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Review

Development of Lightweight Steel Framed Construction Systems for Nearly-Zero Energy Buildings

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Abstract: Light steel frame (LSF) building systems offer high structural resilience, lower costs due to fast prefabrication, and high ability to recycle and reuse. The main goal of this paper was to provide state-of-the-art main components for such systems with the intention to be implemented for use in nearly-zero energy buildings (NZEBs). A brief historical outline of the development of LSF systems was given, and the key parameters affecting the design and use of LSF systems were discussed. The influence of the individual components of the LSF system (steel studs, sheathing boards, and insulation materials) was then thoroughly discussed in light of relevant research on energy efficiency and other important properties (such as sound protection and fire resistance). Web of Science and Scopus databases were used for this purpose, using relevant key words: LSF, energy efficiency, sheathing boards, steel studs, insulation, etc. Several research gaps were identified that could be used for development and future research on new LSF systems. Finally, based on the analysis of each component, an innovative LSF composite wall panel was proposed which will be the subject of the authors' future research. Conducted preliminary analysis showed low thermal transmittance of the system and indicates the path of its further research.

Keywords: lightweight steel frame (LSF); nearly-zero energy buildings (NZEB); sheathing boards; insulation materials

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1. Introduction

As the building sector accounts for about 40% of total final energy consumption in the European Union and is responsible for 36% of total carbon dioxide (CO_2) emissions, energy efficiency measures in buildings are increasingly recognized as a tool to achieve sustainable energy supply, reduce greenhouse gas emissions, and promote the competitiveness of European economies [1,2]. Therefore, European legislation has established a cross-cutting framework with targets for high energy performance of buildings based on two key documents: the Energy Efficiency Directive (EED) [3] and the Energy Performance of Buildings Directive (EPBD) [4]. The EPBD has established several new or strengthened requirements, such as the obligation for all new buildings to be a 'nearly-zero energy building' (NZEB) by the end of 2020 [5]. In general, an NZEB is a building with a very high energy performance, a significant portion of which should be met by energy from renewable sources, including energy from renewable sources generated on-site or nearby [5]. The requirements of the EED and EPBD are primarily aimed at reducing heat losses through the building envelope, since heat losses through the building envelope account for a large share of the total energy consumption of buildings. While thermal performance of the building envelope is only one of the many factors influencing the energy needs of the specific building, i.e., geometry, orientation, climate conditions, thermal mass, HVAC systems, etc., it is the parameter most easily influenced by the building industry.

Poor thermal performance of the building envelope causes large heat losses, making the benefits of highly efficient HVAC systems negligible.

Light steel frame (LSF) structures are already recognized worldwide (especially in the United States of America (USA), Australia, and Japan [6]) as the most suitable building system with the possibility of achieving low energy demand. This is due to the great flexibility of the system, the possibility of innovation, and the increased use of modern insulating materials as an essential part of the construction with different construction techniques to increase the effectiveness of energy saving. In addition, LSF structures have other significant advantages that make them a popular alternative to traditional masonry and mortar structures. The advantages of LSF structures compared to conventional building systems include light weight, short construction time, reduced labor and cost, reusability and recyclability, industrial quality control, structural resistance, etc. [1,7]. For example, being lighter and thinner than conventional building envelope elements, they provide the same net floor area while decreasing the gross heated volume. Moreover, all these advantages have an impact on the reduced carbon footprint of a building, thus offering a potential for the use of LSF structures in European countries, especially for low-rise buildings such as residential houses and buildings blocks.

Considering the potential of LSF buildings for meeting the NZEB requirements of EED and EPDB, and as the heat losses are easiest to influence, this paper reviews the development of such systems throughout history, presents the current state-of-the-art, evaluates the types of their components, and identifies research gaps that could lead to further development of such systems for use in NZBs. The Web of Science and Scopus databases were used to find the available insulation, sheathing, and face sheets used in LSF construction and relevant research on the energy efficiency of such systems.

2. Historical Development of Light Steel Framed Construction Systems

Early usage of LSF constructions can be found during the "Gold Rush" in the mid-19th century [8], and they were considered as the first prefabricated houses [9]. At first, they were built of wood, but for fire safety reasons, the wood was replaced by an iron skeleton and sheathed with iron plates.

According to [10], 1850 is the year when the use of cold-formed steel (CFS) members in construction started. This was the opportunity for steel to gain a foothold in the construction industry [11]. The first example of a highly detailed prefabricated building was the "DUCLOS iron demountable buildings", as shown in Figure 1. They were made of iron bars with bolted and riveted joints and had cladding of metal plates. This was a patent by France Duclos in 1890 in France [12].

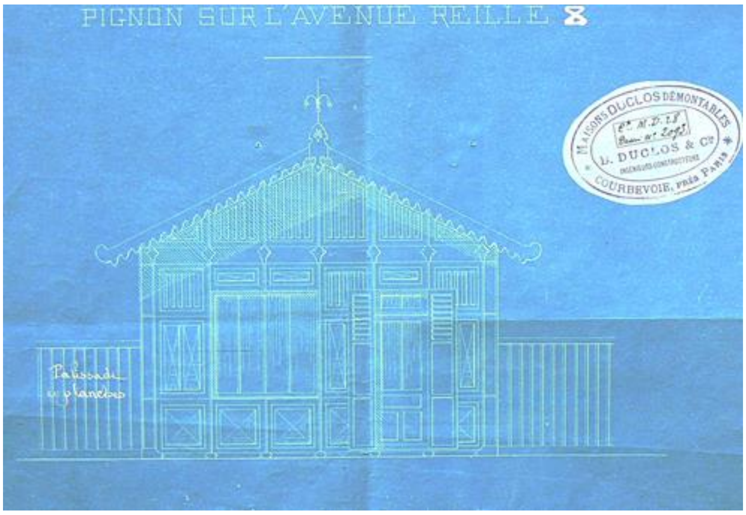
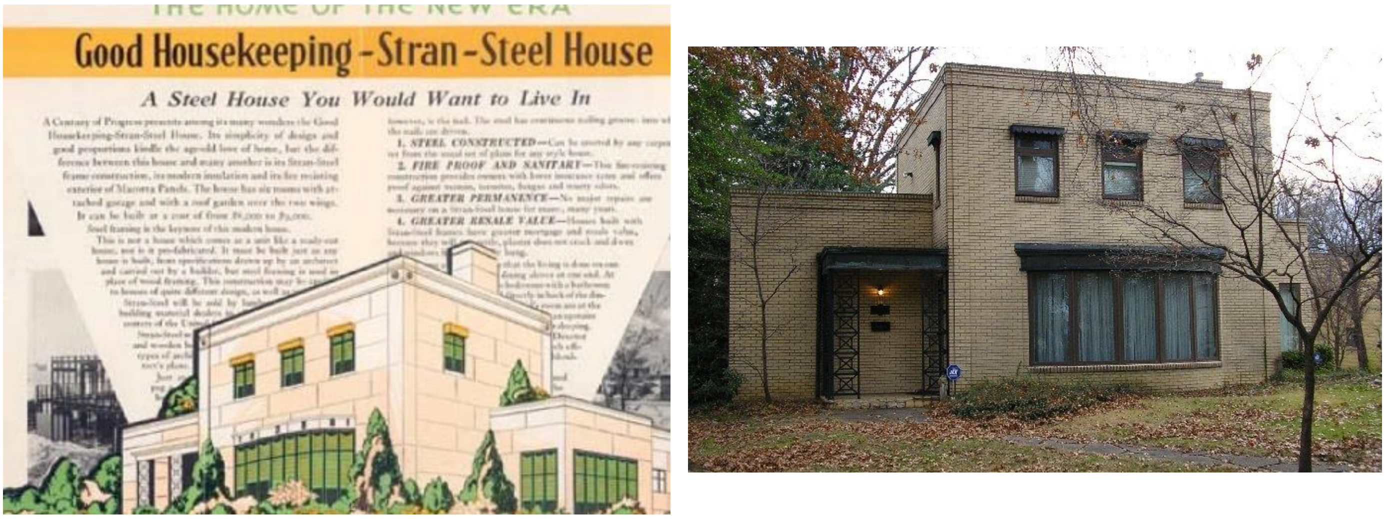


Figure 1. DUCLOS iron demountable buildings (France patent, 1890) [13].

With the rise of the lightweight construction industry, insulation materials became very important. The first use of insulation materials in lightweight construction was recorded in 1897 when an American chemical engineer, Charles Corydon Hall, manufactured rock wool from limestone and began commercial production of rock wool in Alexandria (Indiana, USA) at his factory called the Crystal Chemical Works. Rock wool was a very popular insulation material for lightweight structures [14]. Later, rock wool was replaced by asbestos and was touted as the best alternative [15]. Although it was available, insulation was not considered necessary until the 1920s, when public awareness of the importance of thermal insulation was raised. The increasing popularity and use of lighter building materials and the gradual introduction of air conditioning contributed to a higher need for thermal insulation [16].

A notable achievement in LSF design was made by architect Howard Z. Fisher, who developed the "House of the Future" in Chicago in 1933. The house was built entirely of steel frame construction with the knowledge of leaders in the railroad and automobile industries. He also founded "General House", opening up a completely untapped field of residential construction. Additionally in 1933, "Armco Steel Corporation" introduced the first standing seam metal roof panel. A significant increase in the development of such houses was recorded in the mid-20th century by the "Lustron houses". During World War II, Lustron used roof, siding, and sheet metal products to develop warehouse buildings, and in 1940, "Lustron Homes" built and sold nearly 2500 fully equipped steel-framed houses [17].

In addition to residential construction, cold-formed steel has also proven successful in commercial and industrial applications. One example is the Virginia Baptist Hospital, built around 1925 in Lynchburg (Virginia, USA). The walls were masonry but the floors were framed with double back-to-back cold-formed steel sections. After observations during the renovation, it was confirmed that these beams were still supporting loads after more than 80 years [18]. This also shows that the service life of this type of construction can be considerable, as shown in Figure 2a,b. Figure 2a shows a postcard from 1933 advertising a "Stran-Steel house", while Figure 2b shows the same house today.



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

Figure 2. (**a**) Postcard advertising Stran-Steel house at the 1933 Century of Progress World's Fair; (**b**) "The Ensign-Seelinger Home", a Stran-Steel house in Huntington, West Virginia is on the National Register of Historic Homes by Dr. Kathy L. Seelinger [19].

After World War II, Lustron began building houses in an assembly line fashion using steel plates for framing, siding, trusses, and roof tiles. Their houses were cost effective, fast, and easy to build [17].

As cold-formed steel became more popular as a building material, the use of gypsum board (GB) sheathing also grew. In 1931, the Gypsum Association conducted a series of fire tests and published a manual on the fire resistance of gypsum board. The United States Gypsum Company developed a nailable stud framing system called "Trussteel", which was advertised as "the original stud framing system of open construction for erecting hollow, fire-resistant partitions . . . " This led to the 1950s, which became known as the era of gypsum board [20] and steel stud framing for non-combustible partitions with the introduction of self-drilling screws.

As the market grew, it was difficult to specify standard products because all products had their own span and load tables until the Metal Stud Manufactures Association (MSMA) developed a unified catalogue. The last major development in LSF design occurred in the 1990s, when manufacturers realized that many engineers did not understand the complexity of AISI specifications, and as a result, an association called the Light Gauge Steel Engineers Association was formed. In 2001, it published the North American Specification for the Design of Cold-Formed Steel Structural Members. AISI then formed the Committee on Framing Standards (COFS) to develop specific standards for steel framing used in lightweight structures.

Nowadays, product standardization is in its final stages and new products are being developed. The Cold-Formed Steel Engineers Institute (CFSEI) has developed design guides for each of the COFS standards, as well as computer-aided design details (CAD), technical notes, and online and live courses for steel design. Software developers have released programs that leverage the provisions of the specifications and standards to provide fast, accurate, and in some cases, complete 3D building information modelling that incorporates the design of steel framing elements and systems.

Australian company Framecad is one of the leaders in the construction industry of CFS. Drawing on previous knowledge from historical developments, it offers research and development of intelligent systems that can be incorporated into the design and construction of CFS structures, providing fast and safe buildings for various project requirements [21].

Today, LSF structures have been developed as a fast and relatively simple system since most of the components are prefabricated. It depends on the type of prefabricated elements: (1) stick-framing or stick-built, (2) panelized or areal, and finally, (3) modular or volumetric construction. From the environmental point of view, systems (1) and (2) are better adapted to microclimatic conditions [22,23]. The stick-built construction method is fully assembled at the construction site, where the elements are often pre-cut but the connections are made on site. This method of construction is not often used for larger buildings because it increases construction time and cost. As stick-built LSF construction is still heavily site-based, the trend for modern buildings is more toward the modular system because it provides better quality control and allows for precise prefabrication that would otherwise not be possible on site. Panelized constructions are prefabricated in the factory and later assembled on the construction site. This ensures geometric accuracy and reliability while reducing construction time. Modular LSF structures are completely prefabricated at the factory and often delivered to the construction site with all components, finishes, and features.

3. Components and Its Influence on Achieving NZEBs

The composition of LSF structures in use today has not fundamentally changed over the years and consists of three different main components: cold-formed steel sections, sheathing boards, and insulating materials [22]. In addition, there are fastening materials such as self-drilling screws, rivets, nails, staples, etc., as well as air- and water-tight membranes and the finishing cover layers [24]. The finishing layers can be plaster, tiles, bricks, cladding panels, etc., depending on the desired purpose and construction. Since the load-bearing steel elements increase the heat loss through the component, it is important to separate them from direct exposure, and here, the face layer can have a great influence.

3.1. Cold-Formed Steel Members

CFS members are widely used in the construction industry because they offer many advantages compared to other building products and materials [23]. CFS is considered the most sustainable and increasingly popular modern building product in the construction industry [25] and is mainly used in the commercial sector where entire buildings are constructed. Table 1 shows the advantages of CFS over conventional materials, some of which compare directly with hot-rolled steel (HRS) as the next product in terms of performance. CFS components are used for a variety of project requirements, whether as a complete structure or for smaller structures where only a portion of CFS is used, such as steel connectors, vertical deflection connectors, rigid connectors, and more. The different types of CFS have specific applications in different parts of buildings, such as main walls, shear wall panels, roof elements, etc. [23]. These types differ from each other by the shape of the profiles, which are formed in cold rolling machines. Two main types of CFS are framing members and panels (decks). Framing members are used for shell construction and are usually in the form of C-sections, Z-sections, I-sections, angles, hat sections, T-sections, and tube sections [26]. Of the above, C-sections are most commonly used for LSF structures. The main function of each frame member is to support loads and provide structural strength and stiffness. Secondary elements from CFS are joists, studs, decks, or panels. This category of CFS is generally used for roof and floor slabs, wall panels, cladding materials, and bridge formwork. Some basic thermophysical properties are explained in the next section.

Table 1. Advantages of CFS in comparison with current traditional construction methods [25].

Easy adaptation to project requirements	Corrosion resistance
Less cost to environment (manufacturing process)	Lower long-term cost (maintenance and durability)
Easy of prefabrication (automation)	Easy extension
Less steel with same performance	No moisture-related expansion
Side effects of cooling (manufacturing process)	Recyclable
Precision (dimensional stability)	Does not contribute to the fire development
High strength and stiffness	Safer in natural disasters (earthquake)
Fast construction (assembling)	Easy erection of installations
Mold resistance	Economic in transportation and handling

CFS is necessary for the modern construction industry, which requires maximum safety and strength embedded in a supporting structure [25]. It is very beneficial for achieving thermal performance of NZEB buildings because it can be easily combined with other components as the main structural system. CFS is usually thin in relation to its width and can buckle at stresses below the yield stress. Such elements do not necessarily fail when their buckling stress is reached and often continue to carry the load. In recent years, deformation buckling has been considered as one of the most important limit states for the design of CFS beams and columns. Since the cross-sections of CFS are relatively thin and in some sections, the center of gravity and the sheer center do not coincide, flexural torsional buckling can be a critical factor for compression members. Web curvature is also a known problem that often becomes critical in design. The efficiency of using high-strength steel depends on the type of failure mode. Under certain conditions, such as columns with large slenderness ratios, failure is usually limited by elastic buckling; therefore, the use of high-strength steel is not always justified in terms of total cost.

The main disadvantage of CFS with respect to NZEBs is the high thermal conductivity of steel. Significant heat loss (thermal bridging) can be minimized by sheathing, insulation, and careful detailing. Better thermal performance can be achieved in other ways besides increasing insulation and sheathing thickness. In reviewing the literature, it was found that different authors have studied different ways to reduce thermal bridging. Authors such as Roque et al. [1] have found that direct contact between the steel and the sheathing reduces the U-value of the structure and that the thermal performance is overestimated by about 50% if this is not taken into account. In the work of Soares et al. [24], some techniques to reduce thermal bridges are presented, such as the simplicity of the façade geometry, the application of a continuous insulation layer on the outside of the steel framing, the avoidance of interruptions of the insulation layers, the installation of windows and doors in contact with the insulation, and the attachment of the studs to the external insulation layer with fasteners with low thermal conductivity.

Slotted webs of this type of studs can improve the thermal insulation of exterior walls [27]. Santo et al. [7] concluded that the spacing between steel studs, the thickness of the steel, and the cross-sectional profile significantly affect thermal bridging. Slotted steel studs are now available in the market to improve thermal performance [28]. Kosny et al. [29] studied how the spacing between steel studs affects the R-value for different insulation thicknesses and concluded that the R-value can be increased by 20% by optimizing these parameters. Santos in [7] also presented some other strategies such as: slotted steel studs, flange stud indentations, thermal brakes, and thermal break strips. Martins et al. [30] added that fastening bolts can be used instead of horizontal steel plate connections to reduce thermal bridging. He also concluded that the best solution is a combination of several strategies, such as rubber strips (10 mm), slotted steel sections, and a reduction in bolted connections. On the other hand, Feng et al. [31] concluded that the shape of the cross-section does not have a decisive effect on the temperature distribution. Dias et al. [32] concluded that the variation of the bolt cross-section can also contribute to the increase in the strength, taking into account the influence of the sheathing limitations.

As can be seen from the literature review, the introduction of CFS into the NZEB system as the main structural component increases the possibility of potential thermal bridges, and the main problem arises from the direct connection of CFS to the sheathing. In order to reduce the thermal bridges and increase the thermal performance, possible configurations of CFS should be introduced in LSF by changing the parameters derived from the above-mentioned previous research. These parameters should be carefully selected because they affect both thermal and structural performance. For example, increased spacing between bolts can improve thermal performance but degrade structural performance. In addition, the static performance of CFS is also affected by other components (sheathing and PUR) that provide lateral restraint against instability. For this reason, all components must be analyzed together when solving such a complex problem.

3.2. Sheathing Boards and Finishing Layers

Appropriate boards for LSF are usually selected based on the requirements of fire resistance, sound insulation, moisture resistance, durability, and economy [33,34]. As noted by Soares et al. [26], the most common sheathing panels for low-rise residential buildings are oriented strand boards (OSBs), structural plywood, and GBs. For non-residential industrial buildings, steel sheathing is often used due to its high stiffness and strength, good surface finish, and high impact resistance. Sheathing boards can be divided into metallic and non-metallic.

The thickness of steel sheathing is about 1 mm [35] and is offered in various profiles and connected to the rest of the LSF structure by rigid connections such as self-drilling screws. This, in turn, can also affect the acoustic performance of the entire building [36]. As for thin steel elements used as load-bearing elements in LSF structures, the steel sheathing has a very high thermal conductivity. This fact makes them impractical for NZEBs, since thermal bridges predominate. For comparison, the thermomechanical properties of some steel variants are shown in Table 2.

Table 2. Typical mechanical and thermal properties of steel [35,36].

Material	ρ [kg/m^3]	E [GPa]	ν [–]	α [°C·10^{-6}]	λ [W/mK]
Mild steel	7800	206	0.29	13	46
Steel-cold rolled HS	7800	206	0.30	11	46
Stainless steel	7700–7900	196	0.29	11-18	14

Since the high thermal conductivity favors the formation of thermal bridges, it is essential to provide adequate insulation to minimize this effect. In most cases, steel is often incorporated in the form of sandwich cladding panels with mineral wool (MW), polyurethane (PUR), or polyisocyanurate (PIR). The U-value of such panels is highly dependent on the type of insulation and thickness but generally ranges from 0.11 W/(m^{2}K) to 0.56 W/(m^{2}K) [37–39]. This means that the use of sandwich cladding panels can potentially meet the NZEB requirements, as they comply with the prescribed thermal transmittance values (U-values). In addition, there are some steel sheathing options that are used as fire protection layers. Steau et al. [38] reported that two types of fire-resistant composite steel panels are currently available on the market, containing a fiber-reinforced or lightweight cement core and using steel (perforated and galvanized) as the outer protective layer. However, these steel sheathing panels do not provide adequate thermal insulation and require additional insulation to meet NZEB requirements for building elements at the building envelope.

Other sheathing options are non-metallic and therefore better suited to achieve NZEBs due to their lower thermal conductivity compared to steel. The main problem with these types of sheathing boards is that most of them are manufactured in fixed lengths that rarely exceed 3.5 m [39]. This creates additional problems for the LSF structural system, as the joints between the panels can lead to additional thermal bridges or provide a path for moisture, flames in case of fire, dust, and other particles to enter the interior of the LSF structure.

Table 3 provides a comparison of the properties of the most commonly used non-metallic sheathing boards at room temperature.

Table 3. Thermophysical properties of commonly used non-metallic sheathing materials for LSF [38,40,41].

Material/Reference	ρ [kg/m^3]	E [GPa]	ν [–]	λ [W/mK]	Cp [J/kgK]
OSB [36]	600–620	5.500 [1]/2.200 [2]	0.30	0.12	1420–1550
Gypsum [36]	700–1000	2.500	0.27	0.21	880–1000
Magnesium oxide [42]	1000–1100	N.A.	0.35–0.37	0.30–0.60	1400
Magnesium sulphate [43]	1000–1100	N.A.	0.35–0.37	0.30–0.60	≈1400
Calcium silicate [42]	≈800–1100	N.A.	N.A.	≈0.25	≈1000–1100
Perlite boards [42]	≈200–280	N.A.	N.A.	≈0.10	≈750–900
Fiber cement boards [43]	≈1000–1400	N.A.	N.A.	≈0.25–0.30	≈900–1000

[1] Longitudinal Axis, [2] Transverse Axis

Most non-metallic sheathing boards, with the exception of OSBs and plywood, are used specifically as passive fire protection layers. Since OSBs and plywood are wood-based composites, OSBs are susceptible to ignition [42], and there is a need for an additional fire protection layer. OSBs are composite multilayer boards made of wood strands with a specific shape, thickness, and adhesive strength [43,44] which are very similar to plywood, with the only significant difference being the price. This has led to OSB panels replacing plywood in the construction sector [45]. The main use of plywood and OSBs is the outer sheathing, which is often similar to steel, so they are used as an alternative to steel sheathing. For this reason, designers nowadays use them as a finishing layer for walls and ceilings [26], and they are often used in low-rise residential buildings [44]. Because OSBs are wood-based composite laminates, they are susceptible to termite and mold which can lead to swelling and disintegration, resulting in loss of structural strength [46]. Basic definitions of OSBs, requirements, and classification are laid out in the European standard EN 300 [47].

While OSBs are used for external sheathing, GBs are often used as internal sheathing in LSF structures. Since OSB and GB boards are non-metallic, thermal bridging problems are easier to overcome because they have much lower thermal conductivity compared to steel. The boards are also connected to the steel structure with self-tapping screws. GBs are known for their fire protection properties as a passive fire protection layer [48]. Standard gypsum boards are composed of approximately 80% gypsum (calcium sulphate dihydrate), which contains 15–18% chemically bound water and 4–5% free water [33]. During heating, considerable energy is required to evaporate the free water, which delays the temperature rise [49] on the other side of the board. In other words, this reaction is endothermic, meaning that it consumes energy that would otherwise raise the temperature of the material. When heated, gypsum undergoes two main chemical decomposition reactions. The first reaction leads to the decomposition of gypsum into calcium sulphate hemihydrate at temperatures between 80 and 120 °C, while the second reaction decomposes the calcium sulphate hemihydrate into calcium sulphate anhydrite at temperatures between 200 and 240 °C, which affects the specific heat change [50]. To further increase the fire resistance of GBs, various additives such as cellulose fibers and fly ash can be added [41]. The diagram in Figure 3 represents the change in specific heat values of GBs at different temperatures compared to other non-metallic sheathing boards, showing the endothermic reactions mentioned above. The current European standard that regulates the requirements and classification of GBs is EN 520 [51].

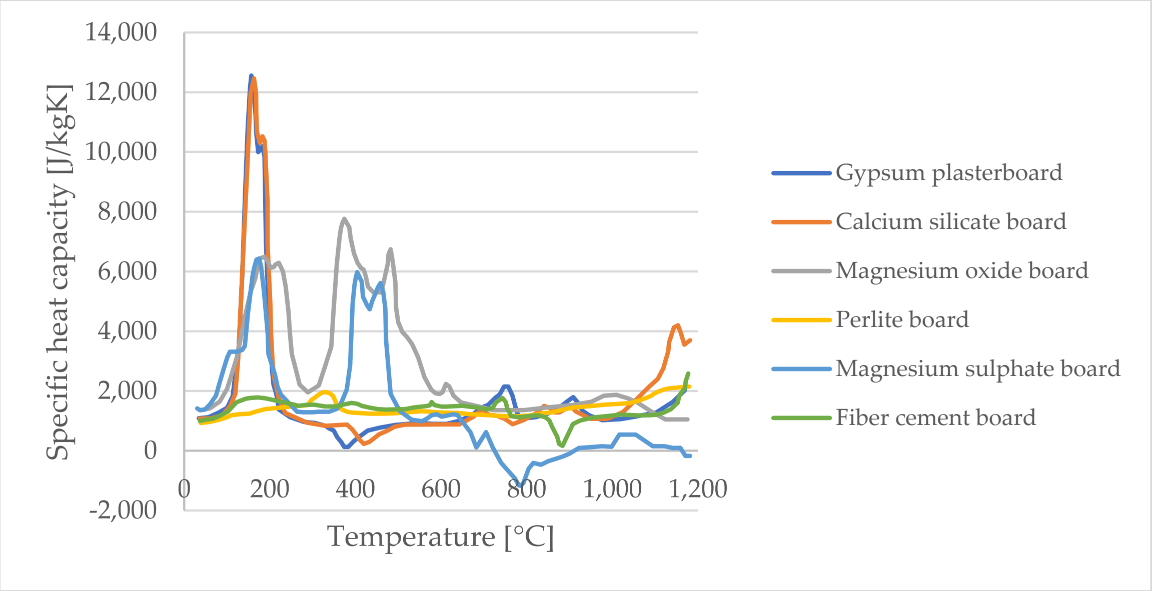
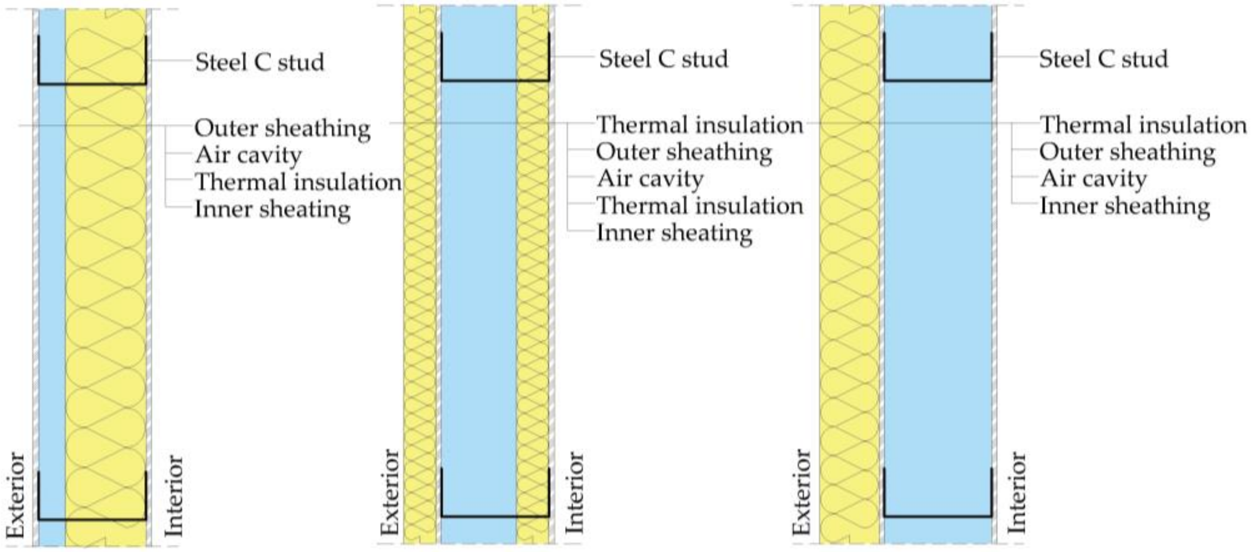


Figure 3. Comparison of different specific heat values of the mentioned boards from different researchers [38,41,50].

Other non-metallic, mostly fire-resistant boards include magnesium oxide boards, magnesium sulphate boards, cement fiber boards, perlite boards, calcium silicate boards, and boards with phase change materials (PCMs).

Magnesium oxide boards are generally used to improve the acoustic properties, impact resistance, and structural strength of panel systems [52]. The chemical composition of the board is mainly composed of two elements: magnesium oxide (MgO) and magnesium chloride ($MgCl_2$). As with GBs, the boards are mainly used as inner cladding for LSF elements. Rusthi et al. [52] conducted a study on two types of MgO boards, which differed only by the percentage of MgO in the board, to evaluate their thermal properties and fire behavior. In a more recent study, Steau and Mahendran [53] tested numerous sheathing boards, including MgO boards. Both studies showed that MgO boards undergo endothermic reactions, similar to GBs, due to the significant amount of free and bound water. As shown in Figure 3, the first two peaks occurred at about 180–230 °C, the third and fourth peaks occurred at 400–475 °C, and the last peak occurred at about 520 °C [53]. According to Rusthi et al. [52,54], the first two peaks were due to dehydration of magnesium oxychloride and evaporation of water, the third and fourth were due to hydrolysis and pyrolysis, and the last peak was due to the release of chemically bound water. Although the boards have an advantage over GB and OSB panels in terms of acoustic properties, the authors concluded that the main disadvantage of this type of boards is that they have a very high mass loss at elevated temperatures, about 15% higher compared to GBs. These results were later confirmed by Steau et al. [38] and Martins et al. [55]. Therefore, under the high thermal load, cracks occur in the board and the integrity of the whole assembly is compromised. Another disadvantage of this type of sheathing is the chemical degradation of the material when exposed to higher humidity. Aiken et al. [56] and Rode et al. [57] investigated this effect and concluded that the board is not suitable for exterior façades or other climates where the board is exposed to higher moisture content. Upon contact, the board forms saline water on the surface, which can lead to corrosion and significant damage. As a fairly new fire protective board, to date, there is no harmonized European standard defining the terms, requirements, and tests for this type of board.

A variant of MgO boards is magnesium sulphate boards which have a similar chemical composition to magnesium oxide boards. They are composed of magnesium oxide (about 55%), sulphate (about 25%), and glass fibers (about 18%) [41]. Replacement of MgCl2 in basic magnesium oxide boards with $MgSO_4$ eliminates the corrosive effect of chlorides [41]. Gnanachelvam et al. [41] studied the thermal properties of this type of board at elevated temperatures and found that the fire behavior of magnesium sulphate boards was slightly better than that of magnesium oxide boards, but the same rapid cracking and mass loss occurred. Since magnesium oxide and magnesium sulphate boards are similar, their chemical decomposition at elevated temperatures is identical; the process is shown in Figure 4. As with magnesium oxide boards, to date, there is no harmonized European standard defining the terms, requirements, and tests for this type of board.



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

Figure 4. (**a**) Cold-framed construction; (**b**) hybrid-framed construction; (**c**) warm-framed construction [7].

Commercially available calcium silicate boards can be divided into three categories: low density (200–500 kg/m^3), medium density (500–1000 kg/m^3), and high density (1000–1800 kg/m^3) [42]. They are generally stiffer than GBs, which sometimes makes them more attractive than GBs. Their main material is calcium silicate, and at high temperatures, the specific heat values reach similar peaks to GBs due to the water evaporation process, as shown in Figure 4.

In addition, perlite boards are also a sheathing alternative made from volcanic glass. Perlite boards are lightweight, easy to handle, and offer low cost, high strength, and chemical stability [53]. Modern sheathing boards also include PCM plasterboards which consist of microencapsulated PCM, gypsum core, and small quantities of additives [41]. PCMs absorb or lose considerable energy and undergo a phase transition, melting during the day and solidifying at night, helping to maintain indoor thermal comfort [50]. Although PCM plasterboards are expected to have a higher heat absorption capacity at elevated temperatures due to their higher specific heat capacity, their fire performance might be worse compared to insulation materials due to their higher mass loss and thermal conductivity [41]. In a study by Gnanachelvam et al. [48], it was also demonstrated that the PCM gypsum board has a very high mass loss at elevated temperatures due to dehydration and evaporation PCM.

Since the market offers different sheathing options, it is important to evaluate the best option depending on the requirements needed and the building environment in which the board will be installed.

3.3. Thermal Insulation Materials

When considering NZEBs, insulation materials are the most important component of the LSF building system because they provide the required thermal properties and thermal comfort. Based on the position of insulation in LSF structures, they are divided into warm-framed, cold-framed, and hybrid-framed [7] structures, as shown in Figure 4.

For all three types, different types of thermal insulation materials can be used, which are described in detail in the rest of the text. In warm-framed LSF constructions, it is common to use ETICS for the outer face layer [24]. Commonly used materials for ETICS are expanded polystyrene (EPS), and since the materials are quite similar, extruded polystyrene (XPS) [7].

The thermophysical properties of the different insulation materials used in LSF panels are shown in Table 4. As can be clearly seen from the table, the thermal conductivity of polymers is significantly lower compared to the other materials listed.

Table 4. Thermophysical properties of different insulation materials [58,59].

Material	ρ [kg/m^3]	λ [W/mK]	Cp [J/kgK]
MW	12–200	0.030–0.040	0.8–1.0
EPS	10–80	0.032–0.045	1.25
XPS	15–85	0.025–0.040	1.45–1.7
PUR	30–160	0.022–0.035	1.3–1.45
PIR	28–40	0.020–0.035	1.4–1.5
Cellulose fibers	30–70	0.038–0.040	1.3–1.6
Vacuum-insulated panels	180–210	0.008	0.8
Gas-insulated panels	N.A.	0.040–0.046	N.A.
Aerogels	100–150	0.013–0.021	1.0

MW is often used when higher fire resistance of the entire building system is required and is the most commonly used insulation material for LSF constructions. The market share of MW in Europe is about 60% [58]. This proves the wide range of applications of this material. Researchers have shown that the thermal insulation performance of mineral wool for construction purposes is not affected by high temperatures [59], since it is an inorganic material containing a small amount of organic components (binders). In addition to the high fire resistance, the sound insulation of the material is also a remarkable advantage [59]. Wool acts as an absorber due to the flexible, porous structure of the material. The thermal conductivity, the most important factor for thermal insulation materials, is λ = 0.035 W/mK [60]. This thermal conductivity can meet the requirements of energy efficient construction. The biggest problem for this material arises when the wool is used in places where there is a risk of condensation and greater moisture exposure. When water enters the system, MW absorbs the moisture, which increases the thermal conductivity of the material, reducing its insulating properties. This in turn requires additional membranes and precautions, which are discussed later. The basic requirements for mineral wool are defined in the European standard EN 13,162 [61].

EPS and XPS for ETICS in LSF systems are polymeric materials similar in structure and properties. They are both classified as highly combustible, closed-cell foams without significant acoustic properties [59]. The lower acoustic properties are due to the rigid structure of the material compared to MW. EPS and other petrochemical-based foams account for 27% of the European market [58]. The thermal conductivity is slightly lower and therefore, the thermal insulation is better than MW and ranges from 0.032 to 0.045 W/mK [59,60]. The notable difference between EPS and XPS materials is that EPS has higher moisture absorption compared to XPS [59]. The basic terms and requirements for EPS and XPS are defined in the European standards EN 13,163 [62] and EN 13,164 [63], respectively.

When considering sandwich cladding panels used for LSF systems, PUR and PIR have had a great influence on the use of the sandwich concept, as they are generally less costly, solid, easy to bond at the macroscopic level, and provide high thermal insulation (thermal conductivity around $\lambda = 0.025$ W/mK [60]) [36]. For this reason, these two types of insulation materials have seen a strong upsurge in the construction sector and in LSF building systems. In general, PUR foams have higher thermal resistance (R-value) compared to other commercially available insulation products, thus PUR results in thinner building elements with lower height while increasing space utilization, maximizing efficiency, and reducing operating costs [64]. In recent decades, PUR in particular has been used with other materials to obtain composites with low density, high toughness and ductility, high impact resistance, efficient sound insulation, and excellent mechanical properties [64]. They are produced in many variations and in densities ranging from 30–500 kg/m^3 [36], allowing different mechanical, dynamic, thermal, etc. properties to be obtained [65]. On the other hand, fire behavior is one of the main problems of PUR. Although the overall fire resistance can be improved by adding additives, there are significant concerns about the gases formed during the combustion process of the material. PIR foam is formed by a similar chemical reaction as PUR, and the two materials are similar but differ significantly in fire resistance. Of all the foams, PIR has the best fire resistance [59]. The thermal conductivity of the material is also slightly lower, ranging from 0.020–0.035 W/mK, depending on the density of the material [59]. The European standard for rigid foam boards PUR and PIR is EN 13,165 [66].

Cellulose fibers for thermal and sound insulation purposes are produced in a mill from recycled paper, wood fibers, and some chemical composites to improve their vermin, fire, and rot resistance [59]. Although panels and mats can be produced, it is more commonly marketed as a loose material that is blown into wall cavities [59]. Due to its elasticity and porosity, the material is excellent for sound absorption in floating floors. The thermal conductivity of the material ranges from 0.038–0.040 W/mK [58,59]. Water, i.e., moisture, has a negative influence on the thermal properties of the material.

Several innovative materials have also been invented to reduce the thermal conductivity of insulating materials and increase the overall thermal resistance of building components. These materials are vacuum-insulated panels, gas-filled panels, and aerogels. Their properties, durability, and overall safety are still being researched and developed [20,41]. Materials such as cork could be used for LSF floor systems, while sheep wool could be used as cavity insulation. Materials made from cork grains are also characterized by good acoustic properties in terms of impact sound insulation, airborne sound insulation, and sound absorption, are marketed in the form of boards, strips, loose material, or plaster additives, and can be easily recycled [59]. The thermal conductivity of these materials ranges from 0.037–0.050 W/mK [58,59]. Sheep wool is an organic material mixed with polyester or fixed on a polypropylene grid. Like cork, the material is usually marketed in rolls and its elasticity allows it to be used as a resilient material in floating floors [59]. Before use in construction, sheep wool must be treated with flame retardants, moth repellents, and parasiticides, and the material is easily recycled and reused [60]. The thermal conductivity of the material ranges from 0.035–0.04 W/mK [58,59].

As can be seen, insulation materials for LSF building systems have different properties, each of which has its advantages and disadvantages. Among conventional insulation materials, polymeric materials such as PUR and PIR provide the best insulation properties at room temperature due to the significantly lower thermal conductivity of the material. Of the modern insulation materials, i.e., vacuum-insulated panels, gas-filled panels, and aerogels, aerogels appear to have the best insulation properties at ambient temperatures, but more research is certainly needed to properly evaluate these materials.

When new insulation materials are developed, their use and compatibility with LSF structures should be further researched, as some issues such as high flammability of polymeric materials and low permeability of MW limit their application in different building environments, thus affecting the usability of such systems.

3.4. Wind and Air Tightness Membranes

The airtightness of buildings, i.e., the resistance of the building envelope to air leakage to the inside or outside, is a crucial aspect of building energy efficiency [67]. In addition, air leakage can allow pollutants and other particles to enter the building, affecting occupant safety. No building is 100% airtight because infiltration is an uncontrollable process that occurs through walls, windows, and all types of cracks and breaks in the building envelope. Air leakage in LSF systems is a problem that must be properly addressed. The interior of an LSF structure is often used as a pathway for utility installations, creating holes and various pathways for contaminants and other harmful particles within the building.

The infiltration process is caused by the difference in air pressure between the inside and outside of an envelope element. Wind further enhances infiltration, and tall buildings have a chimney effect that draws air in at the bottom of the building and pushes it out at the top [67].

To reduce air infiltration and interstitial condensation, two membrane layers should be used along the LSF building exterior envelope [24]. The first barrier should be placed on the warm side of the insulation layer and is commonly known as a vapor barrier. It prevents the moisture in the air from entering the interior of the LSF elements and prevents condensation on the colder elements (usually steel). The other membrane, i.e., the wind barrier, should be placed on the cold side and should be vapor-permeable to allow moisture to escape from the LSF elements [24]. The most common air leaks found in field measurements in the literature are at the junctions between the exterior wall and ceiling or floor, exterior wall and window or door, and exterior wall and penetrations in the barrier layers [68]. To improve overall airtightness, sealing tapes should also be used in combination with the above-mentioned membranes.

4. Discussion of General Requirements for Development of LSF Systems

Thermal performance of LSF structures is mostly influenced by the choice of configuration, being cold-framed, warm-framed or hybrid-framed, the components that create the whole assembly, and how well thermal bridges are reduced as they decrease the energy performance. There is no clear and easy path to deciding what component should be used because it ultimately influences other performance criteria of the assembly, for example, the fire resistance, acoustic performance, or mechanical resistance.

When considering the fire resistance of the system, it is one of the key aspects and requirements that must be met for any building element. CFS as main load-bearing system requires additional protection against high temperatures because of instabilities that are related to thickness. Additionally, the influence of other components on the structural response is not negligible. As shown earlier, OSBs and plywood are a good alternative when it comes to the load-bearing capability of the sheathing, but they have a reduced fire protection which must be further protected by implementing a suitable fire protective board. Furthermore, some boards have shown great thermal performance on ambient temperatures but significantly reduced properties at elevated temperatures. This also goes for polymer insulation materials. By choosing a polymer insulation, thermal properties would theoretically be increased as they generally have lower thermal conductivity, but at the same time, fire performance of the assembly is decreased due to high flammability of polymers.

Further, the cost associated with the assembly process of the system is also connected with the system design as some components cost more due to the cost of raw materials and manufacturing. A potential solution to this is solving the thermal-structural response of system introducing the interaction between components. This may lead to a potential reduction in steel that has a significant influence on the overall cost.

As stated earlier, by widening the distance between the steel studs, a 20% increase in the thermal properties can be achieved in LSF structures. On the other hand, by increasing the distance of mechanical properties, the structural stability of the assembly may become questionable.

5. Proposal of New Light Steel Framed Construction Panel

Considering the advantages and disadvantages of the materials described in the previous sections, the goal of modern LSF systems for NZEBs is to achieve better thermal comfort while reducing thermal bridging within the system. Research has shown that thermal bridging is mainly due to the profile of CFS and its high thermal conductivity, and that the best way to reduce the influence of steel on the thermal bridging effect is to physically remove the steel from the outer sheathing [1]. At the same time, it is important that the overall structural performance of the system is not compromised. Therefore, within the scientific project “Composite lightweight panel with integrated load-bearing structure (KLIK-PANEL)”, an LSF composite panel is proposed as it is conceptually shown in Figure 5. The main objective of the project was to develop a walling panel which satisfies all the important aspects required for NZEBs with adequate structural performance properties by combining all the components into a cohesive and composite structural assembly.

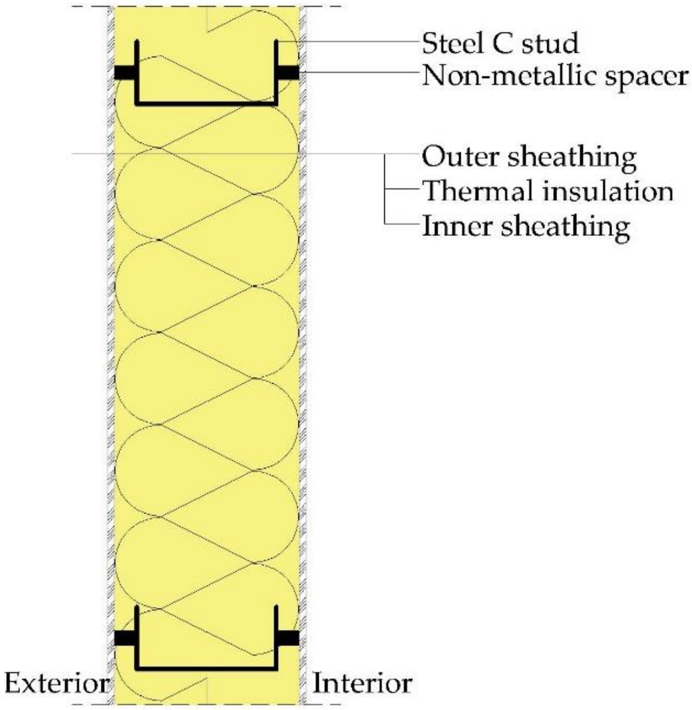
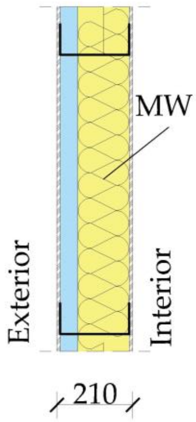
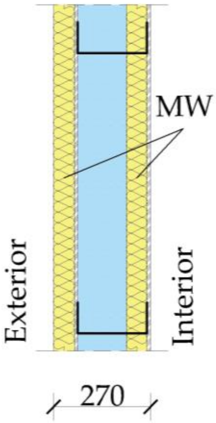
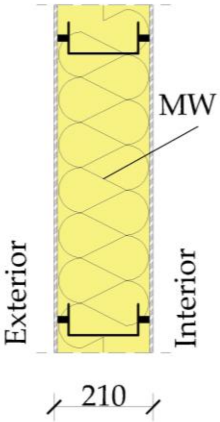
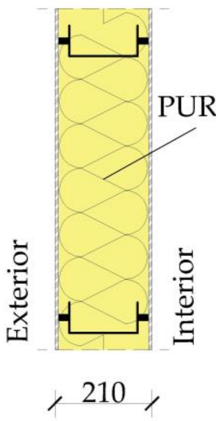


Figure 5. Proposed concept of a LSF composite panel.

When considering thermal insulation materials, it was found that polymer foam provides significantly better insulation performance at ambient temperatures compared to other materials. Consequently, the use of polymer foam in LSF structures would reduce the U-value of the building element, which in turn would provide better thermal protection for the building. In addition, since polymer foam has better water permeability than MW, airtight membranes would not be required. In addition, the adhesive property of the foam inside the cavity provides bonding between components and support for the structure as a whole. By considering the positive effects of foam and sheathing components, the optimal design of CFS structural components can be achieved.

A brief analysis of the thermal transmittance (U-value) of four different configurations of LSF wall panels was performed as a possible technical solution for the construction of NZEBs. For analysis shown in Table 5, U-values of the thermal envelope were calculated using the HRN EN ISO 6946 [69] standard for calculating thermal transmittance for building components and building elements. The influence of thermal bridges by the steel studs was not considered in the analysis.

Table 5. Comparison of different LSF wall panel configurations.

Configuration	A	B	C	D
Section				
Wall composition (from interior to exterior side)	Gypsum fibreboard 25 mm Air layer 40 mm MW 120 mm Gypsum fibreboard 25 mm	MW 60 mm Gypsum fibreboard 25 mm Air layer 100 mm MW 60 mm Gypsum fibreboard 25 mm	Gypsum fibreboard 25 mm MW 160 mm Gypsum fibreboard 25 mm	Gypsum fibreboard 25 mm PUR 160 mm Gypsum fibreboard 25 mm
U-value [W/(m^{2}K)]	0.294	0.293	0.183	0.117

The same sheathing material was used for all configurations (gypsum fibreboard with a thickness of 25 mm). The thermal conductivity of the air layer was calculated according to HRN EN ISO 6946 [69], taking into account the effects of convection on heat transfer.

Configurations A and B were taken as the most commonly used configurations in the past, with a total of 12 cm MW, while configuration C is similar to configuration A with 16 cm MW. As expected, the proposed concept of the panel with 16 cm PUR (configuration D) had the lowest U-value (0.117 W/(m^{2}K)). This U-value would meet both the EU requirements for a decentralized NZEB and the requirements for a passive house, with a relatively low wall thickness compared to possible other configurations with the same U-values. The achieved result is of course due to the PUR insulation and its lower thermal conductivity (0.025 W/(mK)) compared to the thermal conductivity of MW (0.04 W/(mK)). In the development of the panel system with an integrated structure, it is necessary that the panel is thermally adjustable, that is, regardless of structural and other aspects, it is possible to adjust the thickness of the thermal insulation which directly affects the U-value of the panel itself. It is also necessary to design the panel in such a way as to minimize the thermal bridges created by the supporting steel structure of the panel and also by the connections of the panel with other structural and non-structural elements of the building. In addition, it is necessary to define the panel joints (extensions, corners, angles, collisions, etc.) so that the thermal bridges can be minimized and sealed according to the requirements for maximum allowable air permeability and fire resistance. At the same time, further development of the panel would allow the integration of technical systems such as electricity, water supply, sewerage, mechanical ventilation, heating and cooling systems, etc. Since the fire behavior of PUR foam is of great importance, a suitable non-combustible sheathing material with sufficient thickness must be used to achieve the best possible fire protection. As mentioned before, in the field of energy efficiency, technical requirements regarding the rational use of energy and thermal protection of the building element must be met during the design and construction of new NZEBs.

As mentioned earlier, heat losses through the building envelope account for a large proportion of the total energy consumption in buildings and the implementation of insulation materials helps in delaying the heat transfer on the envelope. The effectiveness of this phenomenon is described by the compelled thermal transmittance (U-value).

The compelled thermal transmittance (U-value) for outer walls in the EU has been defined in the respective country's regulations and varies from 0.18 W/(m^{2}K) in northern Europe (Sweden) to 0.28–0.35 W/(m^{2}K) in central Europe (Germany and Austria), 0.80 W/(m^{2}K) in parts of Spain, and 1.57 W/(m^{2}K) in Malta as representative of the south European climate, while voluntary certification systems such as Passivhaus require a U-value of outer walls lower than 0.15 W/(m^{2}K).

In addition, the lower U-values ensure the thermal protection of the building during the summer and prevent the occurrence of construction damage, which occurs, for example, due to condensation of water vapor. To conclude, the conducted preliminary analysis of the thermal transmittance (U-value) showed the low thermal transmittance of the proposed system and indicates the path of further research. It should be noted that this is a complex task since numerous experimental and numerical studies are required to find a suitable solution for the thermal and structural response [70].

6. Conclusions

LSF building systems have been used since the "Gold rush" of the mid-19th century with an upsurge at the end of the Second World War and continue to evolve today. Since the overall performance of such systems has improved drastically, today, there are no major restrictions on their use in residential and non-residential buildings all across the world. Although due to differences in building traditions, their use in Europe is not yet as widespread as in the USA, Japan, and Australia, it is constantly increasing as the need for sustainability is becoming an increasing demand. Nevertheless, after the systematic literature review, it could be seen that they can be used for NZEB buildings, as they have the potential for high energy efficiency as well.

Although the performed preliminary analysis was mostly related to the influence of the type and placement of the insulation layer to the thermal performance of LSF structures, the other two main components, namely, steel members and sheathing, do influence the overall thermal performance. The thermal conductivity of steel, which ranges around 54 W/mK, is the main concern when designing an energy efficient LSF structure as it increases the thermal bridges especially when steel is in direct contact with sheathing. As shown in the paper, there are several methods of preventing thermal bridges, but the easiest one is to physically isolate and distance the steel members from the sheathing by implementing some form of spacer to minimize the negative influence of the steel.

The sheathing also influences the thermal performance of the LSF system as holes, drills, and other imperfections can decrease its airtightness. As the infiltration process cannot be stopped, the airtightness aspect must be addressed properly. When considering the type of sheathing, only non-metallic sheathing is suitable for NZEBs due to the aforementioned thermal conductivity of metallic materials, i.e., steel. Out of the non-metallic sheathing options, it is important to evaluate them not only based on their ambient temperature thermal properties but also based on fire and noise protective properties. This is because non-metallic boards, e.g., OSBs and plywood, as wooden materials, have considerably lower fire resistance. Other non-metallic boards that are used as fire protective boards have fairly similar properties at ambient temperatures, and the optimal choice depends on the required functionality of the LSF system.

Most LSF systems are comprised of MW cavity insulation because of the ease of installation, fire protective properties, and acoustic dampening. Although mostly used, MW's thermal properties at ambient temperatures are very susceptible to condensation which decreases their thermal performance. Additionally, MW cannot easily isolate the steel members from the outside sheathing which was identified as a major concern for the energy efficiency of LSF structures. In this regard, polymer materials are better as they are not susceptible to condensation, but on the other hand, their fire performance is problematic as they are highly flammable. This is why the polymer insulation is commonly placed on the outside of the LSF structure. Consequently, this solution increases the width of the assembly and decreases the available net floor area, and from an economic point of view, it is not a preferable solution.

Based on the observations described in this paper, a new LSF composite walling panel was proposed. Since cladding panels have a similar construction to LSF systems, i.e., both have sheathing and an insulating layer in between, the knowledge and technology used to manufacture cladding panels can also be applied to the manufacture of innovative LSF panels. To create a modern LSF panel system that can be used in NZEB buildings, the authors introduced the concept of manufacturing cladding panels with an integrated LSF structure. By implementing the insulating properties of polymer insulation, e.g., PUR, the fire protection properties of GBs, and the load-bearing properties of CFS, the new LSF system could be considered a new building block for a faster NZEB construction with all the advantages of traditional LSF systems.

The conducted preliminary analysis of the thermal transmittance (U-value) showed the low thermal transmittance of the proposed system and indicates the path of further research. It should be noted that this is a complex task since numerous experimental and numerical studies are required to find a suitable solution for the thermal and structural response. Further studies should be conducted to evaluate the properties of the components and assess the overall performance of this innovative structural system. Considering that there is no relevant research on cavity-insulated LSF constructions with polymeric materials such as PUR or PIR, special attention should be given to the research gaps that were identified in this work: the interaction of different sheathing materials with polymeric cavity insulation materials, the influence of spacers on the integrity of the panels and their impact on the thermal performance of the LSF structure, and the potential influence of PUR on the structural response of LSF systems.

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