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Review of thermal performance of LSF walls used for nZEB: Influence of components

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Abstract

Light steel framed (LSF) panels are relatively new construction systems that are light weight, highly resistant, recyclable, and reusable. In general, this building system incorporates three main parts: steel studs, sheathing boards, and insulation materials. Each part of a LSF panel has a distinct and significant role in fulfilling basic building requirements. Based on literature review, this article gives a brief overview of the properties of insulation and sheathing materials, various panel configuration performances, their main advantages and disadvantages, with the focus on the thermal performance at ambient and elevated temperatures.

Key words: LSF panels, thermal performance, sheathing boards, insulation, ambient temperatures, elevated temperatures

Pregled toplinskih svojstava LSF zidova koji se primjenjuju za nZEB: Utjecaj komponenti

Sažetak

Paneli od čeličnih, tankostijenih elemenata odlikuju se smanjenom težinom, mehaničkom otpornosti, mogućnošću recikliranja i ponovne uporabe. Sistem se može podijeliti na tri osnovna djela: čelični profili, obložni materijali i izolacijski materijali. Svaki dio ima različitu i bitnu ulogu kojom se ispunjavaju osnovni zahtjevi za građevinu. U ovom članku daje se kratki osvrt izolacijskih i obložnih materiala koji se mogu koristiti ili koji se koriste u panelnim sistemima te ostala istraživanja gdje su istraživane različite panelne konfiguracije, njihove prednosti i mane s fokusom na ponašanje na sobnim i povišenim temperaturama.

Ključne riječi: tankostijeni čelični panel, toplinsko ponašanje, obložni materijali, izolacija, sobne temperature, pvovišene temperature

1 Introduction

Light steel framed (LSF) walls are increasingly used as an alternative to traditional brick, mortar and concrete building systems. When compared to traditional construction, LSF construction offers advantages such as: reduced weight with simultaneous high mechanical strength; easier prefabrication, allowing modular elements and higher quality control; shorter on-site assembly periods; no dimensional variations caused by moisture; low cost; reusability and recyclability. Additionally, the implementation of LSF panels can satisfy the necessary nearly zero-energy building (nZEB) requirements due to the use of thermal insulation materials in the system. Load-bearing or non-load bearing types of LSF panel configurations are being used in structures, depending on the type of construction and the designed load path. For loadbearing types, three main parts of assembly are: steel studs, sheathing boards, and insulation material. The base of this system, i.e., steel studs, are made of bended cold-formed steel plates, and they are the main load-bearing support. Being a metallic material, these steel studs are vulnerable to outside influences (water, chlorides, fire, etc.) and they need to be protected with adequate sheathing boards and insulation. The boards do not only protect the steel and the cavity but they also provide an adequate surface finish and aesthetics. Furthermore, they also have a structural role in load-bearing walls, mainly for horizontal loads (e.g., wind) in the plane of the wall [1]. The thermal insulation of LSF panels can be placed inside the cavity i.e. between the two sheathing boards or at the outside of the boards. LSF panels are therefore classified as cold frame, hybrid frame, and warm frame constructions [2], as shown in Figure 1.

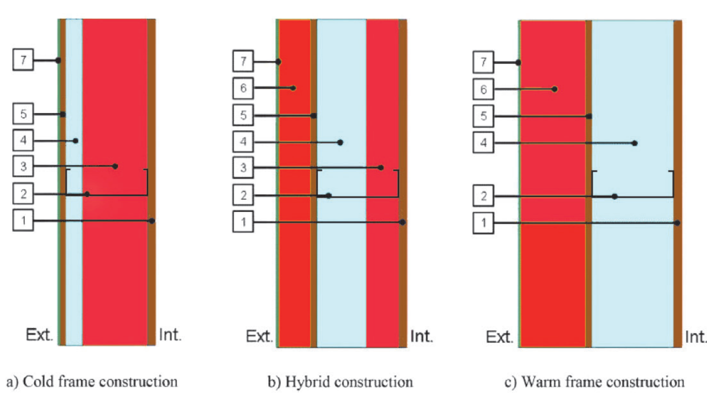

Figure 1. Classification of LSF constructions depending on position of insulation materials (1- Gypsum; 2- LSF; 3- Insulation ; 4- Air gap; 5- OSB; 6- EPS; 7- ETICS) [1]

The biggest downside of the LSF panel is the lack of thermal mass and the somewhat questionable fire behaviour. At elevated temperatures, LSF components behave very differently than at ambient temperatures and it is therefore crucial to observe their behaviour when evaluating the overall performance of the panel. Thermal diffusivity has to be defined to understand thermal performance of the components and of the entire panel system. Thermal diffusivity is the rate of temperature spread through a material and it can be expressed as [3]:

$$\alpha=\lambda/(\rho\cdot Cp) \quad (1)$$

where λ is the thermal conductivity of the material, ρ the material density and Cp the specific heat capacity. A material with a higher thermal diffusivity transfers heat through the material faster and, therefore, it is important to evaluate these properties to understand thermal performance of the material. Consequently, if LSF components have a higher thermal diffusivity it is reasonable to assume that the failure time of the whole panel will increase.

The main goal of this manuscript is to briefly present the current research data about the most often used sheathing and insulation materials for LSF panels, and their main properties (thermal conductivity, specific heat capacity and material density) as needed to evaluate thermal performance of the components at ambient and elevated temperatures. Furthermore, some studies of various panel configurations exposed to high temperatures are presented to show influence of the sheathing and insulation materials.

2 Sheathing boards

Sheathing boards for LSF panels can be divided into two distinct groups: metallic and non-metallic. As stated by Gnanachelvam et al. [4] fire resistance, sound insulation, impact and moisture resistance, durability and economy influence the choice of suitable wallboards. Out of the mentioned parameters, reaction to fire of the boards is especially important given that the load bearing elements, i.e., steel studs, are susceptible to structural failure due to the reduction in mechanical properties at elevated temperatures [5].

2.1 Metallic sheathing

The only more widely used metallic sheathing material is the thin steel sheathing that is often used for industrial hall applications [1]. The application of sheathing can also be attributed to other benefits this sheathing provides. According to Steau et al. [6] the use of thin steel sheathing has been found to provide enhanced stiffness to structural members while improving strength, high impact resistance, blast resistance, mechanical or seismic vibration resistance and enhanced durability. Steel itself is a well-known material and it shares the same thermal performance properties as the load-bearing studs. The basic thermal performance parameters of steel are given in Table 1. The temperature dependent properties are further defined in HRN EN 1993-1-2.

Table 1. Thermophysical properties of steel at ambient temperature[7]

Type of board	Thermal conductivity [W/mK]	Density [kg/m^3]	Specific heat capacity [J/kgK]
Steel	40-50	7600-7800	450-460

As shown in Table 1, steel is a high thermal conductor and it has a high thermal diffusivity which makes it unpractical for energy efficient buildings. Additionally, the thin sheathing material itself is susceptible to the same failures and degradations (especially when exposed to fire, i.e., elevated temperatures) as the steel studs. However, experimental studies on fire performance of steel sheathed LSF walls have rarely been conducted to date [8].

2.2 Non-metallic sheathing

The use of non-metallic sheathing is more common in LSF construction systems that are used for residential and non-residential buildings. Unfortunately, they are produced in fixed lengths that rarely exceed 3.5 m [9]. This in turn demands a greater attention to detail when designing the joints and connections of LSF panels. The most usual sheathing panels are made of Oriented Strand Boards (OSB for short) and gypsum plasterboards for the outer and inner layers of external walls, respectively [1]. Many sheathing options also include magnesium oxide boards, calcium silicate boards, and various types of fiber cement boards [8] while new sheathing options are continuously being developed. Apart from OSB boards, other aforementioned boards are purposefully used as fire protective boards in LSF panels to prevent the temperature rise inside the cavity and steel members due to their low thermal diffusivity. Table 2 gives a summary of the thermo-physical properties for various non-metallic boards used in LSF panels, while a brief description of the boards that are most commonly used (OSB and gypsum plasterboards) are given in following sections.

Table 2. Thermo-physical properties of described non-metallic sheathing

Type of board	References	Thermal conductivity [W/mK]	Density [kg/m³]	Specific heat capacity [J/kgK]
OSB Board	[10,11]	0.109-0.129	600-680	1420-1550
Gypsum plasterboard	[12–14]	0.23	600-1000	880-1000
Gypsum fiber board	[15,16]	0.32-0.38	1000-1250	880-100
Magnesium oxide board	[4,12,17]	0.39-0.47	1025	1400
Magnesium sulphate board	[12]	0.53	1080	1400
Calcium Silicate board	[18]	0.21-0.26	830-870	560-750

All non-metallic boards, except OSB, experience a thermal conductivity decrease while exposed to elevated temperatures while the specific heat capacity rises at first, and then rapidly falls due to the loss of bound and free water inside the structure of the board. Due to the loss of water, the density also decreases. Because of this effect, the boards are good in preventing a rapid temperature rise on ambient side, which makes them perfect as fire protective boards. Changes in specific heat, thermal conductivity and mass loss of the aforementioned boards are represented in Figure 2. The data on thermal behaviour of calcium silicate boards are limited and are therefore not represented in the figure. In addition, the type I and type II magnesium oxide boards differ in their chemical composition, which is why they are both represented in the figure.

As shown in Figure 2, most mentioned boards experience similar changes at elevated temperatures. As thermal conductivity and specific heat show similar behaviour, the choice of adequate board falls on the changes in the density i.e. on the mass loss of the board. A rapid mass loss leads to faster integrity failure and subsequently lower thermal performance at elevated temperatures.

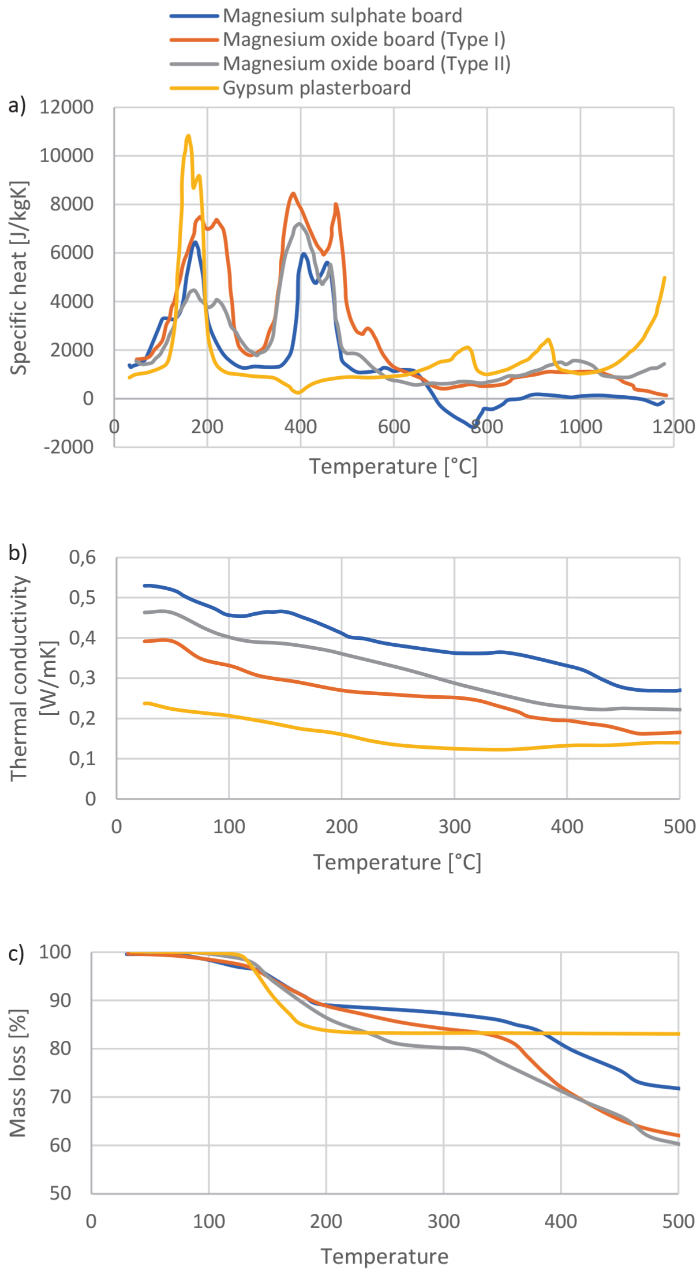

Figure 2. Thermal properties of varous sheathing boards: a) thermal conductivity , λ, b) specific heat, Cp, and c) mass loss i.e. ρ change) with temperature increase [4,12]

2.1.1 OSB boards

OSB boards are composite materials, and they have wood chips as their matrix and adhesives as reinforcement [19]. The rise of OSBs as a sheathing material is due to the fact that they provide sufficient mechanical strength and resistance. At ambient temperatures the thermal performance of the OSB boards is fairly consistent, as wood materials are thermal insulators and do not conduct heat [20]. The thermo-physical properties of the board highly depends on the structure, material components, compression methods, and additives [10]. Thermo-physical properties, i.e., thermal conductivity, specific heat, and density, is presented in Table 2. On the other hand, as a timber-based material, OSB boards are prone to ignition [20,21] and they contribute to the overall fire load which makes them unpractical when considering modern fire safety standards. Given the poor fire performance, the use of these boards is limited and should be considered with care.

2.1.2 Gypsum plasterboards and gypsum fibreboards

The gypsum board remains the most widely used sheathing product [8] because it acts as a passive protective layer [22]. It contains approximately 80 % of gypsum (Calcium Sulphate dihydrate), around 5 % of cellulose, and around 5 % of vermiculite [4]. Other additives can also be added into the mixture to increase certain properties. Additionally, the boards incorporate around 20 % of chemically bound water and 4-5 % of free water [22]. Thermo-physical properties of the boards are given in Table 2. Water content is important for understanding the mechanisms that develop during exposure of boards to elevated temperatures, i.e., fire, because the water evaporates and preserves the integrity. The dehydration process is an endothermic reaction and it occurs on two separate occasions, the first one around 100-120 °C, and the second around 300 °C [4,8,12,13,22]. Gypsum fibreboards are a variation of gypsum plasterboards, the only notable difference being the added cellulose fibres in the gypsum core and a somewhat better reaction to fire [23].

3 Thermal insulation materials

LSF panels are often provided with cavity insulation to minimize energy consumption of buildings because the insulation resists the heat flow to the buildings from the external environment [24]. When considering thermal insulation materials, several factors not associated with thermal performance, have to be taken into account during selection of insulation materials such as sound insulation, fire resistance, permeability, environmental impact, and impact on human health [12]. Generally, there is no single classification of insulation materials and it ultimately depends on the author but, for the purposes of this paper, they are divided into organic and inorganic materials. Insulation materials frequently used for LSF panels include mineral wool (MW), expanded polystyrene (EPS), polyurethane (PUR) foams, or extruded polystyrene (XPS) [1,25]. It is also important to mention that some new innovative materials, such as vacuum insulated panels and aerogels, are also used, but their properties, service life, and overall safety, are still being researched and developed [1,12]. A brief summary of the most frequently used materials is given in this section. Thermal properties at ambient temperatures, for insulation materials described in this section, are presented in Table 3.

Table 3. Thermo-physical properties of various insulation materials

Insulation material	**Reference**	**Thermal conductivity [W/mK]**	**Density [kg/m³]**	**Specific heat capacity [J/kgK]**	**Reaction to fire in accordance with EN-13501-1** [26]
MW	[27–29]	0.030-0.040	15-200	800-1000	A1
EPS	[27–29]	0.032-0.045	10-80	1250	E-F
XPS	[27–29]	0.025-0.040	15-85	1450-1700	E-F
PUR	[27–29]	0.022-0.040	15-160	1300-1450	D-F
PIR	[28,29]	0.018-0.035	28-45	1400-1500	D-F

3.1.1 Mineral wool (MW)

Mineral wool is an inorganic fibrous material that can be used in a broad spectrum of applications [30]. It covers glass wool (fibre glass) and rock wool, which is normally produced as mats and boards, but occasionally also as a filling material [29]. Glass wool is produced from borosilicate glass at a temperature of approximately 1400°C, while rock wool is produced from melting stone (diabase, dolerite) at about 1500°C [29]. Thermal properties at ambient temperatures are shown in Table 3. Both glass wool and stone wool have a reaction to fire class A1 according to European standard EN13501-1 [26], which means that they do not produce smoke or flaming droplets. Due to this, they can be used at very high temperatures, normally reaching up to 600 °C and, in certain cases, up to 1000 °C [30]. Livkis et al. [31] tested the insulating capability of stone wool in fire conditions and determined that, although considered as a non-flammable, the temperature inside the stone wool rose above the exposure environment temperature. According to the authors, this is due to the small amount of organic components i.e. binders that are added during production of the wool.

3.1.2 Expanded polystyrene (EPS) and extruded polystyrene (XPS)

The EPS and XPS are considered to be organic insulation materials due to the fact that they are produced as petrochemical derivatives. EPS is one of the most widely used thermal insulation materials for buildings due to its excellent insulation effects and low cost [32]. The EPS and XPS are fairly similar products, the only notable difference being the moisture resistance, i.e., XPS absorbs less moisture and costs more, while both materials have the same combustion issues [28]. Thermal properties at ambient temperatures are presented in Table 3. The EPS and XPS are resistant to short term temperatures of 90 °C and long-term temperatures of 80 °C. Above these temperatures, EPS will soften, until at approximately 150 °C it will begin to shrink and return to its original density as a solid polystyrene. Continued heating will melt EPS to a liquid and then gas form above 200 °C. Such gas can be ignited at temperatures between 360 and 380 °C, and self-ignition occurs at approximately 500 °C [32].

3.1.3 Other organic materials

Other organic cellular insulation materials that are used for LSF panels are PUR and PIR foams. These insulation materials have seen a surge in construction industry [28]. They have superior thermal insulation properties than other organic and inorganic materials¸, while also preserving advanced acoustic properties. In general, PUR foams, as cellular materials, have a higher insulation R-values compared to commercially available insulation products. Thus, PUR gives thinner walls and roofs of lower height, while increasing space utilization, maximizing efficiency, and reducing operating costs [33]. Its thermal properties at ambient temperatures are given in Table 3. PUR is produced in many variations and densities, which enables achievement of various mechanical, dynamic, thermal, and other features [33]. However, PUR foam lags behind PIR when it comes to reaction to fire and thermal performance at elevated temperatures. Out of all polymer materials, PIR exhibits the best reaction to fire [28]. Similar to EPS and XPS, PUR is considered flammable and prone to ignition but the overall fire resistance of the material can be slightly improved by adding adequate flame retardants. Gunther et al. [34] examined the influence of the flame retardants, and found that PUR with the retardants exhibited an increased fire resistance due to formation of a char layer, which temporally prevented rapid decay. Also, the same authors concluded that although the reaction to fire of such foam is better, PUR foam with and without the retardant ignites and starts to decompose at 250-500 °C. An additional issue of flame-retarded PUR foam is formation of poisonous gases while burning, which has an hazardous effect on the safety and security of the panel [29].

When choosing an insulation layer, it is important to evaluate the reaction to fire, decomposition temperature of the material, and subsequent behaviour at elevated temperatures. As the sheathing boards have an important role in preventing the temperature and fire spread, the selection of insulation should also be made with care.

4 Research on thermal performance of various LSF panel configurations

Thermal performance of LSF panels is often regarded through their properties at elevated temperatures because they must offer adequate fire resistance to prevent property damage and loss of lives during fire accidents. The easiest way of reaching this goal is by using adequate insulation and sheathing materials with proper thermal performance characteristics, as described in previous chapters. Various LSF panel configurations have been subjected to full scale fire tests and the thermal performance is described through the failure time of the system. Some researchers like Gnanachelvam et al. [4] performed fire tests on LSF panels with various wallboards devoid of insulation layer, in order to determine failure time of the sheathing boards only. A failure time is defined based on three main criteria: insulation, integrity or stability. As stated in [35], LSF panels are generally provided with cavity insulation to minimize energy consumption of buildings, because the insulation resists the heat flow to the buildings from the external environment. While the applied insulation provides sufficient thermal comfort and energy efficiency, the best composition of the panel is still debated. The same authors cited that the performance of such panels decreased and they are supported by Steau and Mahendran [36] who concluded that the failure time of the panel decreased by 12 % when cavity insulation was used. On the other hand, Ariyanayagam et al. [37] proved that the failure time increases with the application of cavity insulation when the panel is used as a non-load bearing element. The testing on loadbearing and non-loadbearing panels is not the same and therefore an increase in failure time for non-loadbearing panels is due to different criteria. Table 4 gives a few examples found in literature on the research conducted about different cavity insulated LSF panels and their configuration, the goal being to determine their overall thermal performance. All fire tests were conducted in a furnace following the ISO, using the cellulose fire curve. The failure time given in Table 4 represents the minimum time needed for the panel configuration to fail according to the insulation, integrity, or mechanical resistance criteria.

Table 4. Summary of previous studies on various LSF configurations

Author	Board thickness [mm]	Type of board	Board configuration	Insulation	Application	Failure [min]
Gunalan et al. [38]	16	Gypsum plasterboard	Double layer	Glass fiber	Loadbearing walls	101
				Rock fiber		107
				Cellulose fiber		110
Ariyanayagam et al. [37]	16	Gypsum plasterboard	Single layer	-	Non-loadbearing walls	94
	16	Gypsum plasterboard	Single layer	Glass fiber		106
Steau et al. [36]	19 mm Plywood, 16 mm Gypsum plasterboard	Plywood and gypsum plasterboard	Double layer of plasterboard on the fire side Single layer of plywood	Mineral wool	Celling	120
Le Dréau et al. [39]	18	Gypsum fibreboard	Single layer	Rigid PUR	Not defined	33

As can be seen in Table 4. the configuration with gypsum plasterboards and fibre insulation can easily withstand a fire load for more than 100 minutes. In turn, this configuration could be used for buildings with the fire resistance rating of REI30, REI60, or more. The configuration with a single layer of gypsum plasterboard and flammable PUR foam showed a greatly reduced failure time. This shows that the choice of insulation matters and that it greatly influences the usability of such panels in fire conditions. Therefore, it can be concluded that such configurations can only be used in buildings with lower requirements for fire resistance. Furthermore, the configuration with plywood and gypsum plasterboard also has a formidable failure time but it is important to mention that the plywood was not directly exposed to fire load during testing. As the materials are fairly similar, the same can be concluded for the OSB boards.

5 Conclusion

A brief review presented in the paper describes materials that are frequently used in LSF panels, and their behaviour at ambient and elevated temperatures. Through the review, it can be seen that a wide variety of sheathing wallboards and insulation materials are used in LSF systems, and that the thermal performance of the panel highly depends on the materials applied. As thermal performance is a major factor that influences the quality of living inside a LSF building, the choice of adequate material is of crucial significance. Through the literature review it can be seen that cellular organic insulation materials like PUR and PIR provide the best insulation properties, i.e., they have the best thermal performance at ambient temperatures and can easily fulfil the nZEB requirements, but are highly flammable. As they show great promise as an adequate thermal insulation material, organic cellular materials and the thermal performance of such panels should be further considered and examined. Research review showed that only one paper addressed the potential combination of rigid PUR foam as a cavity insulation and gypsum fibreboards, but the thermal performance was significantly lower when compared to other systems. On the other hand, given the excellent thermal performance of the insulation material at ambient temperatures, this type of configuration could still be used in low-rise buildings where there is no need for significant resistance to fire.

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