a building, are constructed using different dry materials compared to the materials used in the internal wall configurations that have been previously studied by researchers.

In addition to providing relevant information about the fire behaviour of the walls in LSF of different typologies and regions, the bibliographic review also highlights the need for future research, especially in exploring more sustainable materials and products used in Europe. The results obtained from this study, and future research, may inform the development of fire design rules, aid in decision-making, and provide recommendations that are aligned with the principles of national and European regulation. With the collection of the obtained information, it can be observed that, even with a significant number of published articles and several tests carried out between 1995 and 2021, there is a need for new experimental tests and numerical simulations, to be held in Europe, in order to compare them with results already obtained in the literature. Such experiments will contribute to increase the knowledge of the behaviour of materials produced and marketed.

Additionally, a gap was identified in the existing bibliography with regard to research on the fire behaviour of external walls, so further research in this area will greatly contribute to better engineering practices, reduce human risks, and to increase the degree of housing

conservation, especially in the event of forest fires.

3. Numerical simulation of external walls

3.1. Numerical model

To numerically obtain the temperature evolution in an LSF wall consisting of different materials and layers, a finite element model was developed using Ansys [80]. Two-dimensional (2D) analyses were made using the finite element PLANE55 and SURF151 available in the Ansys library. The PLANE55 element is defined by four nodes with a single degree of freedom (temperature), and uses linear interpolating functions and full gauss integration to define the conductivity matrix (2x2). The SURF151 finite element is overlaid onto an edge of the PLANE55 finite element, either representing an interface element with gypsum material or representing an interface element with the steel material to define the heat flow by radiation between this edge surface and the nodal bulk temperature of the cavity. This element is defined by three nodes, being two nodes coincident with the region in contact with the cavity and the third node to define the bulk temperature evolution (geometric centre of the cavity region). The interpolating functions are also linear and the number of integration points is two.

In order to automate the creation of numerical models, the APDL

programming language was used to define all the desired models. The geometric data of the LSF wall and the material properties were defined by this code. The mesh was defined based on a convergence test, in order to define the most appropriate element dimension to be used. For the axis “x”, see Fig. 4, such divisions were made according to: the region corresponding to the thickness of the web of the LSF profiles was divided into four equal parts; the region corresponding to the areas of the flanges of the LSF profiles in twenty-five equal parts; and the region of the cavity’s areas eighty equal parts. For the other axis direction “y”, the divisions were as follows: four equal parts in the region of the flange thickness; in ten equal parts of finite elements in the region of the gypsum board and OSB plates; in ten equal parts in the region of the webs of the profiles close to the flanges; and in fifteen equal parts of finite elements in the area of the region of the cavity. The mesh is represented in Fig. 4, assuming “x” as the horizontal direction and “y” as the vertical direction. The mesh size changes according to the typologies of the samples.

An additional node was defined where the temperature is imposed to follow the standard fire curve, assuming the heat flow by radiation and convection to the exposed side (through the SPCNOD command). The material properties are established using the MPTMP command to define the temperature dependant thermal properties. The material properties are defined in section 3.2.

The boundary conditions are defined in this study, with only one side of the wall exposed to fire, the temperature is defined according to the standard fire ISO 834 [81], or the external fire curve defined in the EN 1991-1-2 [35]. The boundary conditions were imposed using the SFL (surface load on lines) command, assuming heat transfer by radiation (fire emissivity $\epsilon_f = 1$) and convection ($\alpha_c = 25 \text{ W/m}^2\text{K}$) on the exposed side. The heat transfer by convection ($\alpha_c = 9 \text{ W/m}^2\text{K}$) was applied on the unexposed side, to include the radiation effect (see Fig. 5). The analyses were carried out assuming two different models: the first model considers the heat conduction through solids and assumes perfect contact between the insulation materials used in the cavity region; the second model considers heat flow by conduction between solid parts and radiation with the cavity bulk temperature (usually two bulk nodes for each cavity region).

The options related to the radiation solution (RADOPT) were considered with their default values in Ansys. At the beginning of the simulations, the temperature of the unexposed side was defined as equal to the initial temperature ($T_0 = 20 \text{ }^\circ\text{C}$).

The nonlinear transient analysis was performed in Ansys with the default options activated (incremental and iterative). A maximum variation of the time step equal to 60 s and a minimum of 1 s was defined and the option AUTOTS was set in Ansys to adjust automatically the time step during the incremental solution process within the defined maximum and minimum intervals. The convergence of the solution considers the analysis of the heat flow, with a tolerance value of 10^{-3}

and a reference value of 10^{-6} W .

Finally, the numerical model used in this study was previously validated by comparing the results with those from Ref. [7] and, as expected, the results were identical since both numerical models share the same modelling assumptions.

3.2. Thermal properties

3.2.1. Steel

The thermal properties of steel were obtained from the Eurocode 3: Part 1–2 (EN 1993-1-2:2005) [82], assuming the temperature variation for the specific heat, thermal conductivity and density, as represented in Fig. 6 following the values provided in Table 1. The density of the steel remains constant at 7850 kg/m^3 . The same data were used in Ref. [7] to obtain the results of the typologies chosen for numerical validation against results from the literature. The emissivity of the steel was considered as $\epsilon_a = 0.7$ according to the literature data and to the Eurocode 3: Part 1–2, [82].

3.2.2. Gypsum board

The thermal properties of the gypsum were obtained from the Eurocode 5: Part 1–2 (prEN 1995-1-2:2025) [83], assuming the temperature variation for the specific heat, thermal conductivity and density, as represented in Fig. 7. The density and emissivity of gypsum were considered as 576 kg/m^3 , $\epsilon_g = 0.8$ according to research developed by Sultan and used by other authors [7,21]. See details of values in Table 2.

3.2.3. Rockwool

The thermal properties of rockwool were obtained through the research developed by Steinar Lundberg [84], and updated by the new standard the Eurocode 5: Part 1–2 (prEN 1995-1-2:2025) [83], the specific heat and thermal conductivity are also density dependent. All thermal properties are presented in Fig. 8. The density of rockwool was considered equal to 75 kg/m^3 , as used in Ref. [7]. The emissivity of rockwool was considered as $\epsilon_1 = 1$ according to the research developed by Sultan and used by other researchers [7,21]. See details of values in Table 3.

3.2.4. Superwool

The thermal properties of the superwool were obtained according to the manufacturer’s specifications [85,86]. The specific heat, thermal conductivity and density are presented in Fig. 9. The same data were used in Ref. [7]. The emissivity of superwool was considered $\epsilon_1 = 0.9$ according to the manufacturer [85], and used by other researchers [7,9]. See details of values in Table 4.

3.2.5. Oriented strand board (OSB)

The thermal properties of the OSB were obtained from the Eurocode

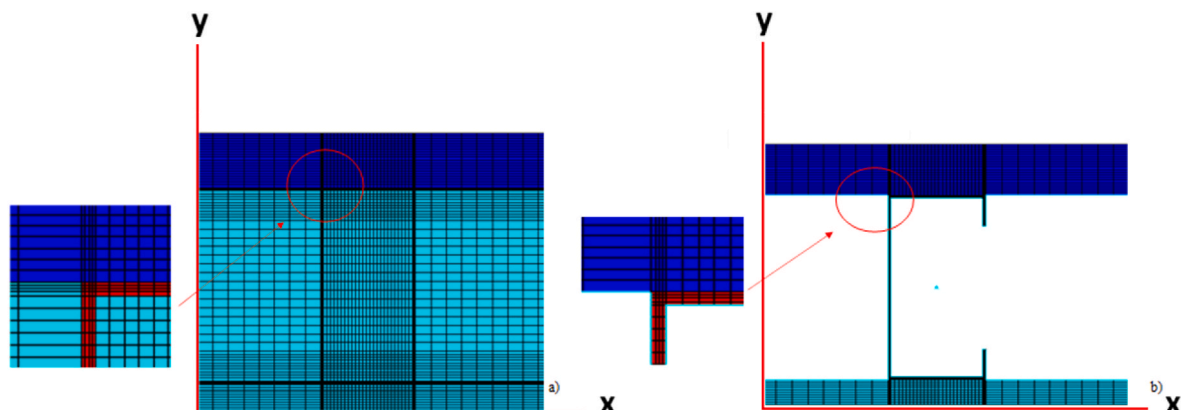


Fig. 4. Examples of finite element mesh extracted from the region of the sample profiles a) with material in the cavity and b) without material in the cavity.

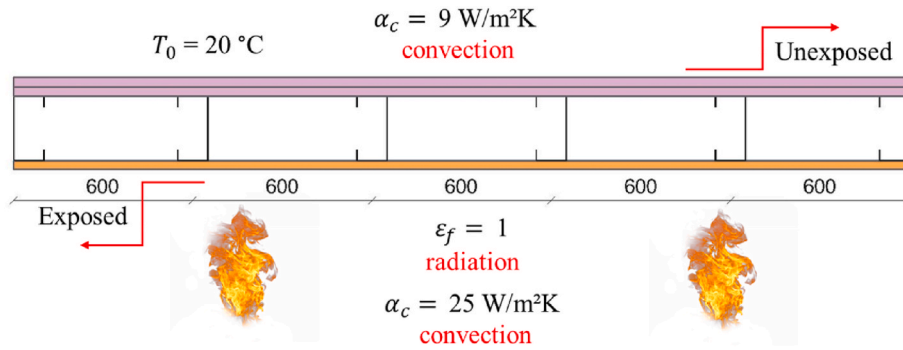


Fig. 5. Contour condition of numerical modelling.

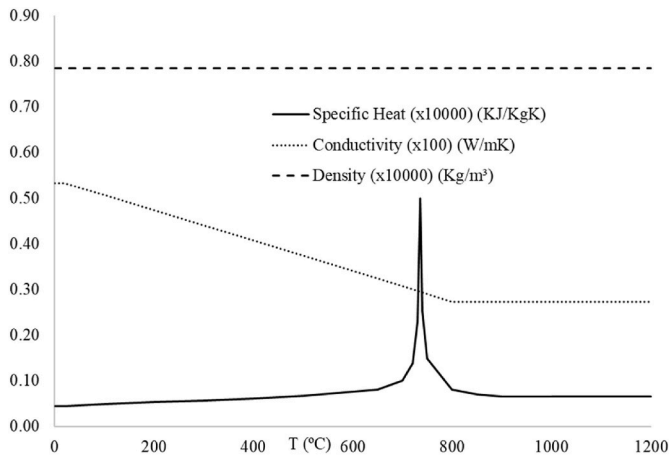


Fig. 6. Thermal properties of Steel.

Table 1
Thermal properties of Steel.

Thermal properties - Steel				
T [°C]	Density (x10000) (Kg/m ³)	Conductivity (x100) (W/mK)	T [°C]	Specific Heat (x10000) (KJ/KgK)
0	0.7850	0.533	0	0.0440
20	0.7850	0.533	20	0.0440
100	0.7850	0.507	100	0.0488
200	0.7850	0.473	200	0.0530
300	0.7850	0.440	300	0.0565
400	0.7850	0.407	400	0.0606
500	0.7850	0.374	500	0.0667
600	0.7850	0.340	600	0.0760
700	0.7850	0.307	650	0.0814
800	0.7850	0.273	700	0.1008
900	0.7850	0.273	720	0.1388
1000	0.7850	0.273	730	0.2291
1200	0.7850	0.273	735	0.5000
-	-	-	740	0.2525
-	-	-	750	0.1483
-	-	-	800	0.0803
-	-	-	850	0.0695
-	-	-	900	0.0650
-	-	-	1000	0.0650
-	-	-	1200	0.0650

5: Part 1–2 (prEN 1995-1-2:2025) [83], assuming the temperature variation for the specific heat, thermal conductivity and density, as represented in Fig. 10. See details of values in Table 5. It should be mentioned that the OSB plates are likely to burn when exposed to fire and increase the fire temperature in the steel profiles. This complex behaviour was not modelled and should be addressed in the future

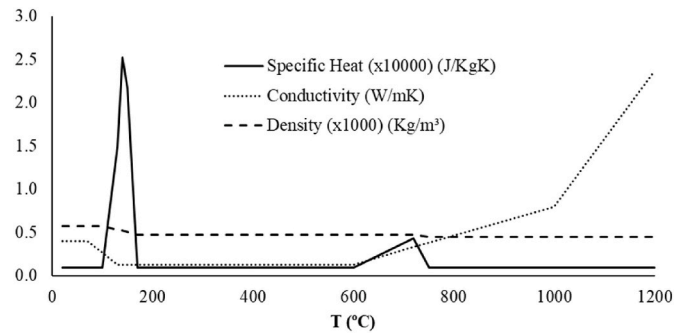


Fig. 7. Thermal properties of gypsum board.

Table 2
Thermal properties of Gypsum board.

Thermal properties - Gypsum board			
T [°C]	Density (x1000) (Kg/m ³)	Conductivity (W/mK)	Specific Heat (x10000) (J/KgK)
20	0.576	0.40	0.0960
70	0.576	0.40	0.0960
100	0.576	0.27	0.0960
130	0.533	0.13	1.4900
140	0.520	0.13	2.5200
150	0.505	0.13	2.1700
170	0.477	0.13	0.0960
600	0.476	0.13	0.0960
720	0.476	0.33	0.4360
750	0.447	0.38	0.0960
1000	0.447	0.80	0.0960
1200	0.447	2.37	0.0960

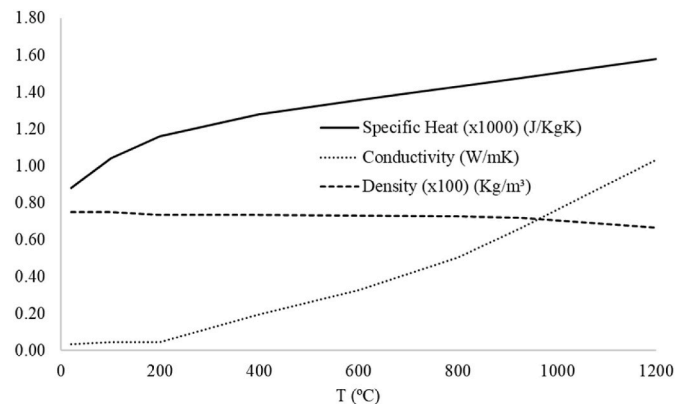


Fig. 8. Thermal properties of rockwool.

Table 3
Thermal properties of rockwool.

Thermal properties - rockwool			
T [°C]	Density (x100) (Kg/m ³)	Conductivity (W/mK)	Specific Heat (x1000) (J/KgK)
20	0.750	0.04	0.8800
100	0.750	0.05	1.0400
200	0.735	0.05	1.1600
400	0.733	0.20	1.2800
600	0.730	0.33	1.3550
800	0.728	0.50	1.4300
925	0.720	0.66	1.4770
1200	0.665	1.03	1.5800

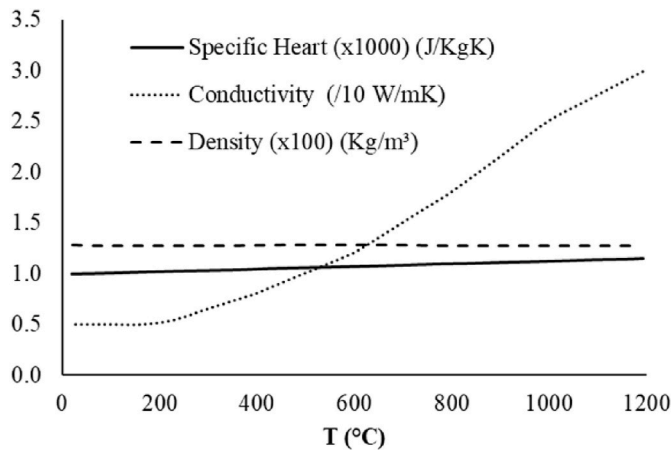


Fig. 9. Thermal properties of superwool (ceramic fibre).

Table 4
Thermal properties of superwool.

Thermal properties - superwool					
T [°C]	Density (x100) (Kg/m ³)	T [°C]	Conductivity (/10) (W/mK)	T [°C]	Specific Heat (x1000) (J/KgK)
20.88	1.2862	27.31	0.50	20.08	0.99342
67.47	1.2796	59.44	0.50	107.63	1.00329
219.28	1.2796	107.63	0.50	228.11	1.01974
337.35	1.2796	165.46	0.50	359.84	1.03289
449.80	1.2829	231.33	0.55	425.70	1.04605
683.53	1.2829	297.19	0.65	514.06	1.05592
795.18	1.2796	375.90	0.77	601.61	1.06579
909.24	1.2796	395.18	0.80	678.71	1.07566
1108.43	1.2796	435.34	0.88	744.58	1.08553
1187.15	1.2796	486.75	0.98	788.76	1.09211
-	-	544.58	1.09	832.13	1.09539
-	-	586.35	1.18	875.50	1.10197
-	-	595.98	1.19	930.92	1.10855
-	-	629.72	1.29	984.74	1.11513
-	-	640.96	1.33	1050.60	1.12500
-	-	658.63	1.38	1094.78	1.13158
-	-	703.61	1.52	1161.45	1.13816
-	-	738.96	1.62	1193.57	1.14474
-	-	787.15	1.76	-	-
-	-	803.21	1.82	-	-
-	-	853.01	1.99	-	-
-	-	910.84	2.19	-	-
-	-	931.73	2.27	-	-
-	-	1001.61	2.51	-	-
-	-	1085.94	2.72	-	-
-	-	1156.63	2.90	-	-
-	-	1195.98	3.00	-	-

preferably using physical tests.

3.3. External wall typologies

The numerical model described previously was used to conduct a study of 6 (six) typologies of non load-bearing external LSF walls, with a real scale of 3 × 3 m considering the analysis of a 2D cross section. The typologies that were considered in this study are presented in Table 6. Typologies 1–3 correspond to full-scale external LSF wall, with a 12 mm thick OSB layer on the external side and a layer composed by two 12.5 mm thick gypsum board layers on the internal side. The cavity had a depth of 90 mm and the LSF wall was composed of six studs, spaced every 600 mm. The studs were considered with a C-shape cold-formed steel (CFS) section, with a height of 90 mm, flange width of 43 mm and a flange lip of 15 mm, the thickness of the profile was 1.5 mm. For the Typology 1, no insulation material was considered in the cavity, while Typologies 2 and 3 contained rockwool and superwool, respectively, as the insulation material. Typologies 4–6 are identical to the previous ones but with a 150 mm CFS cross-section height, instead. For these typologies, the corresponding cavity depth was set to 150 mm, and similarly, the Typology 4 had no insulation material in the cavity, while rockwool and superwool were considered as the insulation material in Typologies 5 and 6, respectively.

All typologies considered in this work represent external walls typically used in Portuguese building stock for the LSF system, as mentioned in the introductory section. The use of the double layer of gypsum boards is recommended in the literature by the scientific community since it increases the fire resistance and prevents the fall off of the plate during the fire, as observed in experimental tests [37,44].

For the numerical analyses, the ISO 834 (see Fig. 12) standard fire curve was used [87] to investigate the fire resistance of these wall typologies resulting in the samples A1 to A6 (Fig. 11 and Table 7). Then, for a direct and easier comparison on the influence of the side of fire exposure, the same heating curve was considered for the same typologies but considering heating from the outer side, resulting in samples A7 to A12 (see Fig. 11 and Table 7). Finally, these latter samples were also simulated using the external fire curve (see Fig. 12) [35], in order to consider a less severe scenario that corresponds to fires occurring at the perimeter of a building but impacting these walls from the outer side, resulting in samples A13 to A18 (see Fig. 11 and Table 7).

It should be mentioned that both the ISO 834 and the external fire curve represent heating curves of fires outbreaking from within inside the building and are used here solely for comparison purposes and do not represent a fire action occurring from the outside of the building, as for example those resulting from forest fires, for which subsequent studies must be carried out. Nevertheless, this underlying and oversimplified assumption enables a comparison between the usual fire resistance calculation for LSF walls, which is based on the ISO 834 fire curve, and its most likely inadequacy for fires impacting the LSF exterior walls from the outside, especially if the resistance criteria (R) is to be evaluated, once the temperature in the steel profiles increases faster in these cases.

3.4. Results

The results were acquired through a numerical simulation with a total duration of up to 300 min in all samples, collecting the temperature from each node according to their location in the samples (see Fig. 13). For each numerical simulation, the temperature evolution is presented for steel (HF, WEB, CF), for the gypsum boards and for the OSB plates (FS), for the cavity (CAV), and for the interface between the double layers of gypsum board (PB1-PB2) (see Fig. 14), in which the average temperatures were collected through the nodes present in the regions that comprise the six stud profiles. The results allow comparing the insulation fire resistance of each typology presented, as well as their behaviour at three temperature levels for each node analysed. The

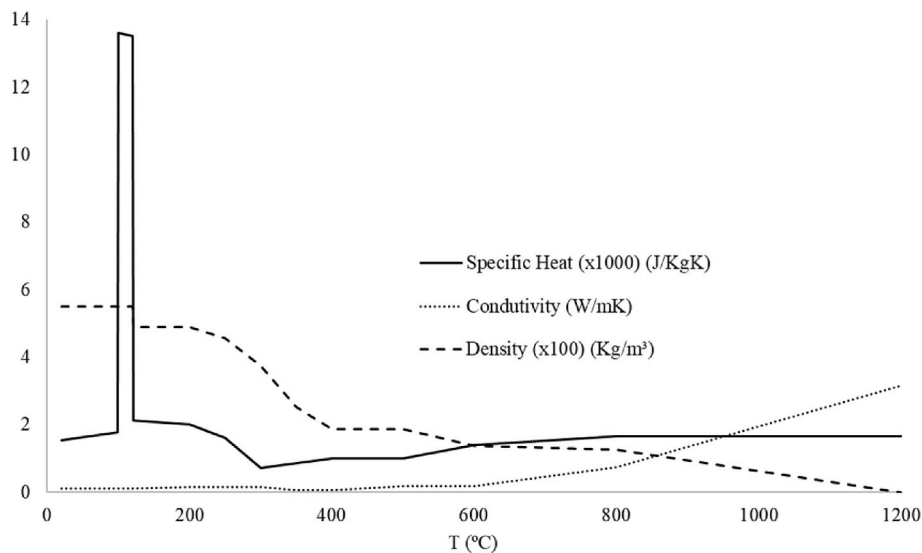


Fig. 10. Thermal properties of the wood derivative (OSB).

Table 5
Thermal properties of Oriented strand board (OSB).

Thermal properties - OSB			
T [°C]	Density (x100) (Kg/ m ³)	Conductivity (W/ mK)	Specific Heat (x1000) (J/ KgK)
20	5.5000	0.12	1.530
99	5.5000	0.12	1.770
100	5.5000	0.12	13.600
120	5.5000	0.12	13.500
121	4.8950	0.12	2.120
200	4.8950	0.15	2.000
250	4.5650	0.15	1.620
300	3.7400	0.15	0.710
350	2.5300	0.07	0.850
400	1.8700	0.07	1.000
500	1.8700	0.19	1.000
600	1.3750	0.19	1.400
800	1.2650	0.74	1.650
1200	0.0000	3.15	1.650

temperature levels were defined as those corresponding to a default critical temperature of the steel, $T(\text{cri}) = 350$ °C, the maximum temperature on the unexposed surface $T(\text{max}) = 180 + 20$ °C, and the average temperature of the unexposed surface $T(\text{ave}) = 140 + 20$ °C. The $T(\text{max})$ and $T(\text{ave})$ are the criteria defined in Ref. [88] for the fire resistance in terms of insulation (I), while the steel temperature 350 °C corresponds to the critical temperature recommended in the EN 1993-1-2 [82] for Class 4 profiles. It worth mentioning that several studies exist in the literature showing that this critical temperature is an oversimplification and could lead to both safe and unsafe results [10] because it depends on the load-level to which the studs are subjected to. A comprehensive discussion on this latter point is, however, out of the scope of the present study and this default critical temperature is herein adopted for comparative purposes.

3.4.1. Fire resistance (I) of LSF walls

The results of the fire resistance (I) based on the unexposed surface of the external walls are given in Table 8 and the temperature evolution is plotted in Figs. 14 and 15 for the ISO 834 fire curve. For samples A1, A2, A3, for a 90 mm cold-formed section height and cavity depth, the maximum fire resistance (I) on the unexposed surface occurred for sample A3 (superwool), reaching the maximum temperature $T(\text{max})$ at 102 min, which represents an increase of 27 min in comparison to sample A2 (rockwool) and 42 min higher than sample A1 (air). With






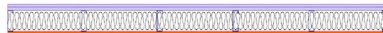
respect to the average temperature $T(\text{ave})$, the highest value was found for sample A3 (superwool), with 156 min. The other samples reached the average temperature, 72 min for sample A2, and 58 min for sample A1. Sample A3 took a longer time to reach the critical temperature of 350 °C in the steel stud at the three measured regions (HF, WEB and CF): corresponding to an increase of 5.77% and 10,00%, at the hot flange (HF); to an increase of 17.46% and 37.04%, at the web; and to an increase of 38.36% and 80.36%, in the cold flange (CF), respectively. For the 150 mm profile and cavity depth, represented by the samples A4, A5 and A6 the highest fire resistance (I) was reached on the sample A6 (superwool), for a maximum temperature $T(\text{max})$ of 140 min, with a difference of 48 min higher than sample A5 (rockwool) and 80 min longer than sample A4 (air) respectively. With respect to the average temperature $T(\text{ave})$, the highest value was found for sample A6 (superwool), with 276 min. The other samples reached the average temperature, 87 min for sample A5, and 69 min for sample A4. Sample A6 took longer to reach the critical temperature of 350 °C at the three regions (HF, WEB and CF): corresponding to an increase of 7.84%, in the hot flange (HF); to an increase of 31.34% and 57.14%, in the web (WEB); to an increase of 69.66% and 160.34%, in the cold flange (CF), respectively.

In summary, the fire resistance ranged from 58 min (sample A1) up to 140 min (sample A6), while the critical temperature in the steel profile was reached between 50 min (sample A1) and 55 min (sample A6), in the hot flange (HF) and between 56 min and 151 min in the cold flange (CF). The presence of the insulation material, as expected, increased the fire resistance of the walls. The fact that the depth of the cavity increased from 90 mm (samples A1-A3) to 150 mm (samples A4-A6) resulted in increased thickness of the insulation material which then resulted in an increased fire resistance (compare the samples A3 and A6 for example). On the other hand, the presence of the insulation material produced greater thermal gradient in the steel profile, as demonstrated by the time needed to reach the critical temperature in HF, WEB and CF in the different samples. For instance, in the sample A4, the critical temperature in HF is reached after 51 min and on the CF after 58 min, while for sample A6 the corresponding times are 55 min and 151 min, respectively.

3.4.2. Comparison with heating on external layer with the ISO 834

For the scenarios where the fire is considered from the outside, using the same heating curve (ISO 834), corresponding to the samples A7-A12 the results are given in Table 9 For the samples A7, A8 and A9, corresponding to the ones with the profile height and cavity depth of 90 mm, the highest fire resistance (I), based on the unexposed surface occurred

Table 6
External wall typologies for numerical modelling.

1	Typologies - Numerical Studies	2	Typologies - Numerical Studies
Outer layer	01 panel OSB - 12 mm	Outer layer	01 panel OSB - 12 mm
Inner layer	02 gypsum board panels - 12.5 mm	Inner layer	02 gypsum board panels - 12.5 mm
Cavity Material:	Air	Cavity Material:	Rockwool
LSF profile data:	90 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm	LSF profile data:	90 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm
Geometry:		Geometry:	
06 LSF profiles spaced between 600 mm axes		a) 06 LSF profiles spaced between 600 mm axes	b)
3	Typologies - Numerical Studies	4	Typologies - Numerical Studies
Outer layer	01 panel OSB - 12 mm	Outer layer	01 panel OSB - 12 mm
Inner layer	02 gypsum board panels - 12.5 mm	Inner layer	02 gypsum board panels - 12.5 mm
Cavity Material:	Superwool	Cavity Material:	Air
LSF profile data:	90 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm	LSF profile data:	150 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm
Geometry:		Geometry:	
06 LSF profiles spaced between 600 mm axes		c) 06 LSF profiles spaced between 600 mm axes	d)
5	Typologies - Numerical Studies	6	Typologies - Numerical Studies
Outer layer	01 panel OSB - 12 mm	Outer layer	01 panel OSB - 12 mm
Inner layer	02 gypsum board panels - 12.5 mm	Inner layer	02 gypsum board panels - 12.5 mm
Cavity Material:	Rockwool	Cavity Material:	Superwool
LSF profile data:	150 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm	LSF profile data:	150 mm thickness Lower flange: 43 mm; Upper flange: 43 mm Lip: 15 mm; Sheet thickness: 1,5 mm
Geometry:		Geometry:	
06 LSF profiles spaced between 600 mm axes		e) 06 LSF profiles spaced between 600 mm axes	f)

for sample A9 (superwool), reaching the maximum temperature T(max) at 137 min, corresponding to an increase of the fire resistance for insulation by 41 min with respect to sample A8 (rockwool) and 76 min with respect to sample A7 (air). Concerning the average temperature T (ave), the highest value was found for sample A9 (air), with 235 min. The other samples reached the average temperature, 97 min for sample A8, and 60 min for sample A7. Sample A9 took a longer time to reach the critical temperature for the steel stud of 350 °C in the three measured regions (HF, WEB and CF): corresponding to an increase of 5.00% and 10,53%, in the hot flange (HF); to an increase of 28.57% and 56.52%, in the web (WEB); and to an increase of 71.79% and 168.00%, in the cold flange (CF), respectively. Concerning the samples A10, A11 and A12 which represent a profile height and cavity depth of 150 mm, the highest fire resistance (I) on the unexposed surface occurred for sample A12 (superwool), reaching the maximum temperature T(max) at 207 min, which represents an increase of 81 min in comparison to sample A11 (rockwool) and 146 min higher than sample A10 (air) (see Table 8,

Figs. 14 and 15). With respect to the average temperature T(ave), the highest value was found for sample A12 (Superwool), with >300 min. The other samples reached the average temperature, 128 min for sample A11, and 61 min for sample A10 (see Table 8, Fig. 14). Sample A12 took longer to reach the critical temperature of 350 °C at the three regions (HF, WEB and CF): corresponding to an increase of 10.00% and 15.79%, in the hot flange (HF); to an increase of 53.13% and 104.17%, in the web (WEB); to an increase of 108.77% and 340.74%, in the cold flange (CF), respectively (see Table 8 and Fig. 14).

Comparing to the results obtained for the inner exposure to fire, similar results for the case of unexposed surface and without any material in the cavity, are observed where a fire resistance of 60 min reached on sample A7 and 61 min on sample A10, but, the critical temperatures in the steel profile are reached earlier, i.e., 19 min for both samples A7 and A10. Moreover, when the insulation material is considered in the cavity, the fire resistance (I) increases considerably, but the critical temperatures reached in the steel profiles average around

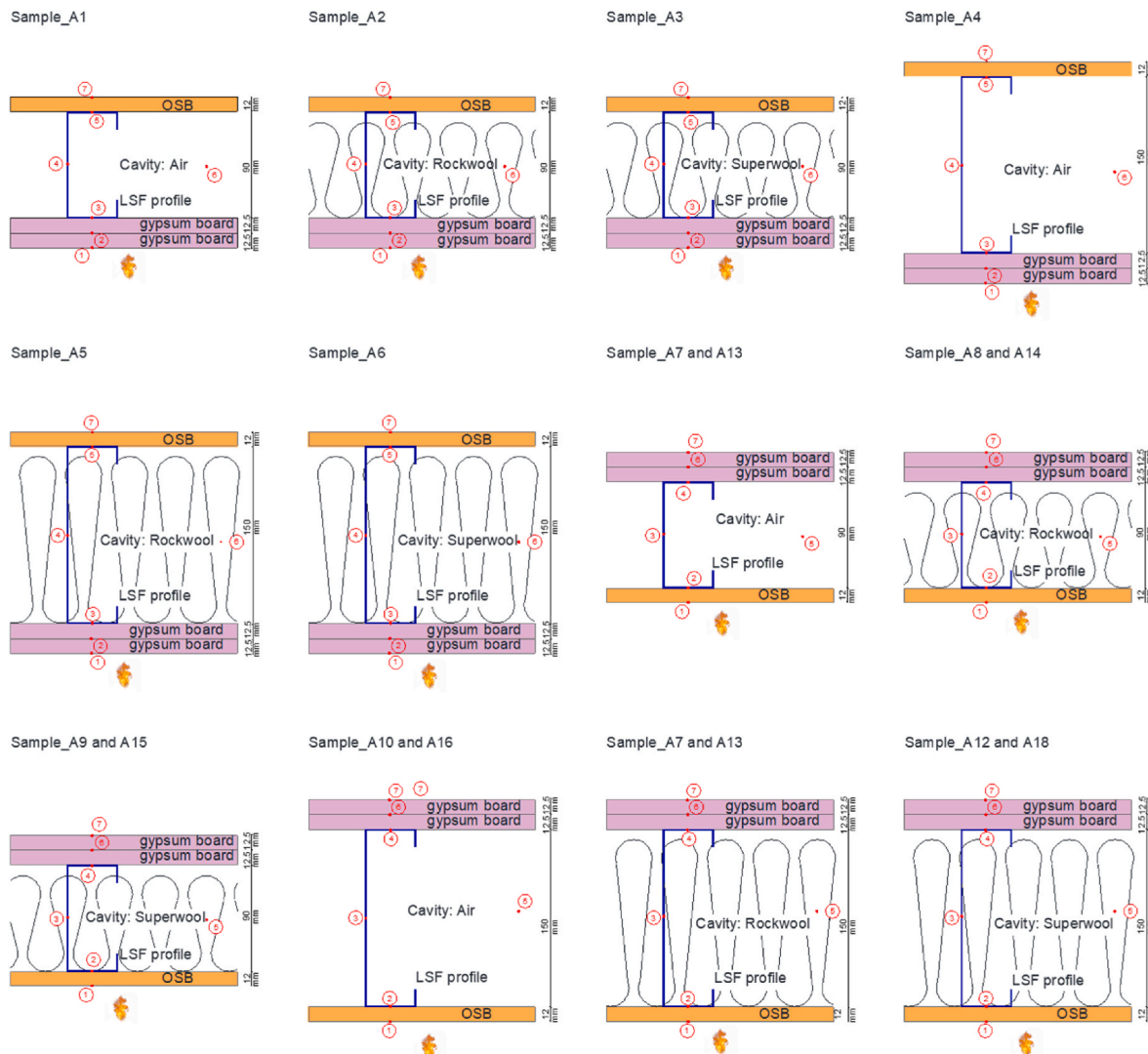


Fig. 11. Samples of external walls and fire heating conditions – LSF stud profiles 90 and 150 mm.

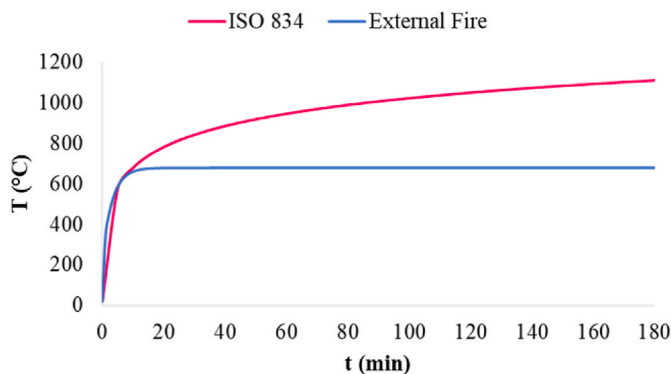


Fig. 12. ISO 834 curve × External Fire curve.

20 min among samples A7-A12, which is much lower in comparison to the cases where the fire is heating the wall from the inside and does not depend on the height of the CFS profile and, naturally, the depth of the cavity and the corresponding insulation material (compare samples A7-A9 and A10-A12). These results suggest a possible inadequacy of considering the same methodology to classify the fire resistance of LSF external walls exposed to fires from the outside. In fact, while the results

show that the same insulation fire resistance (criteria I) can be defined, because the critical temperatures in the steel are reached much earlier a careful analysis of the loadbearing function (criteria R) must be sought.

3.4.3. Comparison with heating on external layer with the external fire curve

Considering the external fire curve, representing a fire scenario from inside a building that has spread to the outside, and that is impacting the outer layer of the external walls (samples A13-A18) the results show an increased fire resistance in comparison to that obtained from a fire heating the inner layer of the walls (A1-A6) as well as an increased resistance in comparison with the samples submitted to the ISO 834 curves from the outer side (A7-A12) because this fire represents a less severe fire scenario [34]. The maximum temperature $T(\max)$ and average $T(\text{ave})$ on the unexposed surface exceeded the time of simulation (5 h) for the samples: A15 (superwool with 90 mm profile); A17 (rockwool with 150 mm profile) and A18 (superwool with 150 mm profile). Other samples obtained results below the numerical simulation limit value, being: A13 (90 mm air profile) $T(\max) = 135$ min and $T(\text{ave}) = 126$ min; A14 (rockwool with 90 mm profile) $T(\max) = 260$ min and $T(\text{ave}) = 186$ min and A16 (air with 150 mm profile) $T(\max) = 136$ min and $T(\text{ave}) = 127$ min.

Focusing on the critical temperature reached in the steel profile on the samples heated from the outer side, A7-A12 with the ISO 834 and

Table 7
Summary of the geometric and technical information of the samples.

Sample	LSF studs	Spacing (mm)	Cavity	Thickness (mm)	Outer layer (mm)	Inner layer (mm)	Curve (heating side)
A1	6	600	Air	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A2	6	600	Rockwool	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A3	6	600	Air	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A4	6	600	Air	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A5	6	600	Rockwool	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A6	6	600	Superwool	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Inside)
A7	6	600	Air	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A8	6	600	Rockwool	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A9	6	600	Superwool	90	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A10	6	600	Air	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A11	6	600	Rockwool	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A12	6	600	Superwool	150	OSB12	Gypsum board2 × 12.5	ISO 834 (Outside)
A13	6	600	Air	90	OSB12	Gypsum board2 × 12.5	External Fire (Outside)
A14	6	600	Rockwool	90	OSB12	Gypsum board2 × 12.5	External Fire (Outside)
A15	6	600	Superwool	90	OSB12	Gypsum board2 × 12.5	External Fire (Outside)
A16	6	600	Air	150	OSB12	Gypsum board2 × 12.5	External Fire (Outside)
A17	6	600	Rockwool	150	OSB12	Gypsum board2 × 12.5	External Fire (Outside)
A18	6	600	Superwool	150	OSB12	Gypsum board2 × 12.5	External fire (Outside)

LSF profile data 90: Lower flange: 43 mm; Upper flange: 43 mm; Lip: 15 mm; Sheet thickness: 1.5 mm
 LSF profile data 150: Lower flange: 43 mm; Upper flange: 43 mm; Lip: 15 mm; Sheet thickness: 1.5 mm

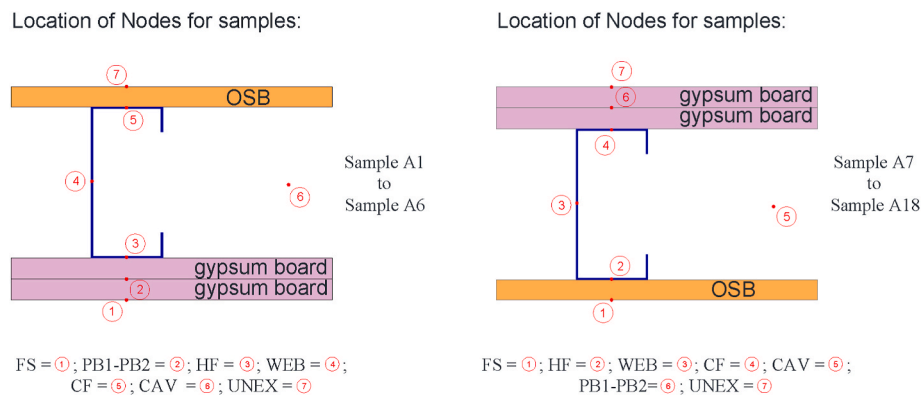


Fig. 13. Location of the nodes to extract the evolution of temperature in each sample.

A13-A18 with the external fire curve, the same conclusions are observed, taking a longer time to reach these temperatures in all samples in the three regions. For the hot flange (HF), the minimum difference is obtained between samples A11 (20 min) and A17 (25 min) representing an increase of 25% while the maximum difference occurs between A9 (21 min) and A15 (33 min) where an 57% increase is noticed; for the web (WEB) these differences become 63% and 133% for samples A10 (24 min) and A16 (39 min) and A12 (49 min) and A18 (114 min), respectively; and for the cold-flange (CF) the differences become 70% between A10 (27 min) and A16 (46 min) and greater than 152% between A12 (119 min) and A18 (>300 min). These differences, ranging from 25% to above 152% highlight the need for a consistent methodology to calculate the fire resistance of the LSF external walls, in particular, if their resistance criteria are to be ascertained.

4. Conclusions

In this work a comprehensive literature review was carried out to highlight the limited research available focusing on the fire behaviour of Light Steel Framing (LSF) external walls typologies, as the majority of the previous studies have focused on the internal walls which are morphologically different. Most of the external walls are also unsymmetrical and for that reason require the fire analysis from both sides, using different fire curves, corresponding to different fire scenarios.

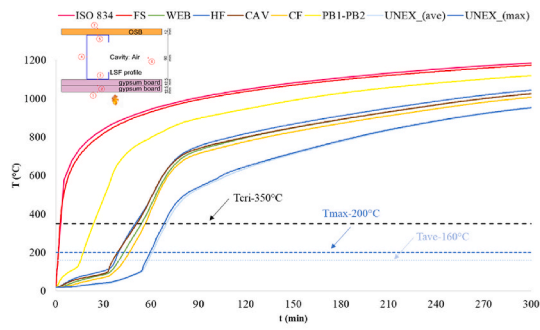
To increase the knowledge on this regard, this work presents a

detailed numerical analysis of the fire resistance of 6 types of external walls that were submitted to different fire scenarios using the finite element method (2D). The samples were modelled following the European rules to determine the fire resistance according to the insulation criterion (I), using the standard fire curve ISO 834 as the heating curve. Typical external wall configurations with and without insulation materials were analysed and with two cavity sizes, namely 90 and 150 mm, that correspond to practical dimensions of the cold-formed steel sections used in the LSF. The external layer of the wall was considered with OSB plates while the internal layer is assumed to be made with gypsum boards. For the insulation of the cavity region, two materials were considered (rockwool and superwool). In terms of insulation material, generally the results showed a higher fire resistance for samples with superwool insulation in the cavity, compared to the other samples in which it was decided to use rockwool or assuming the void cavity modelled by radiation. In addition, a higher fire resistance of the samples with a cavity of 150 mm was observed, due to the presence of a thicker insulation layer.

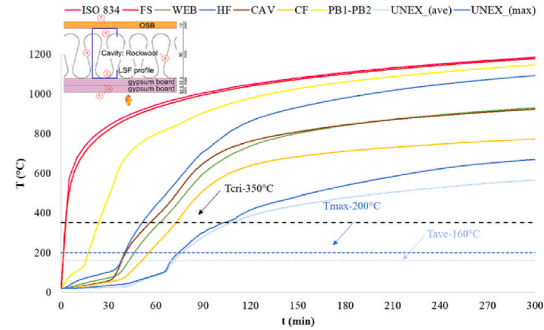
A fire resistance (I) ranging from 58 min for the LSF walls without insulation and 90 mm cavity depth and 140 min for the wall with 150 mm cavity depth and superwool insulation material was obtained.

In addition, seeking a simple and direct comparison between a possible fire exposure from the outside, the ISO 834 curve and the external fire curve were also considered to investigate the temperature evolution in the LSF walls and in the steel profile. Although these two

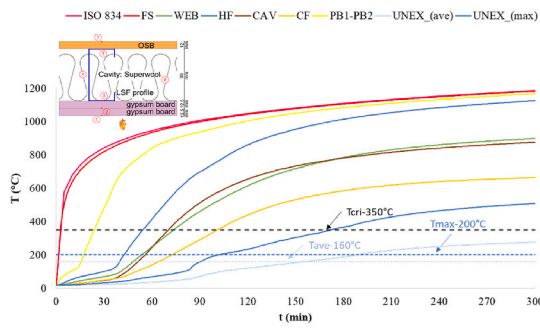
Sample A1



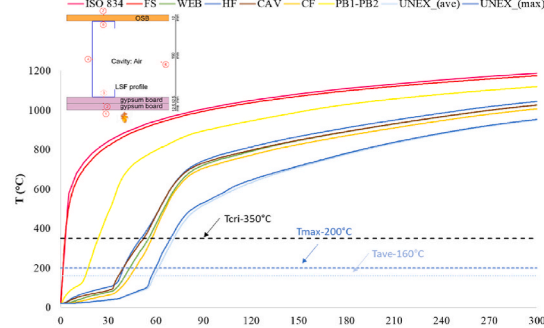
Sample A2



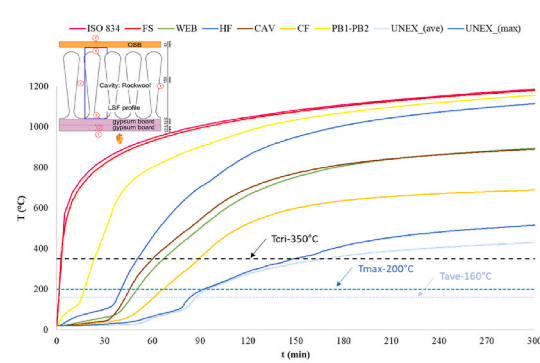
Sample A3



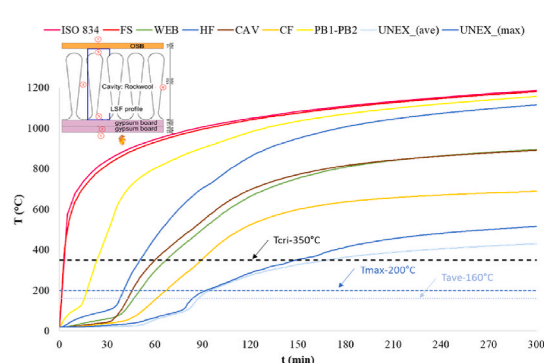
Sample A4



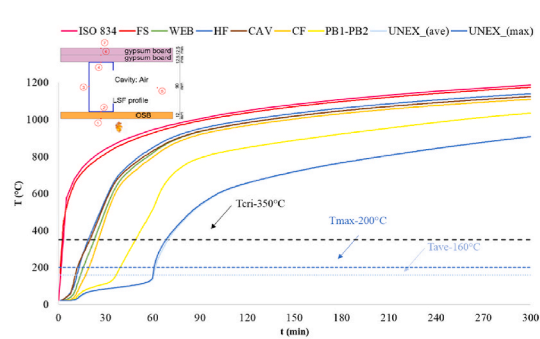
Sample A5



Sample A6



Sample A7



Sample A8

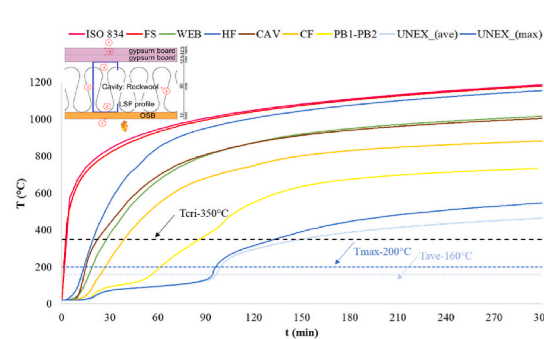
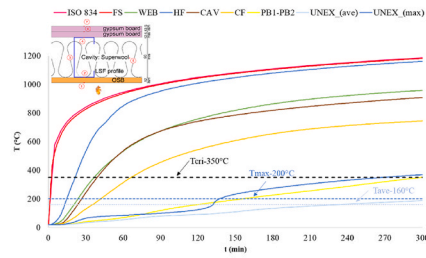
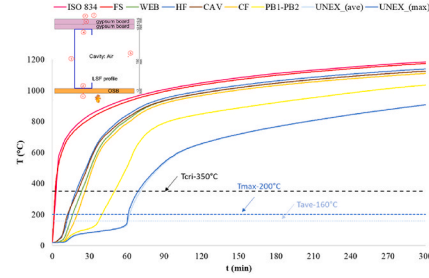


Fig. 14. Results of the temperature evolution with time during the numerical simulations of the various samples.

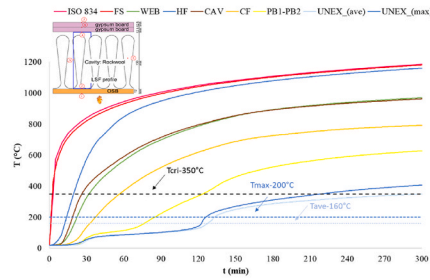
Sample A9



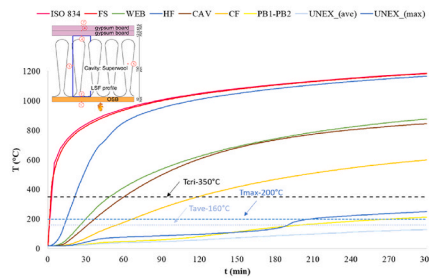
Sample A10



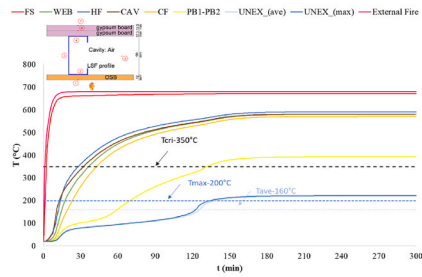
Sample A11



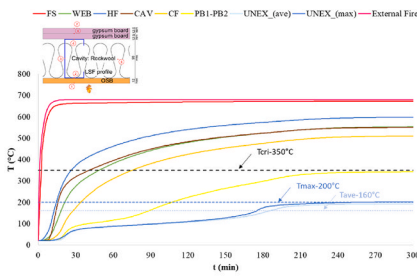
Sample A12



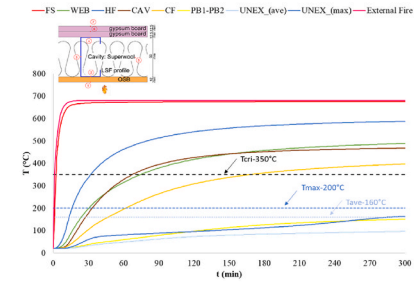
Sample A13



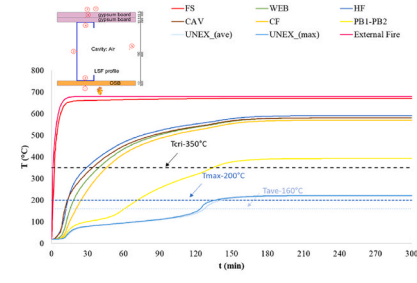
Sample A14



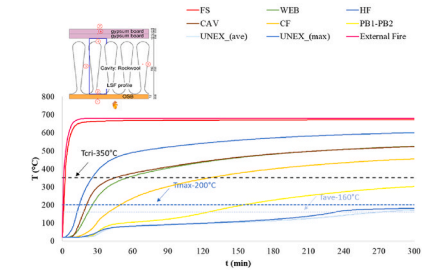
Sample A15



Sample A16



Sample A17



Sample A18

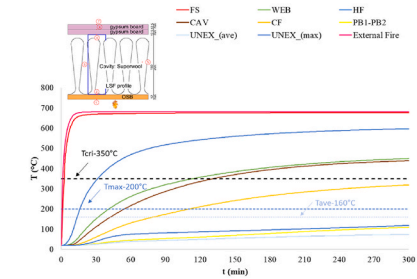


Fig. 14. (continued).

Table 8
Numerical results of the samples at the unexposed surface temperature and critical temperature in LSF profiles.

Maximum and Average Temperature			Critical Temperature in LSF profile			
Samples	T(max) (min)	T(ave) (min)	Samples	HF (min)	WEB (min)	CF (min)
Sample A1	60	58	Sample A1	50	54	56
Sample A2	75	72	Sample A2	52	63	73
Sample A3	102	156	Sample A3	55	74	101
Sample A4	60	59	Sample A4	51	56	58
Sample A5	92	87	Sample A5	51	67	89
Sample A6	140	276	Sample A6	55	88	151

heating scenarios do not represent realistic external fires and were used here as an academic exercise, they allow important insights and inference until a more realistic procedure is developed. Based on these results, it was demonstrated that the evolution of temperature is slower in the LSF walls when exposed to fire from the outside. In fact, comparing the behaviour of the same typology for a standard fire simulation, the differences can be higher than 60 min for the fire resistance for insulation obtained between a fire from the inner side or the outer side. On the other hand, the temperatures reached on a fire from the outside should be less severe and, in these circumstances, it was shown that using a less severe fire curve (external fire curve) can lead to even higher fire resistance. Summing up, it could be recommended that the determination of the fire resistance of external LSF walls be calculated with

the ISO 834 and heating from inside the building, as usual. However, an interesting observation brought up by this study shows that the recommended critical temperature of 350 °C is reached much earlier in the steel profiles when heating is considered from the outer side. This raises some concerns that the fire resistance can be greatly impacted because the steel profiles have a key role in the capacity of these walls added up to the fact that it is expected that they also have a load-bearing function and, for that reason, the methodology to calculate the fire resistance of the walls might not be adequate for the case of heating from the external side.

Finally, this work highlights the need to carry out more research, particularly experimental tests, to validate and confirm these findings. Moreover, new numerical and experimental studies can be performed to further investigate the fire behaviour of external LSF walls built from other materials, for instance by replacing the OSB panels by cementitious boards, panels by Coretech, panels by MGO, among other materials used in typologies of external walls in LSF. Also, it would be crucial to investigate the fire resistance of these walls against more realistic external fire curves such as those resulting from forest or façade fires, which was not covered in this work. Nevertheless, given the limited research on the topic it is expected that this exploratory study will drive more attention to this subject by the fire research community and thus contribute to enhance the global understanding of the fire behaviour of LSF external walls, ultimately leading to safer structures against fire.

CRedit authorship contribution statement

Leonardo Torres: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

Carlos Couto: Supervision, Data curation, Software, Resources, Conceptualization, Writing – review & editing.

Paulo Vila Real: Supervision, Conceptualization, Writing – review &

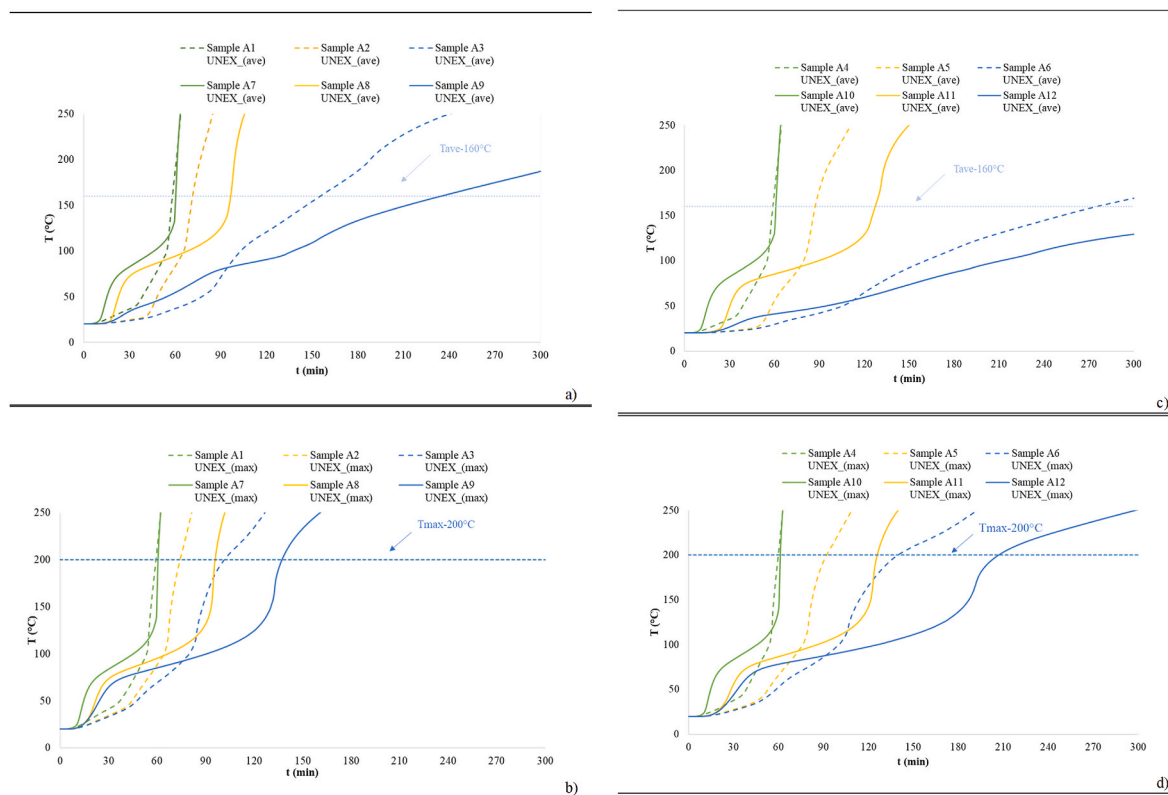


Fig. 15. Comparative graph of the results on the unexposed surface between the samples: a) Unex (ave) – Internal fire exposure (A1, A2, A3) × External fire exposure (A7, A8, A9); b) Unex (max) – Internal fire exposure (A1, A2, A3) × External fire exposure (A7, A8, A9); c) Unex (ave) – Internal fire exposure (A4, A5, A6) × External fire exposure (A10, A11, A12); d) Unex (max) – Internal Fire (A4, A5, A6) × External Fire (A10, A11, A12).

Table 9

Numerical results of comparing samples between ISO 834 curve × External Fire curve at the unexposed surface temperature and critical temperature in LSF profiles.

Maximum and Average Temperature			Critical Temperature in LSF profile			
Sample	T(max) (min)	T(ave) (min)	Sample	HF (min)	WEB (min)	CF (min)
A7	61	60	A7	19	23	25
A8	96	97	A8	20	28	39
A9	137	235	A9	21	36	67
A10	61	61	A10	19	24	27
A11	126	128	A11	20	32	57
A12	207	>300	A12	22	49	119
A13	135	126	A13	28	37	43
A14	260	186	A14	27	50	76
A15	>300	>300	A15	33	75	169
A16	136	127	A16	29	39	46
A17	>300	>300	A17	25	55	125
A18	>300	>300	A18	32	114	>300

editing.

Paulo Piloto: Supervision, Validation, Software, Writing – review & editing.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Acknowledgments

Carlos Couto acknowledges the funding from FCT – Fundação para a Ciência e a Tecnologia, I.P., under the Scientific Employment Stimulus – Institutional Call – CEECINST/00026/2018.

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