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Thermal performance of lightweight steel-framed construction systems

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thermal bridges;
improvement strategies

Abstract – Lightweight steel-framed (LSF) structural elements in building construction provide a way of increasing building sustainability. These structural elements present great potential for recycling and reuse, allowing the conservation of natural resources and the environment. When compared with other materials, these construction components also provide other advantages: reduced weight with simultaneous high mechanical strength; easier prefabrication, allowing modular elements and higher quality control; shorter periods for assembling the building on-site; no dimensional variations caused by moisture; and low cost. The high thermal conductivity of steel could be a drawback, leading to thermal bridges if not well designed and executed. In the case of LSF components (e.g. walls and slabs) it is necessary to take special care with the elements' design optimisation, with it being essential to use continuous thermal insulation. The building envelope thermal performance is crucial to provide good thermal behaviour and energy efficiency, allowing a reduction of operational energy. In this paper, the LSF construction system is analysed in order to show its main advantages and drawbacks. The assessment of embodied and operational energy is essential to perform a life cycle analysis. The reduction of both energies' consumption is crucial to increase the sustainability label. Special focus will be given to the mitigation strategies of operational energy in LSF construction.

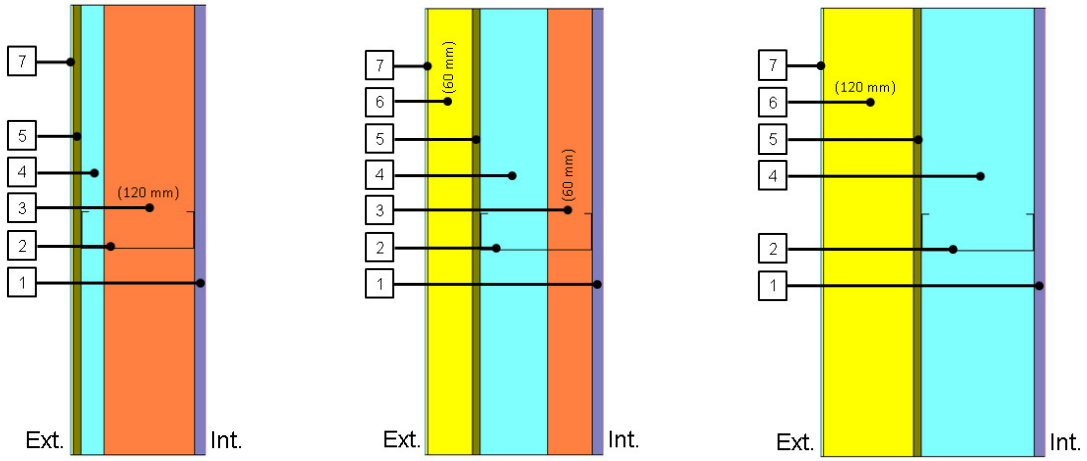
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The demand to reduce the energy consumption in buildings and to use recyclable materials has increased in the last few decades. These concerns have the intent of creating a more sustainable environment. In Europe, buildings are responsible for 40% of the energy consumption, with the space conditioning (heating and cooling systems) having a significant share, which also depends on the climate [1]. Given the high energy consumption of buildings, the European Union established several objectives in the Energy Performance Building Directive (European Directive 2010/31/EU) regarding "nearly zero-energy buildings" for the year 2020. It is defined that not only must the contribution from renewable energy sources be increased, but also an improvement of buildings' energy efficiency must be performed.

In recent years, alternatives to traditional structural systems for buildings have emerged, e.g. lightweight steel-framed (LSF) systems. The LSF construction systems have as base material a steel structure, made of bended cold-formed steel plates. Usually these elements are prismatic and have a thin-walled cross-section.

Given the advantages of steel structures (e.g. cost-efficient; reduced weight; exceptionally solid in relation to weight; excellent stability of shape in case of humidity; rapid on-site erection; easy to prefabricate; great potential for recycling and reuse), the use of steel as a construction material has seen a phenomenal growth in the last few years, being used with success in some low-rise building typologies (e.g. office and also residential buildings). However, if not correctly addressed, thermal bridges are a significant drawback with some difficulty of resolution, which could penalise the thermal behaviour and energy efficiency of steel buildings. In recent years, there has been an effort to assess

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(a) Cold frame construction (b) Hybrid construction (c) Warm frame construction

Fig. 1. Classification of LSF constructions, depending on the position of insulation materials [1] (Materials: 1 – Gypsum; 2 – LSF; 3 – Stone wool; 4 – Air gap; 5 – OSB; 6 – EPS; 7 – ETICS).

and improve the thermal behaviour of constructive solutions with steel structures.

In this paper the LSF construction system is described. First, the three types of LSF construction, depending on the thermal insulation position, are presented. The main advantages and drawbacks of this construction system are also explained. Next, the main issues regarding the thermal performance of LSF construction elements are presented, including: the relevance of thermal bridges and mitigation strategies; the importance of thermal inertia and improvement measures, and; operational energy mitigation measures, depending on the climate. Finally, a case study of LSF wall thermal performance assessment (numerically and experimentally) is presented.

1 LSF construction system overview

1.1 Classification of LSF construction elements

The LSF construction elements (e.g. walls) can be classified into three types, depending on the position of insulation materials. In Figure 1 examples of cold, hybrid and warm frame construction are shown. The presented examples differ in the position of the wall materials: gypsum; lightweight steel frame (LSF); stone wool; OSB (Oriented Strand Board); EPS (Expanded Polystyrene); and ETICS (External Thermal Insulation Composite Systems).

In cold frame construction all the insulation is included within the thickness of the steel, the insulation layer being crossed by the steel studs. Figure 1a illustrates this configuration. This type of construction is not recommended for cold climates; given the lower temperature inside the wall there is a higher risk of interstitial condensation occurring, especially in the steel studs and their vicinity.

Figure 1b shows an example of a hybrid construction, in which the insulation is placed between the steel frames. The thickness of external continuous thermal insulation should be maximised for better thermal bridge mitigation.

In the third type, warm frame construction (Fig. 1c), all the insulation is placed outside of the steel framing. This is the best option, reducing the risk of interstitial condensation and maximising the thermal mass of the building envelope, as can be observed in Figure 2.

1.2 Advantages

The LSF construction system presents great potential for recycling and reuse and several

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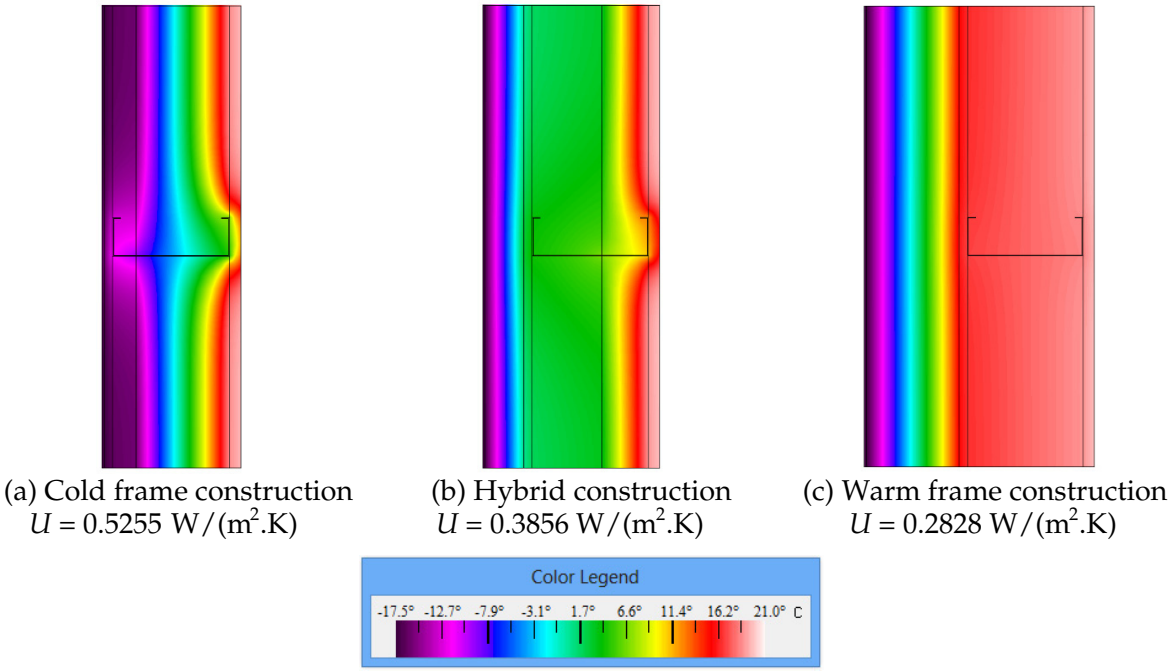


Fig. 2. Temperature distribution inside the LSF walls.

advantages when compared with other types of construction systems. The reduced steel debris in the construction phase and the steel removed during the demolition phase can be totally recycled and/or reused, with evident sustainability advantages.

These construction components also provide other advantages: reduced weight with simultaneous high mechanical strength; prefabrication on a large scale of substructures and subsequent assembly on-site, which allows a shorter assembly time; higher quality control; no dimensional variations caused by moisture; higher architectural flexibility; and low cost. Figure 3 displays an example of robotised prefabrication of LSF panels for modular construction [2].

From the point of view of environmental impacts, this construction technique allows the adoption of sustainability policies that enables the long-term conservation of natural resources, harmonising the relationship between the natural environment and human construction.

Regarding economic issues, the use of modular LSF construction systems provides many benefits, given the increase in construction speed allied with the production in scale and superior quality achieved by factory-based quality control. In comparison with traditional masonry construction, LSF construction is environmentally less sensitive since the weight of the construction is lower and the disruption on-site is reduced. Factory production is also less wasteful and most of the building components could be easily separated and selected for recycling at the end of the building's life.

The recyclable potential of the materials used in LSF construction and their higher durability is also an economic advantage. In the particular case of steel, this material recyclability and reuse rate is often higher than 95%. In addition, at the demolition stage it is also a better solution, due to the possibility of applying screw connections, allowing for quick and easy dismantling.

Another advantage of using LSF modular systems is the decrease in work accidents in the construction site, due to the lightweight elements and type of assembly.

1.3 Drawbacks

One of the main drawbacks of LSF construction elements is the high thermal conductivity of the steel, which can create thermal bridges, whenever its design is not adequate, with it being important to use

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Fig. 3. Use of robots in the prefabrication of LSF modular panels [2].

continuous thermal insulation (e.g. ETICS). Thermal bridges could penalise the thermal behaviour and energy efficiency of steel buildings, if not correctly addressed, increasing energy consumption and costs during the operational phase. Other related problems associated with thermal bridges are the constructive pathologies and reduced levels of comfort and salubrity associated with the occurrence of condensation phenomena driven by localised temperature drops inside construction elements. This is particularly important in buildings where the relative humidity (RH) may be high and can greatly decrease the materials' durability.

Another potential drawback of the LSF construction system is the low thermal mass and consequent thermal inertia, leading to higher daily temperature fluctuations, and greater discomfort for the occupants, and higher energy consumption. This is particularly evident for climates with higher daily temperature swings, e.g. Mediterranean climates.

In the next section several available strategies to mitigate these potential drawbacks of LSF construction will be described.

2 Thermal performance of LSF construction elements

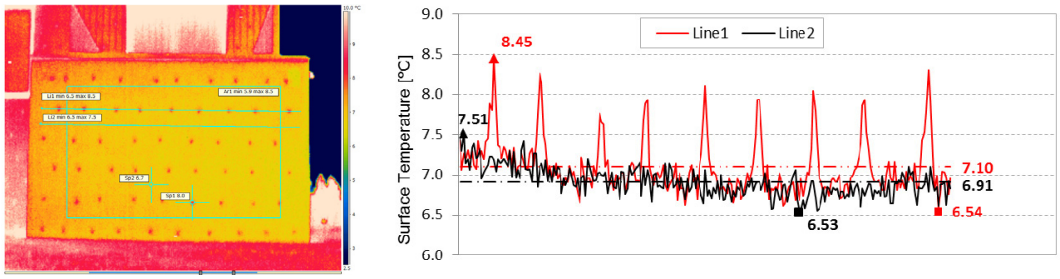
2.1 Thermal bridge relevance

Thermal bridge is the term commonly used to describe localised phenomena where there is an increased heat transfer in the building envelope, showing a reduction of thermal insulation effectiveness. This leads to a higher heating energy need/use and becomes especially important in high-performance buildings. Here, the energy loss due to thermal bridges can be even higher than, for example, the energy benefit provided by thermal solar collectors for domestic hot water production. The total impact of thermal bridges on the heating energy demand is significant, reaching 30%, and is greater than on the cooling energy demand [3].

Thermal bridges have two important consequences compared with unbridged structures: a change in the heat flow rate; and a change in the internal surface temperature [4]. Normally, the effect of a structural element in contact with the exterior envelope may cause a "thermal bridge", i.e. a fast and easy path for conducting heat. The problem of thermal bridges is delicate and extremely inconvenient, and may compromise the effectiveness of any applied insulation system. During the design stage, often the effect of thermal bridges still remains an issue that is neglected or superficially considered in the assessment of buildings' thermal performance.

The Canadian Sheet Steel Building Institute [5] conducted a comparative study of thermal performance between steel- and wood-framed houses, located on the same street, and inspected them on the same evening with an outside temperature of 6 °C, and no wind. The study demonstrated that in the long term the wood presents moisture contents and fissures that may cause air infiltration, increasing heat loss. Because steel does not warp or shrink in contact with moisture, therefore steel has a clear advantage here, allowing heat loss minimisation and energy conservation. "When detailed

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(a) (b)

Fig. 4. Building façade: (a) infrared thermography photo; (b) surface temperature along lines 1 and 2.

with insulation and expanded foam insulation in the stud cavities, the steel homes used 7% less energy than their wood counterparts which were built to the same nominal *R*-value" [5].

As previously mentioned, the use of external continuous thermal insulation is an important thermal bridge mitigation strategy. However, special attention should be given to the selection of the thermal insulation fixation technique. The glued one should be preferred. If mechanical fasteners are adopted they should be, for instance, in PVC material rather in steel. In Figure 4 an infrared (IR) thermography image of LSF in a building façade is shown, where the rise of temperatures in some points of the wall due to the use of steel fasteners to fix the ETICS is visible. This localised surface temperature rise is very visible in Figure 4b.

The mitigation of thermal bridges can be achieved with simple design rules and strategies. Some examples are: keep the façade geometry as simple as possible; avoid the interruption of the insulating layer; at junctions of building elements, the insulation layers must be joined at full width; when the interruption of the insulation layer is unavoidable, a material with the highest possible thermal resistance should be used; and openings, such as doors and windows, should be installed in contact with the insulation layer [1].

Next several techniques are presented and described that can be used to mitigate thermal bridges, particularly focused on steel buildings.

(a) External continuous thermal insulation

As previously mentioned, the use of continuous exterior thermal insulation is an effective way to improve the thermal performance and reduce the thermal bridges. Also, the increased spacing between steel profiles allows a thermal resistance increase (higher *R*-value). Kosny et al. [6] showed that the gain in *R*-value caused by the increased spacing was about 20% with 1.3 cm of EPS and about 15% with 2.5 cm of EPS.

(b) Increasing the heat flux path

The increase in the heat flux path through the reduction area of the steel profile, with the insertion of slots in the web stud, is an efficient way to reduce heat flow (Fig. 5a). Besides, if the flange length is decreased, the *U*-value will also decrease.

(c) Reduction of the profile flange contact area

Another possible solution is to use a profile with a geometry that allows reducing the contact area of the flanges, creating a thermal break, thereby increasing the wall's *R*-value (Fig. 5b). This system is a patent developed for thermally improved exterior wall framing [8] and allows an improvement in the *R*-value of the wall (up to 16%).

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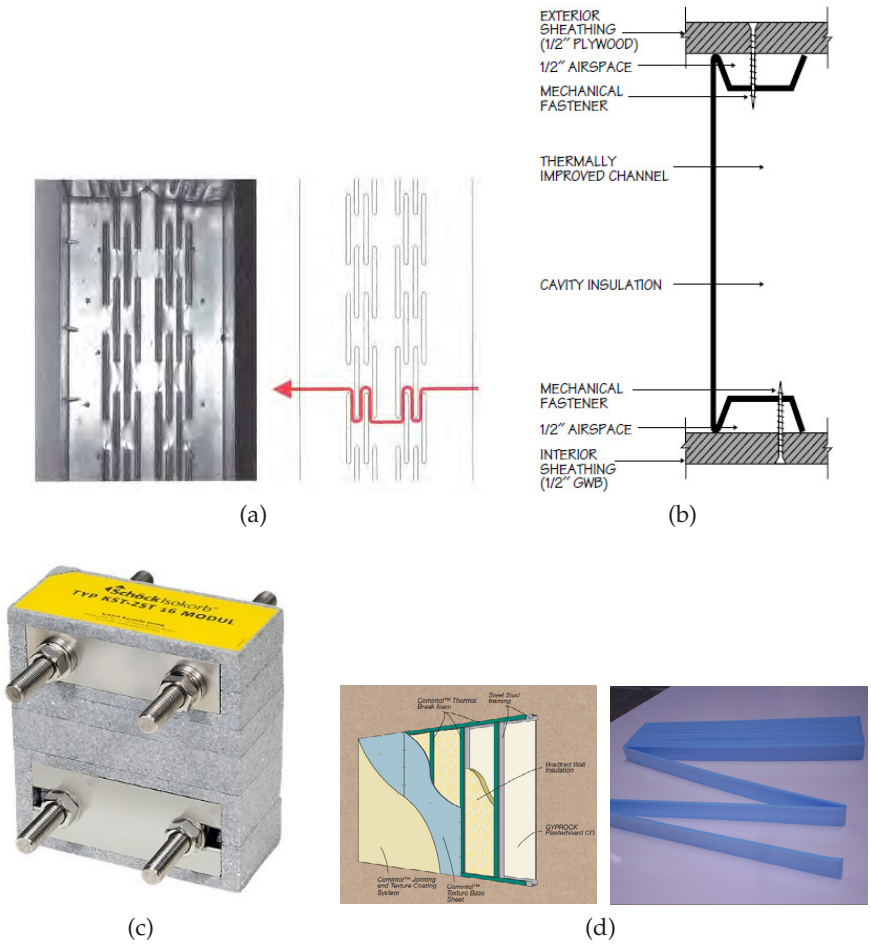


Fig. 5. Thermal bridge mitigation techniques: (a) increasing the heat flux path [7]; (b) reduction of the profile flange contact area [8]; (c) thermal breaks for building components [9]; (d) thermal break strips [10].

(d) Thermal breaks for building components

The introduction of thermal breaks allows the creation of a barrier in the thermal transmission between external components and the internal part of the building (Fig. 5c). Thermal breaks can be incorporated in steel structures, allowing simultaneous transmission of high loads.

(e) Thermal break strips

The placement of insulation material applied locally along the studs allows the mitigation of thermal bridges (Fig. 5d). This solution consists of the placement of insulation straps attached to the steel frame using button screws or an adhesive.

2.2 Thermal mass relevance

The building envelope thermal performance is crucial to provide good thermal behaviour and energy efficiency, and allow a reduction of operational energy. Besides the mitigation of thermal bridges it is also important to provide some thermal inertia for the building in order to "absorb" the daily thermal swings originated by solar and internal heat gains. As mentioned earlier, LSF buildings usually have low thermal inertia. However, there are several strategies to increase thermal mass, such as: use external thermal

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(a) (b) (c)

Fig. 6. Thermal inertia improvement: (a) wall filled with stones [11]; (b) ground heat exchanger air circulation pipes; (c) PCM panels [12].

insulation; use massive construction materials; take advantage of huge ground thermal mass; and use phase-change materials (PCMs), as described next.

(a) Use of massive construction materials

The use of massive construction materials in LSF buildings is not usual. However, there are some simple strategies that allow an increase in the thermal mass of the building. In Figure 6a a stone wall used to store thermal energy obtained from solar heat gains through glazed windows is shown.

(b) Use of ground thermal mass

A geothermal energy system allows the use of the enormous ground thermal mass, taking advantage of it in the summer and winter seasons. These systems can be based on air, such as in Figure 6b, or refrigeration liquid. Due to the high thermal inertia of the soil, the daily and seasonal temperature variations at the surface are reduced deeper in the ground. Besides, a time lag occurs between the variations of the ground and surface temperatures. In this way, the ground can be used as a heat source (in the winter) or as a heat sink (in the summer).

This system can simultaneously promote indoor air quality and energy efficiency in buildings, by providing fresh outdoor air and reducing the energy used for heating and cooling. This is a relevant feature, especially considering the air tightness of modern buildings.

(c) Use of phase-change materials

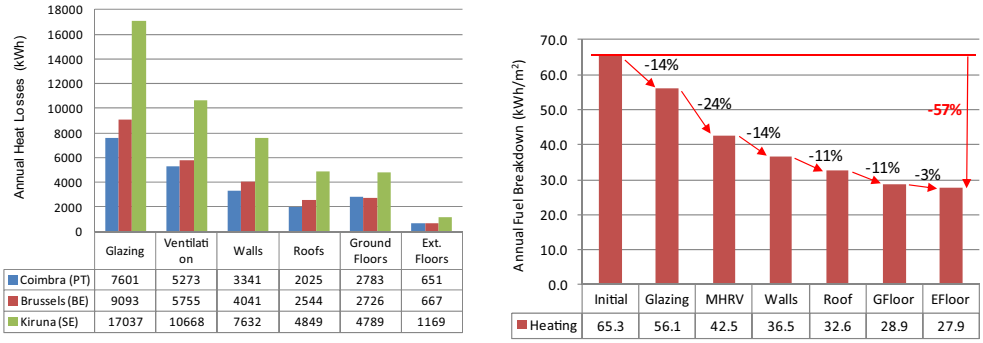
PCMs are also a great solution to increase the thermal mass, without significantly increasing the weight of construction elements. They have the great advantage of higher heat storage, acting as a heat buffer, due to the latent heat. However, the cost of PCMs to be used in building construction elements is relatively high, this being the main drawback of this solution. There are several types of PCMs, with different heat storage capacity, shapes and fusion temperatures, macro- and micro-encapsulated. Figure 6c shows one example.

2.3 Operational energy

The reduction of operational energy used in buildings, maintaining the internal thermal comfort, is essential to achieve a better building sustainability label. This can be accomplished with good design and construction techniques. The best way to test different improvement design solutions is performing advanced dynamic thermal simulations of the building, using the climatic data of the site. This will allow one, for example, to achieve a good compromise between having too much thermal insulation (higher embodied energy) or too little (higher operational energy), towards the optimisation of resources.

Santos et al. [1] performed advanced dynamic simulation studies for a LSF low-rise single family residential building, using DesignBuilder/EnergyPlus software, that allows assessing the importance of the

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(a) (b)

Fig. 7. Operational energy: (a) annual heat losses through the building envelope's main components; (b) heating annual fuel breakdown decrease due to improvements [1].

improvements in the building envelope's main components. Figure 7a shows, in relative terms, the importance of each building component regarding the annual heat losses through the building envelope, for three locations: Coimbra (Portugal); Brussels (Belgium); and Kiruna (Sweden). In the coldest city (Kiruna), the glazing and ventilation systems have the most significant heat losses, evidencing the necessity of improving them.

Figure 7b shows the heating annual fuel breakdown decrease due to improvements in the envelope components, for the building located in Kiruna. Comparing the initial solution with the improved final one, a reduction in energy demands of 57% was obtained.

3 LSF wall case study

In this section a case study regarding a modular LSF wall is briefly presented in order to assess the importance of some thermal bridge mitigation techniques. The modular wall is comprised of a steel structure containing galvanised steel cold-formed studs with different cross-sectional shapes: "C" (100 × 40 × 10 × 1), "U" (75 × 40 × 1) and "Z" (75 × 25 × 1). Each wall module is 1.2 m wide and 2.49 m high. Figure 8a illustrates the assembled steel structure contained in the wall and Figure 8b shows the enclosed materials and thickness.

Having as reference a standard LSF wall, three design improvement measures were implemented and the increased performance of the wall quantified. All the numerical results were obtained from wall models assembled in three-dimensional finite element software. In Table 1 the results obtained (U-value) for each wall model are presented. The first improvement strategy was the insertion of a thermal break strip of rubber between the steel and OSB panel, on the outer surface. This allows a decrease of 1.9% in the U-value (in comparison with the reference case). The second approach was the use of vertical slotted steel profiles, with removal of 14% of the web stud mass. The benefit from this solution is better than the previous one, reducing the U-value by 3.2%. In the last simulation, the thermal bridges created by the horizontal steel connections were reduced by replacing these elements with nine fixing bolts. As expected, this solution improves the thermal performance by reducing the U-value (–2.1%).

IR thermography can be used to assess the temperature surface distribution and evaluate if there is any thermal bridge effect. Figure 9 was obtained during an experimental test of a LSF wall before applying the external thermal insulation coating system (ETICS). As expected, the location of the vertical steel studs can be clearly identified, showing a higher surface temperature in the vicinity of the vertical steel studs due to the increased heat flux through the steel.

The numerical results also show the surface temperature and heat flow increase due to the steel studs. Figure 10 displays the heat flux on the LSF wall external surface

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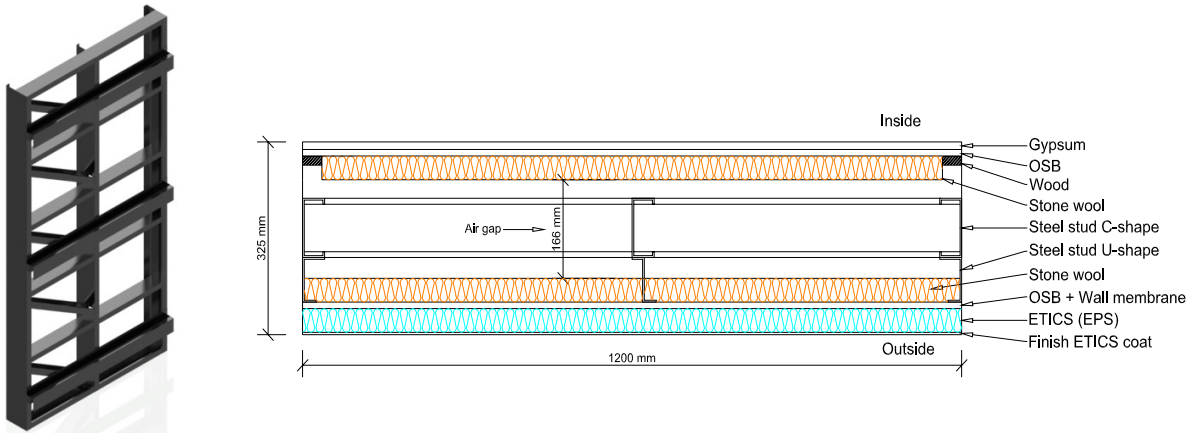


Fig. 8. Wall module: (a) LSF structure; (b) horizontal cross-section.

Table 1. LSF wall case study results.

Model description	U-value W/(m^2.K)	Decrease in U %
Standard LSF reference wall	0.3011	–
Use of 10 mm rubber between the steel and OSB, on the outer surface (λ_{rubber} = 0.037 W/(m.K))	0.2954	–1.9
Slotted steel profiles, removal of 14% of web stud mass	0.2913	–3.2
Use of fixing bolts instead of horizontal steel plate connection λ, thermal conductivity	0.2949	–2.1

before and after the ETICS assembly. The external thermal insulation allows a significant reduction in the heat flux (Fig. 10b) in comparison with the one without ETICS (Fig. 10a). This leads to a more homogeneous wall surface heat flux distribution, and thus better thermal behaviour. Note that the negative heat flux values mean that this wall surface is losing heat (cold surface). The highest heat flux absolute values are in red and the lowest are in blue.

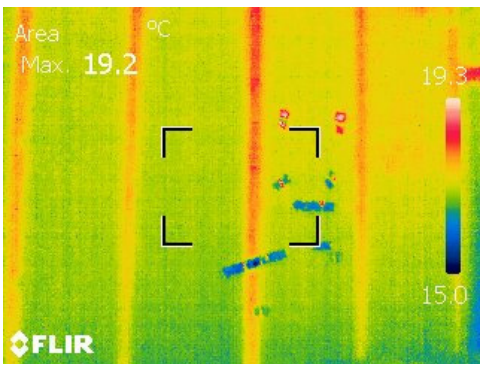
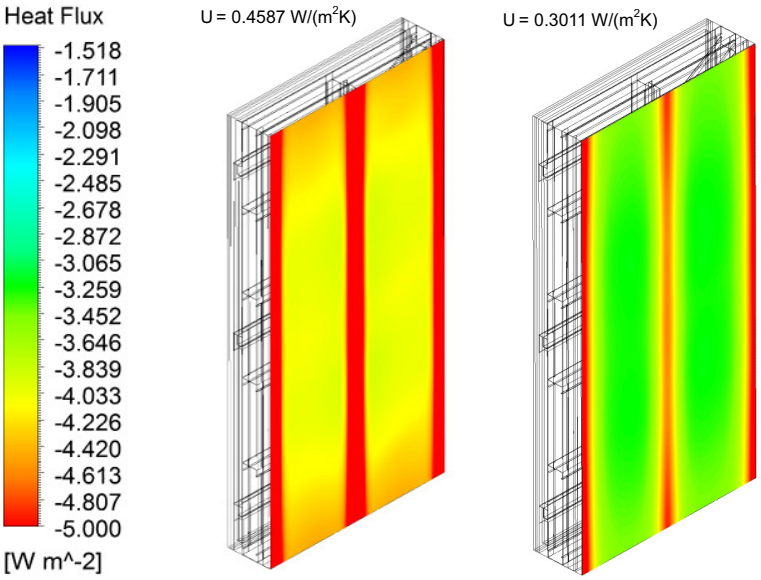


Fig. 9. Infrared thermal photo of a LSF wall without ETICS (external surface).

4 Conclusions

In this work the main advantages and drawbacks of LSF construction systems were described, with huge potential for sustainability being evident. However, adequate design is essential to achieve this high sustainability level; for instance, minimising thermal bridges and improving thermal inertia. These two parameters may have a big influence on the thermal behaviour and energy efficiency of LSF buildings. Several strategies are available nowadays to address these issues, as presented in this paper. Some of these techniques can be applied alone or simultaneously, these specifications being very important at the design stage to minimise operational energy, and increase the energy efficiency and sustainability label of a building.

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(a) Without ETICS (b) With ETICS

Fig. 10. Heat flux predictions for the wall exterior view.

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