Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: a review

N. Soares[a,b], P. Santos[b], H. Gervásio[b], J.J. Costa[a], L. Simões da Silva[b]

[a] ADAI, LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

[b] ISISE, Department of Civil Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: a review

N. Soares[a,b], P. Santos[b], H. Gervásio[b], J.J. Costa[a], L. Simões da Silva[b]

[a] ADAI, LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

[b] ISISE, Department of Civil Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

Abstract

The improvement of the use of renewable energy sources, such as solar thermal energy, and the reduction of energy demand during the several stages of buildings' life cycle is crucial towards a more sustainable built environment. This paper presents an overview of the main features of lightweight steel-framed (LSF) construction with cold-formed elements from the point of view of life cycle energy consumption. The main LSF systems are described and some strategies for reducing thermal bridges and for improving the thermal resistance of LSF envelope elements are presented. Several passive strategies for increasing the thermal storage capacity of LSF solutions are discussed and particular attention is devoted to the incorporation of phase change materials (PCMs). These materials can be used to improve indoor thermal comfort, to reduce the energy demand for air-conditioning and to take advantage of solar thermal energy. The importance of reliable dynamic and holistic simulation methodologies to assess the energy demand for heating and cooling during the operational phase of LSF buildings is also discussed. Finally, the life cycle assessment (LCA) and the environmental performance of LSF construction are reviewed to discuss the main contribution of this kind of construction towards more sustainable buildings.

Keywords: buildings; lightweight steel-framed (LSF); energy performance; thermal energy storage; phase change materials (PCM); life cycle assessment (LCA).

Contents:

1. INTRODUCTION

The International Energy Agency [1] points out that residential and commercial buildings account for roughly 32% of global energy use and almost 10% of total direct energy-related CO_2 emissions. It also highlights the importance of implementing stringent energy-saving requirements for new buildings and retrofitting, and the need to use high-efficient technologies in building envelopes and heating/cooling systems. In this context, the reduction of the environmental impacts of the built environment and the improvement of the energy efficiency of buildings during their entire life cycle is a worldwide prime objective for energy policy. As a result, the demanding legislation concerning the reduction of the energy consumption of buildings has been challenging both the construction sector and the research community to develop new high-efficient products and construction techniques, to set up new methodologies for assessing the energy demand of buildings during each stage of their life cycle, and to develop new technologies to improve the use of renewable energy sources, such as solar thermal energy.

This paper brings together existing research on the assessment of the energy efficiency and thermal performance of lightweight steel-framed (LSF) construction with cold-formed elements in order to provide an overview on how this typology of buildings can contribute to a more sustainable built environment. Indeed, this review aims to point out the main advantages and drawbacks of this type of construction. The paper also intends to provide an overview on how LSF construction can contribute to a more sustainable use of energy during the several stages of the lifetime of buildings and how some technologies can be used to improve the thermal performance of LSF buildings and, at the same time, to take advantage of solar thermal energy.

LSF construction has been attracting interest worldwide and its popularity is increasing for use in both residential houses and apartment blocks [2,3]. Veljkovic and Johansson [4] also pointed out that LSF buildings have a widespread use in the USA, Australia and Japan and are gaining market in Europe. A general description of LSF construction for low rise commercial and medium and high-rise residential buildings can be found in ref. [5] along with an extensive review of the main advantages of this type of construction. As suggested by several authors [3,6-8], LSF construction presents certain advantages over heavyweight construction, such as: small weight with high mechanical strength; reduced disruption onsite and speed of construction; great

potential for recycling and reuse; high architectural flexibility for retrofitting purposes; easy prefabrication allowing modular construction, suited to the economy of mass production; economy in transportation and handling; superior quality, precise tolerances and high standards achieved by off-site manufacture control; excellent stability of shape in case of humidity; and resistance to insect damage. However, the high thermal conductivity of steel elements may lead to significant thermal bridges. LSF construction may also show lower thermal mass which can be problematic in some conditions, leading to several comfort-related problems (*e.g.*, overheating), larger temperature fluctuations and higher energy demand for heating and cooling.

In the first part of this paper, several LSF systems are presented and classified, and some materials, manufacturing/design options and framing methods are listed in order to provide a general overview of this kind of construction. Secondly, some strategies for reducing thermal bridges and for improving the thermal resistance of LSF envelope solutions are discussed. Several strategies for increasing the thermal storage capacity of LSF elements are also presented and particular attention is devoted to the incorporation of PCMs in LSF systems. Nowadays, it is well known that the use of adequate thermal energy storage (TES) systems with PCMs presents high potential in energy conservation in the building sector [9]. The energy consumption for heating and cooling and the thermal comfort of LSF buildings during their operational phase are also discussed, and some methodologies to evaluate the thermal performance of buildings are presented. Finally, in the last part of the paper, the environmental performance of LSF construction and the life cycle assessment (LCA) of this type of construction are discussed, pointing out the main challenges of this sort of analysis.

2. OVERVIEW OF LSF CONSTRUCTION SYSTEM

2.1. Materials

LSF is a building construction system consisting of dry materials [10], mainly for low-rise residential buildings [11]. This dry construction system can be characterized by three main materials that are used in walls and slabs: cold formed steel sections for load bearing; sheathing panels (*e.g.*, oriented strand board (OSB) and gypsum plasterboard) and, insulation materials (*e.g.*, mineral wool and expanded polystyrene) [12]. Further materials are needed for joining and fastening (*e.g.*, self-drilling screws); waterproof and air tightness membranes, and finishing layers [8,11]. In order to avoid problems

related with ground humidity, a LSF building needs a ground floor, usually a concrete slab, being the foundation work done with conventional methods [4]. Notice that, given the lightness feature of LSF buildings, the foundation size is usually smaller.

2.1.1. Cold-formed sections

The load bearing structure in LSF construction is made of cold-formed steel sections. The strength and stiffness of the steel profile depends, besides the steel sheet thickness and grade, on the shape of the cross-section (Fig. 1). The usual steel sheet thickness for LSF profiles ranges from 0.45 to 6 mm [8].
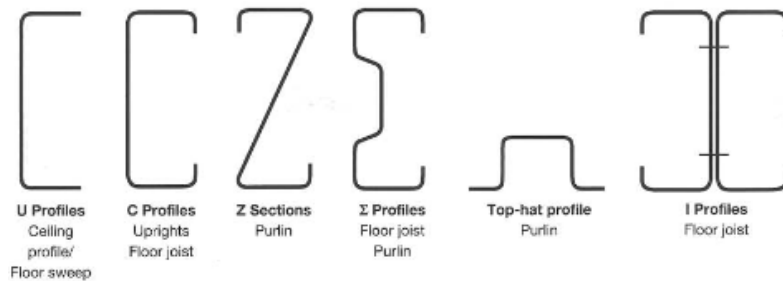

Fig. 1. Examples of cold-formed cross-section profiles. With permission from ArcelorMittal Europe – www.constructalia.com [11].

The cold-formed sections can be manufactured using three processes: drawing, bending and rolling [11]. Drawing consists of pulling the steel strip through non-actuated deforming rolls using jaws. This low-cost manufacturing process is suitable to the production of very thin and complex sections. Bending of the steel sheet can be achieved by using brakes, benders or a drop forcing press. The main difference between this manufacturing process and the two others is that the steel strip does not need to be rolled. In fact, the rolling process is more used in industrial manufacturing of cold-formed steel sections, given its higher productivity levels. Drawing and rolling manufacturing processes are similar; however, the deforming rolls in the later are actuated. EN10162 [13] prescribes the dimensional and cross-sectional tolerances for cold-rolled steel sections produced on roll-forming machines. Cold-formed steel sections are usually manufactured up to a length of 12 meters [11].

The steel grades used for the design of cold-formed members and profiled sheets fabricated from steel are prescribed in Eurocode EN1993-1-3 [14]. To avoid corrosion and to increase durability, the steel sheet is usually galvanised as prescribed in EN10326 [15]. According to this standard, the continuous hot-dip zinc galvanised strip

6

steel is designated S220GD+Z, S250GD+Z, S280GD+Z, S320GD+Z, S350GD+Z or S550GD+Z. In these cases, the basic yield strength changes from 220 to 550 N/mm^2 and there is a minimum G275 coating, with a normal thickness of zinc coating of 0.04 mm (275 g/m^2), leading to an excellent durability for current LSF applications.

Nowadays, slotted steel studs are available on the market to improve thermal performance [4,12]. There are also acoustic studs with a specific cross-section configuration (*e.g.*, slots in the middle of the web [12] or resilient channels [16]) which allow a more elastic connection and, therefore, an improved acoustic behaviour in terms of noise insulation. The internal cavity between steel studs is ideal for inserting pipes, ducts and cables (Fig. 2) [11].

Fig. 2. Technical installations between steel frames.

2.1.2. Sheathing panels

The most usual sheathing panels in LSF low-rise residential buildings are made of OSB and gypsum plasterboards for the outer and inner layers of external walls, respectively. However, in industrial hall applications, the steel sheathing is also often used. These covering materials have also a structural role in load-bearing walls, mainly for horizontal loads (*e.g.*, wind) in the plane of the wall [17]. Thicker OSB panels could also be used for dry floor sheathing. The adopted floor system should take into account the fire resistance [18] and the acoustic performance, being the workmanship quality an important issue in the later [19]. Moreover, the use of a top thinner concrete/mortar layer is able to provide some advantages regarding thermal performance and acoustic behaviour [8].

Regarding OSB panels, the EN 300 [20] defines terms, establishes a classification and specifies some requirements. Several characteristic values for design

calculations are given in EN 12369-1 [21]. Concerning gypsum plasterboard panels, EN 520 [22] presents some definitions, requirements and test methods. There are also several standards specific for ancillary products, such as mechanical fasteners EN 14566 [23], jointing materials EN 13963 [24] and metal framing EN 14195 [25].

2.1.3. Joining and fastening

Fastening is a fundamental issue related with the competiveness of the LSF construction system [11]. The choice of a specific fastening method will depend on: the type and thickness of the connected materials, loading conditions and required strength of connection, availability of fasteners and tools, local of assemblage, cost, durability requirements, and code acceptance [11]. Fig. 3 illustrates several methods for joining and fastening. The most common fastening method is based on self-drilling tapping screws (or self-piercing screws) [8]. These fasteners, when compared with nails, provide a much stronger and more durable connection. These screws could be used with washers to increase the load bearing capacity and/or the sealing capacity. For the later, an additional elastomeric washer (*e.g.*, rubber) is frequently used. Given the high temperatures generated by friction during the drilling process, these screws are usually fabricated from heat-treated carbon-steel (plated with zinc for corrosion protection and lubrication) or from stainless steel with carbon-steel drill point and also plated with zinc for lubrication [8].
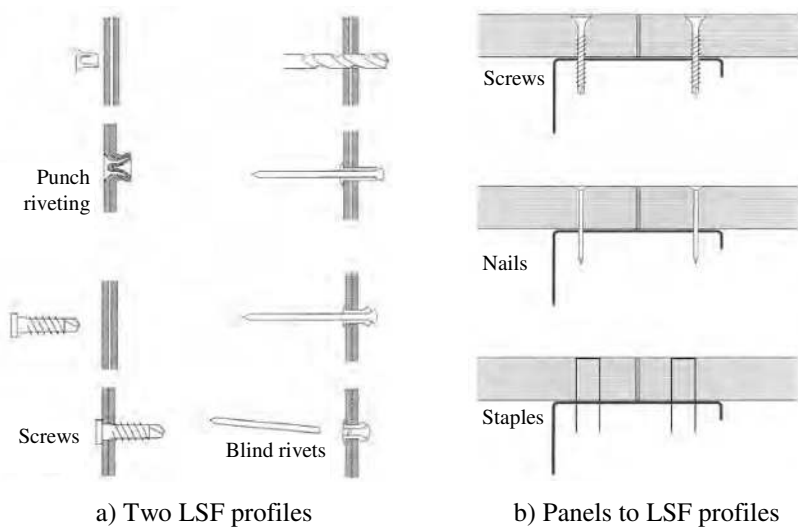

a) Two LSF profiles   b) Panels to LSF profiles

Fig. 3. Options for joining and fastening in LSF construction. With permission from ArcelorMittal Europe – www.constructalia.com [11].

2.1.4. Thermal insulation materials

The most common thermal insulation material used in LSF construction is the mineral wool (MW), which is mostly used between the steel studs. Notice that MW is often used not only in external walls and slabs but also in internal partitions and slabs (Fig. 4a). As MW is an incombustible material, it also provides an increased fire resistance to LSF elements [26]. The requirements for MW thermal insulation products for buildings are specified in EN 13162:2012+A1 [27].

It is also very common to use an ETICS with expanded polystyrene (EPS) as shown in Fig. 4b. The ETICS is very suitable to minimize steel stud thermal bridges as the exterior thermal insulation layer may be continuous [7]. The requirements for EPS thermal insulation products for buildings are specified in EN 13163:2012+A1 [28]. When these thermal insulation products are used in ETICS, there are also standards with specific requirements, including procedures for testing, marking and labelling (*e.g.*, EN 13499 [29]). The European standard EN 12524 [30] provides tabulated design values for heat and moisture calculations for thermally homogeneous building materials and products (including thermal insulation materials). EN ISO 10456 [31], besides the tabulated design values, also presents tests and calculation procedures for determining design thermal values, being the data obtained in EN 12524 [30] reviewed and updated.

a)   b)
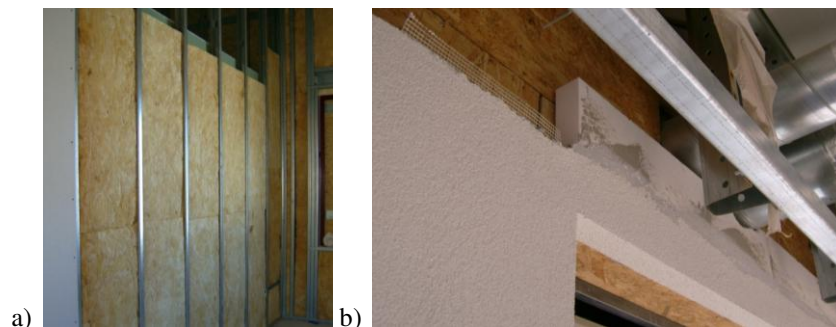
Fig. 4. Thermal insulation in LSF construction: a) MW between the steel studs; b) EPS in ETICs.

2.1.5. Wind and air tightness membranes

Air tightness is very important in cold climates to control heat losses due to air infiltrations [32,33]. Kalamees measured the air tightness and air leakages of new lightweight single-family detached houses in Estonia and concluded that the number of storeys and the quality of workmanship and supervision play a significant role in the condition of air tightness [33]. Kalamees also stated that, in new buildings with higher thermal insulation level, the infiltration can be responsible for about 25% and 3% of

9

heating and cooling loads, respectively [33]. The air permeability of a building is measured using the fan pressurization method following the procedures prescribed in EN 13829 [34].

To reduce air infiltration and interstitial condensation, two membrane layers should be used along the LSF building external envelope [11]. Along the inner side of external coatings, a wind-tight membrane should be used whenever a waterproof membrane does not exist, or it is unable to prevent air infiltration. Additionally, an internal air-barrier should be used to prevent the leakage of warm air within the building envelope elements (walls and slabs) and/or outdoors (air exfiltration). This membrane layer is often denominated as vapour barrier, as it should avoid the air moisture to go inside the LSF elements, where it could originate interstitial condensation when in contact with cooler surfaces. Notice that the external wind-tightness layer should be permeable to vapour in order to allow the moisture outlet whenever it exists within the LSF element, avoiding its accumulation inside walls and slabs (Fig. 5).

Fig. 5. External wind-tightness membrane layer around an opening in a LSF external facade before the ETICS execution.

2.1.6. Finishing options

A LSF building may have any finishing coating layer as a traditional building, *e.g.*, plastered thermal insulation, brick cover or cladding [11,35]. However, as remarked in Section 2.1.2, the most common finishing coating layers are gypsum plasterboards and ETICS for the inner and outer facade walls, respectively [8]. Gypsum plasterboards are also commonly used in ceiling cladding. Nowadays, designers also use OSB as a finishing cover layer for walls and ceiling. Regarding floors, traditional finishing materials can also be used, *e.g.*, ceramic tiles, hardwood, floating floors, carpets, mortar, cork and linoleum. The LSF roofline structure could be similar to other construction systems, *e.g.*, flat, shed, gable or hipped roof. Depending on the adopted roofline

structure, the finishing types and materials could be, for instance, ceramic tiles, shingle type, membrane roofing and sheet metal roofing.

2.2. Classification of LSF construction elements

Regarding thermal behaviour, LSF construction elements are typically classified according to the location of the thermal insulation [6]. Fig. 6 shows the three types of LSF construction: cold frame, hybrid, and warm frame construction. In cold frame construction, the thermal insulation is placed inside the wall between the steel studs. Therefore, this solution may be more susceptible to interstitial condensation, mainly in cold climates, given the lower temperature of the steel studs. Moreover, the steel frames thermal bridges are more expressive in this type, leading to higher heat losses and gains. When the thermal insulation is distributed between the external surface and the wall cavity between steel studs, the LSF construction is classified as hybrid construction. In this type, at least 1/3 of the thermal resistance should be placed outside the wall cavity, in order to mitigate thermal bridges and interstitial condensation risk [8]. Finally, in the warm frame construction system all of the thermal insulation is placed outside the steel framing, which has the best thermal performance. However, this type originates thicker walls, which may lead to smaller net floor area.

a) Cold frame construction *b) Hybrid construction* *c) Warm frame construction*
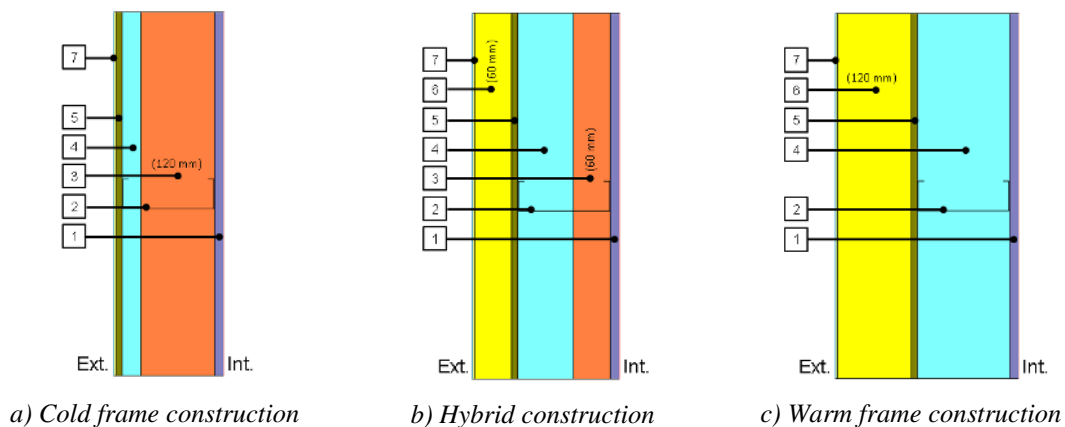
Fig. 6. Classification of LSF constructions depending on the position of insulation materials (1- Gypsum; 2- LSF; 3- Mineral wool; 4- Air gap; 5- OSB; 6- EPS; 7- ETICS) [6].

2.3. Design, manufacturing and framing methods

In European countries, the design of cold-formed structural elements is based on EN1993-1-3: Eurocode 3 [14]. Usually, the floor span of a LSF building goes up to six-seven meters [4,11,36]. One of the major advantages of LSF systems is their suitability

to prefabrication and industrial production. Nowadays, it is even possible to take advantage of automated technologies (*e.g.*, robots) for prefabrication of LSF elements.

The framing production methods of LSF components can vary from stick building to modular construction [4]. The stick-framing method is very flexible and it does not need so much planning. Prefabrication of LSF components with industrial methods has a high potential to improve the construction process (*e.g.*, increased quality control and higher erection speed). In between the onsite stick-framing assemblage and the 3D Modular factory assemblage, the panelised system can be pointed out [8]. In this system, the wall panels and slab cassettes are prefabricated in factory, and then, they are transported to the construction site to be assembled. Nowadays, there are also some "hybrid" modular and panel LSF systems as the one applied to a demonstrating building in UK and reviewed by Lawson and Ogden [36]. These authors stated that mixed modular and panel systems allow to optimize the 3D and 2D components in terms of space provision and manufacturing costs. Typically, 3D modular units are used for the higher value of highly service areas (*e.g.*, bathrooms and kitchens), while wall panels and floor cassettes are used for the more flexible open space.

As mentioned before, LSF construction is mainly used in low-rise construction. However, it is possible to extent the use of LSF to higher multi-storey buildings. Therefore, to achieve greater flexibility in building height and internal planning, a primary steel frame (*e.g.*, "podium" or skeletal structure) is assembled. Lawson and Ogden defined this type of LSF construction as: "hybrid" modular, panel and primary steel frame [36]. Table 1 summarizes the main advantages of each LSF construction system described before.

Table 1. Comparison between the main advantages of several LSF construction systems [8,36].

Stick-framing (or stick-built):
- Construction tolerances and modifications can be accommodated on site;
- Connection techniques are relatively simple;
- Contractors do not require the workshop facilities associated with panel or modular construction;
- Large quantities of structural members can be densely packed and transported in single loads.
Panelised (or areal):
- Higher erection speed of the panels or sub-frames;
- Better quality control in production;
- Minimisation of site labour costs;
- Suitable for automation in factory production;
- The application of sheathing and finish systems is easier and faster with the panels in a horizontal position in shop.

Modular (or volumetric):
- Reduced construction costs, mainly when combined with economy of scale production;
- Much reduced construction time on site;
- Increased profitability of the industry due to economy of manufacturing scale;
- Increased site productivity;
- Greater certainty of on-time conclusion and budget constraints;
- Much reduced wastage in manufacture and on site;
- Greater reliability and quality.

"Hybrid" modular and panel:
- Optimized advantages of both 2D panel and 3D modular LSF construction.

"Hybrid" modular, panel and primary steel frame:
- Similar advantages of "hybrid" modular and panel construction system;
- Taller buildings with even greater flexibility in internal planning.

3. THERMAL PERFORMANCE OF LSF CONSTRUCTION

In this paper, thermal performance refers to how well a building responds to changes in the outdoor environment in order to maintain indoor thermal comfort conditions. These conditions must be achieved involving as little energy demand for heating and cooling as possible. The energy efficiency of the building means using less energy to provide the same indoor thermal conditions. In this context, the thermal performance of LSF construction can be improved by reducing thermal bridges and by considering low thermal transmittance of the envelope elements. This should be coupled with right ventilation strategies and good passive solar techniques. The improvement of the thermal capacity of LSF systems can also enhance the thermal performance of LSF construction by increasing the thermal inertia of the building.

3.1. Strategies for reducing thermal bridges

Thermal bridges are preferential heat paths through the building envelope and they can have a significant impact on the thermal performance of high-insulated LSF buildings, as they increase the heat transfer through the building envelope. Thermal bridges also influence the surface temperature of building components. Due to the lower thermal resistance, the internal surface temperature on components with thermal bridges is lower during winter and some problems of condensation and mould may occur [37]. Moreover, as stated by Gorgolewski [3], thermal bridges can also create a large temperature difference between the stud area and the centre of the inter-studs area, leading to the possibility of wall staining called "ghosting". As suggested by Santos *et al.* [8], thermal bridges can be classified into three main types: (*i*) geometric thermal

13

bridges at corners and junctions including windows and doors, walls/slabs and wall/wall corners; (*ii*) isolated thermal bridges like balconies penetrating insulation layers or steel fasteners penetrating a sandwich insulated panel; and (*iii*) repeated thermal bridges in construction elements due to steel framing. Fig. 7 shows the temperature distribution inside different LSF walls as computed by Santos *et al.* [6].

a) Cold frame construction
U=0.5255 W/(m².K)

b) Hybrid construction
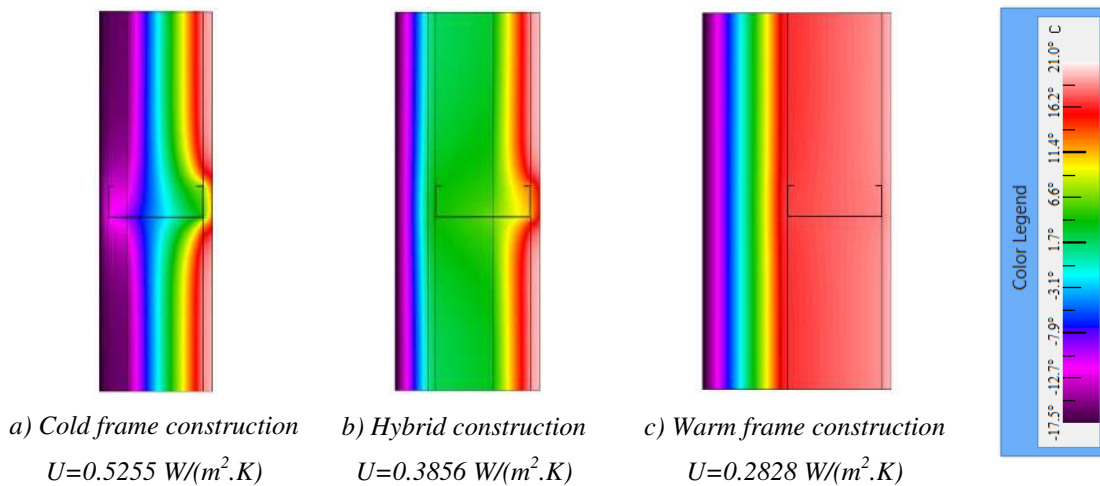U=0.3856 W/(m².K)

c) Warm frame construction
U=0.2828 W/(m².K)

Fig. 7. Temperature distribution inside the LSF walls as computed by Santos *et al.* [6].

Some general design strategies for the reduction of thermal bridges can be listed: (*i*) the simplicity of the geometry of facades; (*ii*) the placement of a continuous insulation layer on the external side of the steel framing; (*iii*) the interruption of the insulation layers should be avoided; (*iv*) windows and doors should be installed in contact with the insulation; (*v*) at junctions, the insulation layers should join at full width, and (*vi*) the studs should be attached to the external insulation layer using fixings with low thermal conductivity. Moreover, Santos *et al.* [8] pointed out that the space between steel frames, the thickness of the steel elements, the length of the web and flanges, the cross-section profile and number of steel frames may also influence the impact of thermal bridges. Therefore, all of these features must be taken into account. For instance, Kosny *et al.* [38] evaluated the influence of increased spacing between steel profiles on the *R*-value of walls with different thickness of the insulation layer. The authors concluded that the gain in the *R*-value caused by the increased spacing was about 20% and 15% for the 1.3 cm and 2.5 cm insulation layer cases, respectively.

Santos *et al.* [6,8] also suggested some strategies to reduce the effect of repeated thermal bridges, such as: (*i*) slotted steel stud to increase the heat flux path; (*ii*) flange stud indentation; (*iii*) thermal breaks for building components; and (*iv*) thermal break

14

strips. In the former, longitudinal slots are introduced in the steel stud to reduce the heat flux through the steel elements. In the second strategy, the shape of standard steel studs is improved to reduce the contact area of the flanges and to create an indentation (*i.e.*, a thermal break) and, thereby, increasing the thermal resistance of the wall. In the third strategy, thermal breaks are introduced to create a barrier against the heat transfer between exterior and interior components. Finally, in the latter strategy, an insulation strap is attached along the steel framing using button head screws or adhesives. Martins *et al.* [7] added that fixing bolts can be used instead of horizontal steel plate connections to reduce thermal bridges.

Höglund and Burstrand [12] evaluated the mitigation of thermal bridges by increasing the thermal resistance through the reduction of the area of the steel profile and the introduction of slots in the web stud. They concluded that the *U*-value of the element decreases when the flange length is decreased. Blomberg and Claesson [39] have also suggested that the use of slotted steel studs is one of the most efficient ways to improve the thermal resistance of LSF elements. The authors pointed out that the heat flow through a steel profile decreases as the number of narrow slots increases, and they concluded that the thickness of a standard steel profile has to be decreased by a factor of six to achieve the equivalent thermal properties of a slotted steel profile. Martins *et al.* [7] carried out an extensive study to evaluate the impact of single and combined thermal bridges mitigation strategies on the thermal performance of a reference LSF wall. The analysis was performed using a 3D finite element method (FEM) derived from a previously validated 3D FEM reference model proposed by Santos *et al.* [40]. The authors concluded that the most favourable combined solution leads to a reduction of *8.3%* in the *U*-value of the reference LSF wall. The best solution combines rubber strips (10 mm), slotted steel profiles (28%) and 9 bolted connections.

3.2. Thermal resistance of LSF elements

The overall thermal resistance of any section of a multi-layered building envelope is the reverse of the overall heat transfer coefficient *U,* considering a unitary area of the building envelope; *i.e.*, under steady state conditions, the rate of heat transfer can be determined from:

$$\dot{Q} = UA(T_i - T_o) = \frac{A(T_i - T_o)}{R}.$$

(1)

The overall *R*-value represents all of the thermal resistances, whether in series or in parallel, between indoor (T_i) and outdoor (T_o) ambient temperatures, therefore including the effects of convection and radiation on the inner and outer surfaces. Leaving apart these effects, the total unit thermal resistance of an envelope section, here named as R_T-value, only takes into account the heat transfer by conduction between inner and outer wall surfaces (surface to surface) and it depends on the configuration and the materials used. It can be interpreted as the temperature difference per unit of heat flux crossing the envelope section. The thermal resistance of each material or layer is proportional to its thickness and inversely proportional to its thermal conductivity.

3.2.1. Methods for assessing the U-value of LSF elements

As stated by Gorgolewski [3], there has been significant discussion over the development of simplified methods to calculate both *R*- and *U*-values of LSF elements. This is difficult to achieve as these methods have to accommodate the effects of non-homogeneous layers and thermal bridges. Depending on the details of the construction, ignoring the effect of steel framing thermal bridges can lead to an overestimation of the thermal resistance by up to 50% [3].

The zone method proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers [41] can be used to determine the *R*-value of an assembly with high thermal conductivity elements in its cross-section. As stated by Santos *et al.* [40], this method is a modification of the parallel path method, in which the wall is considered as a set of several parallel heat flow paths of different conductance from surface to surface and an area-weighting factor. Kosny *et al.* [42] have improved the zone method to account for the influence of thermal bridges in the parallel path method.

EN ISO 6946 [43] presents an analytical method to calculate *U*-values of building elements including masonry and timber framed construction. This method is not applicable for many LSF elements (other than full warm frame construction) in which insulation layers are bridged by metallic elements. To overcome this issue, Gorgolewski [3] suggested a simplified method to calculate *U*-values of LSF assemblies. This method is similar in principle to that used in EN ISO 6946 [43] but adapted to increase accuracy when dealing with hybrid and cold frame LSF construction. As shown by the author, with the improved method the mean error of prediction (compared with finite element modeling) is less than 3% with a maximum

error of 8% for a range of 52 assessed constructions [3]. The improved method involves the calculation of the upper (R_{max}) and lower (R_{min}) limits of thermal resistance: R_{max} is calculated by combining in parallel the total resistances of the heat flow paths through the building element (thermal paths (a) and (b) illustrated in Fig. 8); R_{min} is calculated by combining in parallel the resistances of the heat flow paths of each layer separately and then summing the resistances of all layers of the building element [44]. Each conductance is calculated on an area-weighted basis. For LSF assemblies, the U_T-value is calculated as follows, where the *p*-value depends upon the details of the construction and ΔU_T is a correction to the U_T-value to allow for air gaps and metal fixings:

$$R_T = pR_{max} + (1 - p)R_{min} \qquad (2)$$

$$U_T = R_T^{-1} + \Delta U_T = R_T^{-1} + \Delta U_g + \Delta U_f . \qquad (3)$$

The *p*-value is calculated according to Eqs. (4) and (5), when the flange widths are known not to exceed 50 mm, and when they are above 50 mm but not exceed 80 mm, respectively. In these equations, *s* is the stud spacing (mm) and *d* is the stud depth (mm). If the *p*-value calculated from Eqs. (4) or (5) is negative, it must be reset to zero. For warm frame LSF construction, the *p*-value is set to 0.5 [44].

$$p = 0.8(R_{min} / R_{max}) + 0.32 - 0.2(600/s) - 0.04(d/100) \qquad (4)$$

$$p = 0.8(R_{min} / R_{max}) + 0.24 - 0.2(600/s) - 0.04(d/100) \qquad (5)$$

The U_T-value correction to take into account additional heat losses caused by air gaps, ΔU_g, is calculated according to Eq. (6), where R_I is the thermal resistance of the layer containing gaps, R_T is the total thermal resistance of the element in the absence of air gaps and fixings, and $\Delta U''$ is the air gap correction factor as defined in EN ISO 6946 [43].

$$\Delta U_g = \Delta U''(R_I / R_T)^2 \qquad (6)$$

The U_T-value correction to take into account further heat losses caused by metal fixings penetrating insulating layers, ΔU_f, is calculated according to Eq. (7), where R_i is the thermal resistance of the insulation layer penetrated by the fixings, R_T is the total thermal resistance of the element, λ_f is the thermal conductivity of the fixing, A_f is the cross-sectional area of the fixing, n_f is the number of fixings per square meter of area, and d_i is the thickness of insulation penetrated by fixings [44]. The *α*-value is adjusted

to take into account further heat transfer through the combination of studs and fixings penetrating the insulation layers, and it can be set to 0.8 and 1.6 for warm frame construction and hybrid construction, respectively [44].

$$\Delta U_f = \alpha \lambda_f A_f n_f \left(R_i / R_T \right)^2 / d_i \qquad (7)$$

The corrections ΔU_g and ΔU_f can be ignored provided that they together amount to less than 3% of R_T^{-1}. More details about the improved method described above can be found in ref. [44], including some examples regarding the calculation of U-values of hybrid and cold frame LSF assemblies.
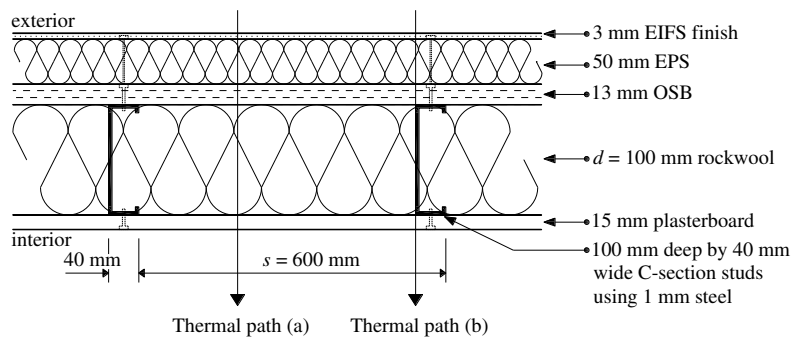

Fig. 8. Illustration of hybrid construction (not to scale). Adapted from Soares *et al.* [2].

The thermal performance of LSF assemblies using fully 3D heat transfer models as proposed by Santos *et al.* [40] and Zalewski [45] are promising, but not common in literature. Instead, simplified one-dimensional heat transfer models are generally used. In these cases, due to the difficulties of an accurate modeling, it has become a frequent practice to neglect some phenomena related to the heat transfer mechanisms and thermal properties of materials, and to approximate the remaining ones when a numerical solution is attempted. Therefore, the validation of numerical models against reliable experimental results is very important to evaluate the accuracy of predictions. Nowadays, several advanced numerical computational methods are available for the evaluation of the thermal performance of LSF assemblies, such as finite element analysis (FEA) and computational fluid dynamics (CFD) methods. To this end, ISO 10211 [46] establishes the specifications to be followed when modeling thermal bridges in buildings, which can be used for the validation of numerical predictions.

As suggested by Santos *et al.* [40], the thermal transmittance of assemblies can be evaluated using either the heat flow meter sensors (ASTM C1155-95 [47], ISO 9869

[48]) or the calibrated hot box method (ASTM C1363-11 [49], GOST 26602.1-99 [50], ISO 8990 [51]). However, since the energy performance of materials and building assemblies are significantly affected by moisture and air flows, the traditional testing using calibrated boxes may need to be improved [40]. Bomberg and Thorsell [52] proposed a new methodology (including both testing and modeling approaches) to evaluate the thermal performance of building enclosures under field conditions. The authors take into account the effect of thermal bridges, moisture and air flows, and they applied the methodology to evaluate the thermal performance of few residential walls [53] and steel-based commercial walls [54]. Infrared (IR) thermography is a complementary technique that helps to locate thermal bridges and heat losses. This technique can also be used to identify the best places for sensor placement (heat flow meter method) to ensure a representative instrumentation distribution along the element (ASTM C1046-95 [55], ASTM C1155-95 [47]). Zalewski *et al.* [45] evaluated the thermal efficiency of complex walls with respect to the quantification of heat losses by thermal bridges. The authors have also used IR thermography as a complementary experimental method to visualize the thermal bridges and to determine the heat losses through the envelope, and they have pointed out some advantages and limitations of IR thermography use.

The experimental characterization of the thermal transmittance value of large-scale non-homogeneous LSF systems may not be accurately carried out by using discrete measurements (of heat flux and surface temperatures) given the higher uncertainty caused by the lateral heat flows during the experiments. Nowadays, the most suitable experimental technique used for this purpose is the Hot Box method according to the procedures defined in ISO 8990 [51], as the measurements are performed in a wide representative continuous surface area. Furthermore, compared to the Calibrated Hot Box, the Guarded Hot Box setup is easier and faster to calibrate and it is less sensible to external factors. However, the Guarded Hot Box is very expensive and the cost of instrumentation complying with international standards (ISO 8990 [51], BS 874 [56] and ASTM C1363-11 [49]) is also large, considering heating/cooling systems, fans, sensors, data-acquisition and control systems.

3.2.2. Strategies for improving the thermal resistance of LSF elements

The simplest way to improve the thermal resistance of LSF elements is by considering the placement of layers of low thermal conductivity materials in its structure. As

remarked above, the placement of thermal insulation layers can also be used to reduce the thermal bridges effect due to steel framing and to improve the energy performance of the building. However, the assessment of the economic and environmental benefits of thermal insulation is a challenging task. Gervásio *et al.* [57] evaluated the influence of several levels of insulation on the energy balance of LSF buildings. The authors also discussed the balance between embodied and operational energies for different scenarios. Dylewski and Adamczyk [58] investigated the economic and environmental benefits of thermal insulation of external walls and Ozel [59] evaluated the optimum insulation thickness, energy savings and payback period of some envelope solutions using life cycle cost analysis over a lifetime of 20 years of the building. Studies as the one developed by the former authors should be extended to LSF construction to better understand the trade-off between embodied energy and operational energy, and economic and environmental benefits, regarding this type of construction.

As suggested by Martins *et al*. [7], the use of new and more efficient insulation materials may also allow a great thermal performance of walls, dealing with lower thicknesses of the insulation layers. Aerogel blankets may be seen as one of the most promising thermal insulation materials as they have a thermal conductivity 2–2.5 times lower than that of conventional MW [60]. A comprehensive review on aerogel and its utilization in buildings was provided by Cuce *et al.* [61]. Another promising technology is the use of vacuum insulation panels (VIPs), which have a thermal resistance 5–8 times higher than other conventional insulation materials [62]. Low thickness VIPs can lead to good thermal performances, but they still have some drawbacks: they are expensive, fragile, difficult to adapt at the building site as they cannot be cut or drilled, and they may exhibit decreasing thermal properties through time [63]. Moreover, Isaia *et al.* [64] showed that the thermal bridging effect due to VIPs assemblies may have a significant influence on the overall building energy performance.

As suggested by Baetens *et al.* [63] the thermal performance of VIPs may result in a great potential for combining the reduction of energy consumption in buildings with slim constructions, which is very interesting for LSF construction. Indeed, with VIPs, slim yet highly insulating facade can be achieved, as pointed out by Fricke *et al.* [65]. The remarkable number of recent review articles [62,63,66-68] shows the interest of the buildings sector in VIPs, and highlights the amount of research that is being developed worldwide in this field. Petter Jelle [69] reviewed the main properties, requirements and possibilities of traditional and future thermal building insulation

materials and solutions, including aerogel and VIPs. The author suggested that future research should be conducted by improving the existing traditional thermal insulation and exploring the possibilities of discovering and developing novel high performance thermal insulation materials and solutions with properties surpassing all of today's existing materials and solutions [69].

In their work, Martins *et al.* [7] numerically evaluated the impact of some strategies for improving the thermal resistance of LSF elements. The study was carried out using several techniques to reduce the *U*-value of a reference LSF wall. The authors concluded that the most favourable strategy leads to a reduction of 68.2% of the reference *U*-value. The best strategy combines rubber strips, slotted steel profiles, bolted connections, and VIPs on both sides.

3.3. Heat capacity and thermal inertia of LSF construction

Thermal inertia is the ability of a bulk material to conduct and store/release heat during a charging/discharging cycle, and it also measures the resistance of a material to time changes in its temperature. In this sense, it can be interpreted as the inverse of the thermal diffusivity, which is the ratio of the thermal conductivity to the volumetric heat capacity of the material. The heat capacity measures the ability of a material to store thermal energy, and thermal conductivity is the property of a material to conduct heat. In building design, heat capacity is usually called thermal mass. Indeed, thermal mass of a construction is a property of the mass of the building that enables it to store heat, providing some inertia against temperature fluctuations. Materials with high specific heat capacity and high density (and moderate thermal conductivity) − low thermal diffusivity − are better for thermal mass in buildings. Moreover, to make effective use of thermal mass, the materials need to be placed on the inside of the insulation layers. The terms heavyweight and lightweight construction are typically used to describe buildings with different thermal mass strategies and to express their thermal response to heating and cooling. When combined with good passive solar design, thermal mass can be very effective in reducing the energy demand for heating and cooling, while improving indoor thermal comfort.

As suggested by Hoes *et al.* [70], it is conventionally accepted that buildings with higher thermal mass require lower energy demand for air-conditioning and provide higher thermal comfort conditions. However, during some operational circumstances,

the higher thermal inertia may have a negative impact on energy demand and thermal comfort, and a fast responding building (with lower thermal mass) may be preferred [70]. As proposed by Santos *et al.* [8], several strategies can be used to improve thermal inertia of LSF buildings (if needed), such as the use of ground thermal mass techniques. Hoes *et al.* [70] also pointed out that, in conventional buildings, thermal mass is a permanent characteristic of the building design, but none of the permanent thermal mass concepts (heavyweight or lightweight buildings) is optimal during all operational conditions. In this context, the authors proposed a hybrid thermal mass concept that combines the benefits of buildings with low and high thermal mass by applying an adaptable-in-time thermal storage capacity to a lightweight building [70]. The authors take advantage of the latent heat involved in the solid-liquid phase change of PCMs to increase the thermal storage capacity of the construction.

3.3.1. Phase change materials

PCM-based systems are commonly grouped into passive and active systems. Here, "passive" means that the solid-liquid phase-change processes occur without resorting to mechanical equipments. As suggested by Soares *et. al* [9], passive PCM-based systems for buildings can: reduce heating and cooling energy demand; reduce air-conditioning power needed and heating/cooling peak-loads; improve the thermal resistance and thermal storage capacity of building's envelope; improve indoor thermal comfort; and make use of renewable energy sources. PCMs are mainly classified as organic, inorganic and eutectic, and the main advantages and disadvantages of each PCM type can be found in refs. [71-77]. Regarding building applications, PCMs should have a melting/solidification temperature in the practical range of application, high latent heat of fusion and improved thermal conductivity [9]. PCMs should also have desirable thermophysical, kinetic, chemical, economic and environmental properties, as pointed out by several authors [9,78-86]. The optimum incorporation of PCMs within construction systems and the evaluation of the energy performance of the building with these elements is very complex and challenging. This entails including the design and location of the building, the typology of construction, its use and indoor loads profiles (*e.g.*, lighting, appliances and users' schedules), and the major TES design parameters, namely the phase-change temperature of the PCM and its quantity. Therefore, the dynamic simulation of both PCM-based TES systems and the energy in buildings with PCMs may be seen as active areas of research.

Regarding liquid leakage, different techniques for incorporating PCMs in building elements have been studied, such as direct incorporation, immersion and encapsulation [87]. Two of the most well-known encapsulation techniques are the micro- and macro-encapsulation. In the former, the PCM is encapsulated within a micropolymeric capsule; in the latter, the macrocapsule may be the only way of confinement to avoid liquid leakage. In recent years, shape-stabilized PCMs (SSPCMs) have also been attracting the interest of many researchers, as reviewed by Fang. *et al.* [88], due to their higher apparent specific heat, suitable thermal conductivity, the ability to keep the shape of the PCM-board stabilized during solid-liquid phase-change processes, and a good performance of long-term multiple thermal cycles [82].

Several passive PCM-based TES solutions for buildings have been studied during the last decades, for both opaque and window facades, such as PCM enhanced drywalls [2,89-104], SSPCM elements [105-120], PCM-based ventilated facades [121-126], PCM-shutters and PCM-window blinds systems [127-131], interior sun protections with PCMs [132,133], translucent PCM walls [134-138], PCM-bricks [139-144], PCM enhanced mortars [145-151], PCM enhanced solar chimney [152,153], and other PCM-based solutions [154-165]. Indeed, many review articles devoted to the description of construction solutions with PCMs and their thermal performance analysis can be found in literature [9,75,78-81,83,84,166-179]. An updated review on PCMs integrated into transparent building elements was recently carried out by Fokaides *et al.* [180]. Cuce and Riffat [181] provided a state-of-the-art review on innovative glazing technologies including those incorporating PCMs. Several PCM-glazing systems were also reviewed and described by Hee *et al.* [182]. Finally, several solar facades were reviewed by Lai and Hokoi [183], including those with PCMs. In LSF construction, mainly when big windows are considered, the management of solar gains through the management of PCM-based TES systems associated to the glazed facades can be a good strategy to improve the energy efficiency of LSF buildings in a passive way, *i.e.* harnessing solar thermal energy for heating during winter and reducing overheating during summer. An updated review on the main PCM-based technologies for the translucent and transparent building envelope was provided by Silva *et al.* [184].

3.3.2. *Main thermophysical properties of PCMs*

Fig. 9 shows the main potential fields of application of PCMs in TES applications. It shows that the latent heat can be stored without a significant temperature change of the

material (read on the temperature axis); that is why PCMs can be used for temperature control of TES applications. On the other hand, the figure also shows that PCMs are able to store large amounts of heat (due to latent heat) at a small temperature change as the phase-change processes occurs within a limited phase-change temperature range (read on the stored heat axis). In comparison with traditional "sensible" materials used in construction (such as rock, wood, steel, concrete, etc.), PCMs provide a large thermal storage capacity over a limited temperature range and they could act like an almost-isothermal reservoir of heat. Therefore, PCMs are very interesting for LSF envelope solutions, as a larger quantity of energy can be stored in a small volume of material maintaining the lighter feature of the construction.
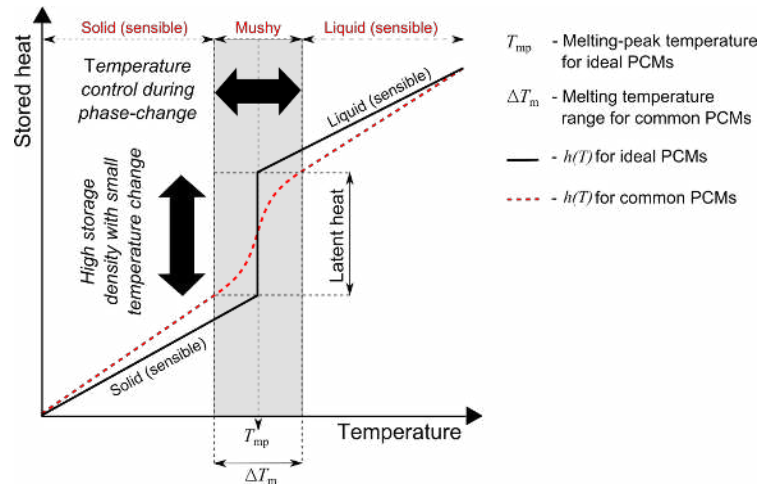

Fig. 9. Potential fields of application of PCMs: (*i*) temperature control and (*ii*) storage and supply of heat with high storage density and small temperature change [185].

The storage capacity of an ideal PCM can be characterized via four main parameters, namely the heat capacity of the solid and liquid phases, the latent heat of fusion and the melting-peak temperature. However, for common PCMs, more than specifying these variables, the enthalpy-temperature curve $h(T)$ should be provided, as it describes the material with much more precision. Therefore, the enthalpy-temperature relationship is one of the most important properties of PCMs as it includes many information about the phase-change processes. In ideal situations, the $h(T)$ curve should be equal during the reversible charging (melting) and discharging (solidification) cycles. However, these curves could be influenced by other phenomena such as subcooling, hysteresis and cycling stability. As remarked by Mehling and Cabeza [186], if the heat released upon solidification is larger than the sensible heat lost due to subcooling, the temperature rises again to the solidifying temperature of the PCM, T_{sp}, which ideally

24

should be equal to T_{mp}. However, if this does not happen, or if the rate of heat lost to the ambient is larger than the rate of heat released during crystallization, the temperature will not rise to the solidifying temperature again, and a real hysteresis will be caused by subcooling. Therefore, subcooling can cause negative effects when performing dynamic experiments, and it can be a problem in technical applications of PCMs. Subcooling can depend on the size of the PCM sample and also on the type and shape of the container used in a macro-scale approach, as recently investigated in refs. [187,188]. Regarding hysteresis, it can be caused by the measurement conditions, mainly in calorimetry experiments. In this case, it is called apparent hysteresis [186]. Fig. 10 shows different causes that can lead to hysteresis. Due to hysteresis, there are typically different data from charging and discharging experiments and the results must be provided for both heating and cooling experiments.
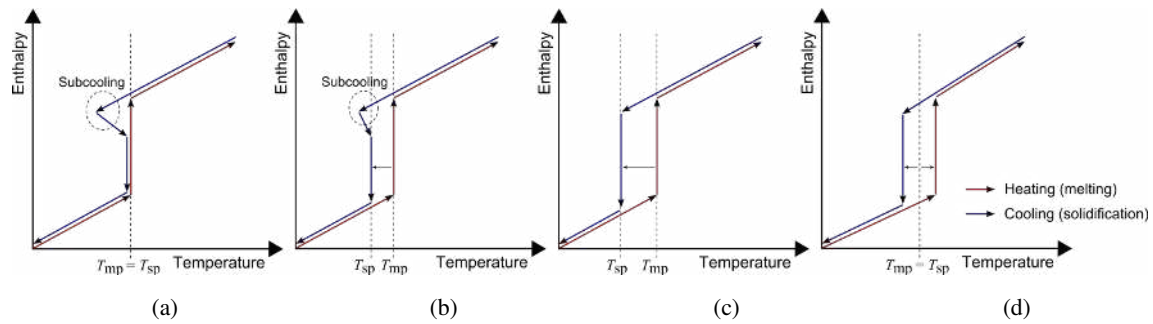

Fig. 10. Real hysteresis as a material property caused by subcooling when: (a) the temperature rises again to the solidifying temperature of the PCM; (b) the temperature does not rise again to the solidifying temperature of the PCM. (c) Real hysteresis caused by slow heat release or a real difference between the phase-change temperatures. (d) Apparent hysteresis caused by non-isothermal conditions in the measurements [185].

Another aspect to take into account when dealing with the heat transfer with solid-liquid phase-change, is the effect of natural convection in the molten free-form PCM as it is one of the major factors that affect phase transition processes [189,190]. Regarding cycling stability of PCM-composites and PCM-based elements, one of the main problems is the phase separation. It should be remarked that a PCM that shows phase separation will show a reduction of the melting enthalpy after repeated cycling [186]. For PCM-based elements, cycling stability can also refer to the capacity to avoid liquid leakage after repeated phase change cycles. A recent review on the thermal stability of PCMs used in TES systems was carried out by Rathod and Banerjee [191].

Finally, PCMs and PCM-based composites should have a good thermal conductivity to improve the storage and release of latent heat in a given volume of the

material in a short period. As PCMs have typically low thermal conductivity, some heat transfer enhancement techniques can be used to improve this feature as reviewed by several authors in refs. [9,79,81,83,192-194]. Regarding LSF multi-layered envelope solutions, thermal bridges caused by steel elements can be used to improve heat transfer rate to the PCM-based layer.

3.3.3. Commercial PCM-based solutions for LSF construction

PCMs can be used to increase thermal inertia of LSF buildings, avoiding the use of massive materials with the associated drawbacks (*e.g.* reduced net floor area given the thicker walls, and weight load increment in the structure). Furthermore, in the refurbishment of buildings, PCMs can be added with a minimum change in the existing building design (*e.g.* adding PCMs bags above the suspended ceiling tiles or adding a PCM board to the walls). Nowadays, there are available on the market several building elements and materials containing PCMs (macro- or micro-encapsulated) to be applied in walls, slabs or windows [195]. Some examples of commercial PCM boards for dry construction containing micro-encapsulated PCMs can be pointed out, such as: *Rigips Alba®Balance* [196], *ebb PCM Clay Boards* [197], *Knauf ComfortBoard* [198], *ThermaCool®* [199] and *ThermalCORE*[TM] [200]. As an example, Fig. 11 illustrates the PCM wall panels and ceiling tiles commercialized by *ThermaCool®* [199].
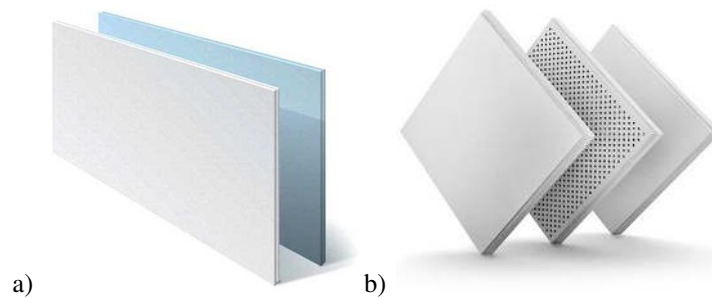

a)   b)

Fig. 11. Examples of PCM boards for dry construction: a) wall panels; b) ceiling tiles. Figure adapted from ref. [199].

It is also possible to use macro-encapsulated PCMs in dry construction. Some examples are pointed out by Santos *et al.* [8]: aluminium laminated panel containing a PCM to be used under standard inner gypsum plasterboard; suspended ceiling tiles with a honeycomb core filled with PCM; and suspended ceiling tiles with PCM bags placed above. Perhaps given the higher cost and higher leakage risk, these macro-encapsulated PCM-based elements are not as popular as the micro-encapsulated ones.

26

Besides the use of PCMs in the opaque building envelope, there are also available on the market some PCM-based elements to be used near glazed openings as interior shading devices. The PCM-enhanced systems can be used to avoid overheating during sunny days and to store solar thermal energy. Fig. 12 illustrates vertical and horizontal window louvers commercialized in Sweden [201]. The PCM-enhanced aluminium lamellas have the advantage of being movable, allowing to control daylighting and solar heat gains. During summer, the aluminium face should be oriented towards outside in order to reflect the solar radiation and reduce solar heat gains. The black solar film allows increasing the solar heat gains during winter.
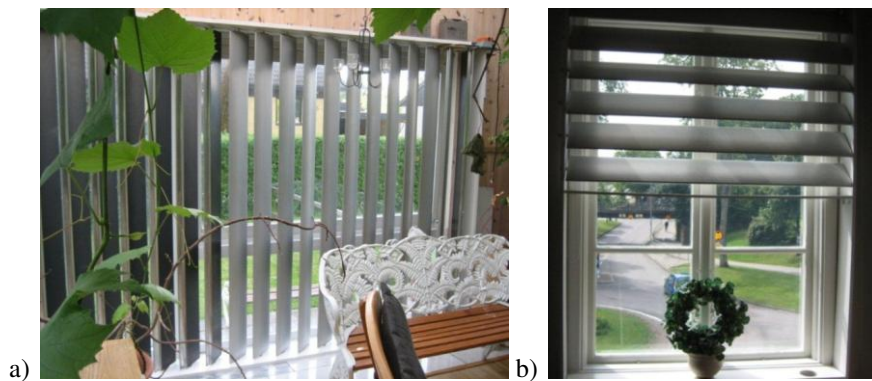

Fig. 12. PCM vertical and horizontal window louvers. Figure adapted from ref. [201].

PCMs could also be used inside the glazing units, as illustrated in Fig. 13 [202], allowing daylighting. The PCM-enhanced glazed units (GlassX Crystal [202]) have several glass layers (1 exterior tempered safety glass, 2 tempered safety glass with low-emissivity coating and 1 interior of clear float glass), and several gaps between glass panes. The outer gap has a prismatic plate inside and it is filled with inert gas. The mid gap is also filled with inert gas, while the inner gap between glass panes contains the PCM hermetically sealed in clear polycarbonate. The prismatic layer allows controlling the solar radiation depending on the season: summer or winter. During summer, the prismatic layer reflects most of the solar radiation as the solar altitude is higher. However, it allows winter solar radiation to pass given the lower solar altitude during this season. In practice, this prismatic layer enables a variable solar heat gain coefficient (SHGC) of this PCM-enhanced glazing unit. As expected, the light transmission depends on the phase state of the PCM, changing from 0.05 for the crystalizing (or solid PCM) to 0.48 for the liquid PCM.
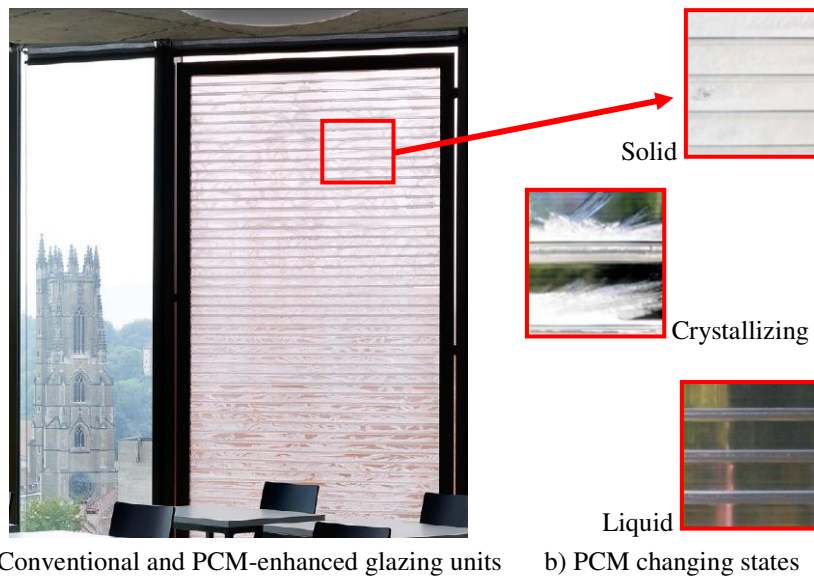
27

a) Conventional and PCM-enhanced glazing units   b) PCM changing states

Fig. 13. PCM glazing system (GlassX Crystal). Figure adapted from ref. [202].

3.4. Energy consumption and thermal comfort of LSF buildings

As suggested by Saffari *et al.* [203], the improvement of the energy performance of buildings can be achieved either by passive solutions related to the building envelope, or by active solutions such as the use of smarter HVAC equipment. The authors pointed out that the investment in the building envelope may be preferable, as a high-quality passive design could bring long-term energy efficiency, lower energy demand for heating and cooling, and higher thermal comfort conditions. They evaluated the economic impact of integrating PCMs in a lightweight building model using the Fanger comfort model, and they proposed a methodology to control HVAC thermostat operation considering both the effects of indoor and outdoor conditions and the characteristics of the PCM. Very few studies are available in literature addressing the application of Fanger comfort control to define thermostat set-point temperatures in LSF buildings. Therefore, more studies should be carried out to evaluate the thermal performance of LSF buildings based on thermal comfort criteria.

The dynamic simulation of energy in buildings (DSEB) can be seen as a cost-effective and time-efficient solution to evaluate thermal comfort conditions and to propose efficient control thermostat operation conditions of the HVAC systems considering indoor and outdoor conditions (*e.g.*, by considering both users behaviours and climatic conditions). Moreover, reliable DSEB tools, such as EnergyPlus, TRNSYS, ESP-r, etc. can be used to estimate the energy demand for heating and cooling, to evaluate the effectiveness of energy saving measures, and to better

understand the dynamics and main drivers of energy supply and demand in LSF buildings. For example, Soares *et al.* [2] numerically investigated the impact of PCM-drywalls in the annual and monthly heating and cooling energy savings of an air-conditioned LSF model in different European climates. The authors carried out a multi-dimensional optimization study, combining EnergyPlus and GenOpt tools, to evaluate the impact of different thermophysical properties of the PCM, different thickness and locations of the PCM-drywalls in the model, and different design parameters such as thermal bridging effect, solar absortance of the inner surfaces, air-infiltration rates, solar gains, internal gains, and set-points, on the energy performance of the model. The authors concluded that the energy performance of the LSF building was improved in all climates when PCM-drywalls were installed, and that an optimum solution can be found for each climate. As remarked by de Gracia *et al.* [122] this effort to develop specific solutions for different locations based on their climate can be seen as a good approach to foster the implementation of a specific technology. Evola and Marletta [204] have also evaluated the effectiveness of PCM-drywalls for the energy refurbishment of lightweight buildings. The authors pointed out that lightweight buildings usually suffer from pronounced overheating in summer, and that the incorporation of PCM-drywalls in the building envelope design, or during refurbishment, can be an effective way to enhance thermal inertia and to improve thermal comfort conditions.

Al-Saadi and Zhai [205] evaluated the performance of lightweight PCM-enhanced walls using a new TRNSYS module, and they found that the best PCM position is the one when the PCM is placed in contact with the indoor controlled environment. Gomes *et al.* [206] used EnergyPlus to investigate the effect of metallic structures in the hourly simulation, and to account for the effects of non-homogenous layers and thermal bridges in the calculation of the *U*-value of LSF elements. The authors evaluated the impact of thermal bridging across enclosure elements on the thermal performance of two air-conditioned commercial LSF buildings in Brazil, and they concluded that the peak thermal load increased approximately 10% due to thermal bridging. They have also pointed out that a 5% increase in the annual energy demand can be caused by thermal bridging effect in the vertical elements.

The influence of climate change on the energy efficiency and thermal comfort of buildings has been addressed by several authors [207-209]. Santos *et al.* [210] evaluated the influence of climate change scenarios predicted by the Intergovernmental Panel for Climate Change for Southern Europe and Mediterranean region on the energy efficiency

of LSF residential buildings in the warm temperature summer dry climate. The authors proposed a numerical model, which was calibrated against normative requirements for dynamic simulation of thermal behaviour and sophisticated CFD models. Santos *et al.* [32] also carried out a parametric analysis of the annual thermal performance of LSF residential buildings in Mediterranean climate zones. The authors compared the thermal behaviour of a LSF dwelling predicted through EnergyPlus dynamic simulations with monitored data obtained through measurements in a real LSF house built in Portugal. The authors carried out a parametric study to evaluate the impact of some construction features and operational strategies during the year, such as the thermal insulation level, the ventilation rate, the use of shading devices and the solar heat gains. At the end, the authors provided design and operational strategies to improve the thermal performance of LSF residential buildings in Csb climate. The previous works emphasize the importance of minimizing the energy demand for heating and cooling during the operational phase of LSF buildings to improve their energy efficiency. They also highlight the influence of climate on the thermal performance of buildings. Therefore, distinct design strategies and operational conditions should be considered for different climates.

Kendrick *et al.* [211] suggested that lightweight construction may lead to higher internal temperatures during the summer, particularly in the warmer future scenarios, due to the lack of thermal mass. The problem of summer overheating in a low-energy steel frame house was also evaluated by Rodrigues *et al.* [212]. The house is highly insulated and extremely airtight. It has a large south facing sunspace and most of the house fabric is constructed using materials with low thermal mass. The authors concluded that some mitigation strategies are needed to overcome present severe overheating, as the temperature in certain spaces could be above comfort zone for more than 30% of the year. The authors also pointed out that the house is likely to be more uncomfortable in future warmer climate scenarios.

The current environmental, social, energy and economic sustainability agendas calls for more adaptable buildings, and LSF construction can play an important role in this field. In a recent paper, Gosling *et al.* [213] have explored the concept of building adaptability providing a conceptual model to rationalise adaptability in the construction sector. LSF buildings can be "designed for flexibility" which, according to Gosling *et al.* [213], enables more adaptable buildings. For example, Hoes *et al.* [70] explored the potential of lightweight low-energy houses with hybrid adaptable thermal storage

(HATS). The idea is to combine the benefits of low and high thermal mass by applying HATS systems and materials to reduce energy demand for air-conditioning, to increase thermal comfort, and to increase the robustness to changing user behaviours, seasonal variations and future climate changes. Indeed, the numerical results have shown that the heating energy demand for the case study in The Netherlands can be reduced by 35% compared to conventional thermal mass concepts. The HATS concept was further investigated by Hoes and Hensen [214]. The authors evaluated the potential of HATS systems to reduce the energy demand of new lightweight residential buildings in The Netherlands, and to maintain or improve thermal comfort conditions. The results have shown that the HATS approach reduces the energy demand compared to lightweight and heavyweight reference cases. Moreover, the authors have concluded that the HATS approach improves thermal comfort compared to the lightweight reference case, and maintains the thermal comfort conditions of the heavyweight reference case. The results of these studies are very influenced by the climatic conditions. Therefore, further research has to be carried out to evaluate the impact of HATS systems in other climates.

4. LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL PERFORMANCE

4.1. Life cycle environmental performance

Dubina *et al*. [215] presented the theoretical background and design rules for cold-formed steel sections and sheeting, members and connections for building applications. The authors also pointed out the importance of the sustainability of cold-formed steel construction. Nowadays, the environmental performance of lightweight steel frames can be assessed by a life cycle analysis, which takes into account all stages, from material production to end-of-life and recycling of materials. The general framework for LCA is provided by ISO 14040 [216] and ISO 14044 [217], which have a general application. Moreover, standards for the assessment of the sustainability of construction works were published by CEN/TC 350: EN 15643-1 [218], EN 15804 [219] and EN 15978 [220]. These standards are focussed on the assessment of the built environment and a life cycle approach is adopted according to the general framework provided by the ISO standards.

LCA can be used to assist the decision making process of the selection of the building structure or construction system, by identifying the main advantages and disadvantages of competing systems over their respective lives. In fact, the early stages of building design, when main decisions are taken, are the stages with the higher

influence on the life cycle performance of buildings as suggested by Gervásio *et al.* [221]. However, in these stages, data is often scarce so that LCA approaches are limited. To overcome this problem, a simplified LCA approach was developed by Gervásio *et al.* [221] to quantify the potential environmental impacts over the life cycle of buildings. With the same purpose, an additional methodology was developed by Santos *et al.* [222] for the quantification of the operational energy of buildings. Both approaches enable the LCA of lightweight construction systems and the comparison of such systems with alternative solutions. Another advantage of life cycle approaches is that the shift of burdens from one stage to the other, over the service life of buildings, is avoided.

4.2. Balance between embodied energy and operational energy

The two most influent factors in the life cycle environmental performance of buildings are materials efficiency and energy efficiency. Materials efficiency is concerned to the use of environmental-friendly materials and to the minimization of construction and demolition waste materials. The embodied energy can be an indicator to describe materials efficiency. Energy efficiency is considered as the optimization of the energy used during the operational stage of the building (*e.g.* heating, cooling, lighting, etc.).

In literature, most of the LCA studies devoted to lightweight construction systems are focussed on the quantification of energy demand and green house emissions during the operational phase. One of the basic solutions to reduce the energy demand for air-conditioning during the operational phase of LSF buildings is by considering more levels of insulation. This may lead to a trade-off between embodied energy and operational energy. In LSF buildings, the relative importance of insulation materials to the global environmental performance is very high, as the use of a lightweight frames enables to reduce the environmental burdens due to the structural component of the building. Hence, the balance between the embodied energy of using more insulation levels and the correspondent operational energy is even more important.

In the last years, a big effort has been carried out to reduce the operational energy demand of buildings (the trend is to reach zero energy buildings by 2020) in a way that, in the near future, the contribution of the embodied energy in the assessment of the environmental performance of buildings will become much more relevant, as pointed out by several authors [223-225]. For instance, Thormark [226] showed that about 40-60% of the life cycle energy of a building is used in the initial stages of

material production and construction. In a parametric study carried out by Gervásio *et al.* [57] on a LSF residential building located in Portugal, different levels of insulation were considered to assess the trade-off between energy efficiency and life cycle embodied energy. In this study, it was showed that 16 years were needed for the operational energy to overcome the embodied energy. Moreover, by increasing the insulation level, a longer delay for the operational energy to overcome the embodied energy (up to 23 years) was needed. The authors concluded that, for typical climatic conditions of southern Europe, it is possible to significantly improve the thermal efficiency of residential buildings by increasing the insulation level of the weaker components of the building envelope without significantly increasing the embodied energy of the building. Rodrigues and Freire [227] also carried out a LCA study focusing on the retrofitting of a roof of a residential building and taking into account the balance between the embodied energy and the operational energy of the building over its service life. The authors concluded that after a certain level of insulation, the increase of the insulation layer would not compensate the increase of the embodied energy.

4.3. Environmental performance of unconventional insulation materials

New insulation materials that take advantage of recycled materials are becoming more frequent; although, they are not at the same commercial level of traditional insulation materials yet. Apart from the thermal and acoustic characteristics of each material, the life cycle environmental performance is also of particular interest. To carry out such analysis, environmental data should be collected for all stages considered in the scope of the analysis. In relation to traditional materials, generic data can be found in available commercial databases, such as ecoinvent (Frischknecht *et al.* [228]) or the European database (Recchioni *et al.* [229]). This type of data is usually based on average data referred to a region (country or continent) or to the world (global data). Data is also available from Environmental Product Declarations (EPDs), which are becoming more frequent. EPDs provide environmental data for the production of specific materials or processes. In this case, data is provided directly by the manufacture of the product according to the framework provided by ISO 14025 [230] and EN 15804 [219].

On the other hand, for new materials, the environmental information related to their production and life cycle performance may be scarce, as they are many times in the stage of prototype or in early stages of commercialization. However, some studies are

already available in literature. The environmental benefits of insulation panels made of polyester fiber obtained from the recycling of post-consumer polyethylene terephthalate (PET) bottles were demonstrated by Intini and Kühtz [231]. Apart from showing lower life cycle impacts due to the use of non-virgin materials, the authors pointed out that the recycling of PET bottles contributes to reduce both energy consumption and the volume of municipal wastes. Asdrubali *et al.* [232] reviewed the thermal characteristics and life cycle environmental performance of unconventional insulation materials made of natural resources and recycled materials. The authors showed that, in comparison to more traditional products, unconventional materials have a good environmental performance in terms of primary energy demand and global warming potential.

Kylili and Fokaides [233] provided a comprehensive review on the LCA of PCMs used as building materials. The authors considered the focus of each work in relation to the different LCA steps, namely, the goal and scope, the inventory analysis and the impact assessment, as they found some inconsistency of previous LCA studies due to different goal, scope and boundary conditions. The authors concluded that PCM-based solutions can be more environmental-friendly than alternative reference solutions, when taking into account the manufacture, operational, and disposal phases.

5. CONCLUSION

This papers presents the key advantages and drawbacks of LSF construction regarding the energy efficiency and thermal performance of buildings. Moreover, some research gaps are identified, providing guidelines for future research. The main driving research topics to improve the thermal performance of LSF construction are related to:

- the development of single and combined strategies to reduce thermal bridges and to improve the thermal resistance of LSF envelope elements;
- increase the thermal inertia and the thermal storage capacity of LSF constructions, for instance, by using PCMs;
- the development of hybrid adaptable thermal storage systems;
- the development of reliable dynamic and holistic simulation methodologies to assess the energy demand for heating and cooling during the operational phase of LSF buildings, taking into account the main features of LSF construction (such as thermal bridging);

- the evaluation of the life cycle assessment and the environmental performance of LSF construction to discuss the main contribution of this kind of construction towards more sustainable buildings.

- the development of new systems to take advantage of solar thermal energy to reduce the energy demand for air-conditioning during the operational phase of LSF buildings, and the development of systematic strategies for the efficient management of solar heat gains.

6. REFERENCES

[1]   International Energy Agency, Energy Technology Perspectives 2012. Pathways to a Clean Energy System. 2012.

[2]   Soares N, Gaspar AR, Santos P, Costa JJ. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy and Buildings 2014;70:411–21.

[3]   Gorgolewski M. Developing a simplified method of calculating U-values in light steel framing. Building and Environment 2007;42(1):230–6.

[4]   Veljkovic M, Johansson B. Light steel framing for residential buildings. Thin-Walled Structures 2006;44:1272–9.

[5]   CSSBI. Lightweight steel framing - architectural design guide. Canadian Sheet Steel Building Institute, 2002.

[6]   Santos P, Martins C, Simões da silva L. Thermal performance of lightweight steel-framed construction systems. Metallurgical Research & Technology 2014;111:329–38.

[7]   Martins C, Santos P, Simões da silva L. Lightweight steel-framed thermal bridges mitigation strategies: a parametric study. Journal of Building Physics 2016;39(4):342–72.

[8]   Santos P, Simões da Silva L, Ungureanu V. Energy Efficiency of Light-weight Steel-framed Buildings. 1st ed. European Convention for Constructional Steelwork (ECCS),

Technical Committee 14 - Sustainability & Eco-Efficiency of Steel Construction, ISBN 978-92-9147-105-8, N. 129; 2012.

[9]   Soares N, Costa JJ, Gaspar AR, Santos P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energy and Buildings 2013;59:82–103.

[10]   Burstrand H. Light-gauge steel framing leads the way to an increased productivity for residential housing. Journal of Constructional Steel Research 1998;46(1–3):183–6.

[11]   European Lightweight Steel-framed Construction. Luxemburg: LSK. Arcelor.; 2005.

[12]   Höglund T, Burstrand H. Slotted steel studs to reduce thermal bridges in insulated walls. Thin-Walled Structures 1998;32:81–109.

[13]   EN10162. Cold rolled steel sections - Technical delivery conditions - Dimensional and cross-sectional tolerances. Brussels: European Committee for Standardization: CEN; 2003.

[14]   EN1993-1-3. Eurocode 3: Design of steel structures. Part 1-3: General Rules. Supplementary rules for cold-formed thin gauge members and sheeting. Brussels: European Committee for Standardization: CEN; 2006.

[15]   EN10326. Continuously hot-dip coated strip and sheet of structural steels - Technical delivery conditions. Brussels: European Committee for Standardization: CEN; 2004.

[16]   Paul S, Radavelli GF, da Silva AR. Experimental evaluation of sound insulation of light steel frame façades that use horizontal inter-stud stiffeners and different lining materials. Building and Environment 2015;94:829–39.

[17]   Davies JM. Light gauge steel cassette wall construction — theory and practice. Journal of Constructional Steel Research 2006;62:1077–86.

[18]   Jatheeshan V, Mahendran M. Numerical study of LSF floors made of hollow flange channels in fire. Journal of Construction Steel Research 2015;115:236–51.

[19]   Trevathan JW, Pearse JR. The effect of workmanship on the transmission of airborne sound through light framed walls. Applied Acoustics 2008;69:127–31.

[20]   EN300. Orientated Strand Boards (OSB) - Definitions, classification and specifications. Brussels: European Committee for Standardization: CEN; 2006.

[21]   EN12369-1. Wood based panels - Characteristic values for structural design - Part 1: OSB, particleboards and fibreboards. Brussels: European Committee for Standardization: CEN; 2001.

[22]   EN520:2004+A1. Gypsum plasterboards - Definitions, requirements and test methods. Brussels: European Committee for Standardization: CEN; 2009.

[23] EN14566:2008+A1. Mechanical fasteners for gypsum plasterboard systems - Definitions, requirements and test methods. Brussels: European Committee for Standardization: CEN; 2009.

[24] EN13963. Jointing materials for gypsum boards - Definitions, requirements and test methods. Brussels, Belgium: Official Journal of the European Union: CEN; 2014.

[25] EN14195. Metal framing components for gypsum board systems - Definitions, requirements and test methods. Brussels: European Committee for Standardization: CEN; 2014.

[26] Kesawan S, Mahendran M. Fire tests of load-bearing LSF walls made of hollow flange channel sections. Journal of Construction Steel Research 2015;115:191–205.

[27] EN13162:2012+A1. Thermal insulation products for buildings - Factory made mineral wool (MW) products - Specification. Brussels: European Committee for Standardization: CEN; 2015.

[28] EN13163:2012+A1. Thermal insulation products for buildings - Factory made expanded polystyrene (EPS) products - Specification. Brussels: European Committee for Standardization: CEN; 2015.

[29] EN13499. Thermal insulation products for buildings - External thermal insulation composite systems (ETICS) based on expanded polystyrene - Specification. Brussels: European Committee for Standardization: CEN; 2003.

[30] EN12524. Building materials and products - Hygrothermal properties - Tabulated design values. Brussels: European Committee for Standardization: CEN; 2000.

[31] ENISO10456. Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values. Brussels: European Committee for Standardization: CEN; 2007.

[32] Santos P, Simões da Silva L, Gervásio H, Lopes AG. Parametric analysis of the thermal performance of light steel residential buildings in Csb climatic regions. Journal of Building Physics 2010;35(1):7–53.

[33] Kalamees T. Air tightness and air leakages of new lightweight single-family detached houses in Estonia. Building and Environment 2007;42:2369–2377.

[34] EN13829. Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method. Brussels: European Committee for Standardization: CEN; 2000.

[35] Varadi J, Toth E. Thermal improvement of lightweight façades containing slotted steel girders. in: Twelfth International Conference on Civil, Structural and Environmental Engineering Computing, 2009, paper 107.

[36] Lawson RM, Ogden RG. "Hybrid" light steel panel and modular systems. Thin-Walled Structures 2008;46:720–30.

[37] Erhorn-Kluttig H, Erhorn H. P148 ASIEPI Project - Impact of thermal bridges on the energy performance of buildings. ASIEPI, 2009.

[38] Kosny J, Christian JE. Thermal evaluation of several configurations of insulation and structural materials for some metal stud walls. Energy and Buildings 1995;22:157–63.

[39] Blomberg TR, Claesson J. Heat transmission through walls with slotted steel studs. in: Thermal Performance of the Exterior Envelopes of Buildings VII, CONFERENCE PROCEEDING by ASHRAE, 1998:621–8.

[40] Santos P, Martins C, Simões da silva L, Bragança L. Thermal performance of lightweight steel framed wall: the importance of flanking thermal losses. Journal of Building Physics 2014;38(1):81–98.

[41] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (1993) Handbook of Fundamentals. Atlanta, GA: ASHRAE. 1993.

[42] Kosny J, Christian JE, Barbour E, Goodrow J. Thermal performance of steel-framed walls. CRADA Final Report ORNL93-0235, 21 November. Oak Ridge, TN: Oak Ridge National Laboratory. 1994.

[43] EN ISO 6946:2007. Building components and building elements - thermal resistance and thermal transmittance - calculation method. 2007.

[44] Doran S, Gorgolewski M. U-values for light steel-frame construction. in: BRE Digest 465, Building Research Establishment, UK, 2002.

[45] Zalewski L, Lassue S, Rousse D, Boukhalfa K. Experimental and numerical characterization of thermal bridges in prefabricated building walls. Energy Conversion and Management 2010;51:2869–77.

[46] ISO 10211:2007. Thermal bridges in building construction – heat flows and surface temperatures – detailed calculations. 2007.

[47] ASTM C1155-95. Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data. West Conshohocken, PA: American Society for Testing and Materials. 2007.

[48] ISO 9869:1994. Thermal insulation – building elements – in-situ measurement of thermal resistance and thermal transmittance. 1994.

[49] ASTM C1363 -11. Standard test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus.

[50] GOST 26602.1-99. Windows and doors. Methods of determination of resistance of thermal transmission. Interstate Standard of Russian Federation. 1999.

[51] ISO 8990:1994. Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box. 1994.

[52] Bomberg M, Thorsell T. Integrated methodology for evaluation of energy performance of the building enclosures - part 1: test program development. Journal of Building Physics 2008;32(1):33–48.

[53] Thorsell T, Bomberg M. Integrated methodology for evaluation of energy performance of building enclosures: part 2 - examples of application to residential walls. Journal of Building Physics 2008;32(1):49–65.

[54] Thorsell T, Bomberg M. Integrated methodology for evaluation of energy performance of the building enclosures: part 3 - uncertainty in thermal measurements. Journal of Building Physics 2011;35(1):83–96.

[55] ASTM C1046-95. Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components. West Conshohocken, PA: American Society for Testing and Materials. 2007.

[56] BS 874:1973. Methods for determining thermal insulating properties with definitions of thermal insulating terms. 1973.

[57] Gervásio H, Santos P, Simões da Silva L, Lopes AMG. Influence of thermal insulation on the energy balance for cold-formed buildings. Advanced Steel Construction 2010;6(2):742–66.

[58] Dylewski R, Adamczyk J. Economic and environmental benefits of thermal insulation of building external walls. Building and Environment 2011;46(12):2615–23.

[59] Ozel M. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. Energy and Buildings 2012;49:552–9.

[60] Baetens R, Jelle BP, Gustavsen A. Aerogel insulation for building applications: a state-of-the-art review. Energy and Buildings 2011;43:761–9.

[61] Cuce E, Cuce PM, Wood CJ, Riffat SB. Toward aerogel based thermal superinsulation in buildings: a comprehensive review. Renewable and Sustainable Energy Reviews 2014;34:273–99.

[62] Alam M, Singh H, Limbachiya MC. Vacuum Insulation Panels (VIPs) for building construction industry – a review of the contemporary developments and future directions. Applied Energy 2011;88(11):3592–602.

[63] Baetens R, Jelle BP, Thue JV,Tenpierik MJ, Grynning S, Uvsløkk S, Gustavsen A. Vacuum insulation panels for building applications: a review and beyond. Energy and Buildings 2010;42:147–72.

[64] Isaia F, Fantucci S, Capozzoli A, Perino M. Vacuum insulation panels: thermal bridging effects and energy performance in real building applications. Energy Procedia 2015;83:269–78.

[65] Fricke J, Heinemann U, Ebert HP. Vacuum insulation panels — from research to market. Vacuum 2008;82:680–90.

[66] Brunner S, Wakili KG, Stahl T, Binder B. Vacuum insulation panels for building applications — Continuous challenges and developments. Energy and Buildings 2014;85:592–6.

[67] Alotaibi SS, Riffat S. Vacuum insulated panels for sustainable buildings: a review of research and applications. International Journal of Energy Research 2014;38:1–19.

[68] Kalnaes SE, Petter Jelle B. Vacuum insulation panel products: a state-of-the-art review and future research pathways. Applied Energy 2014;116:355–75.

[69] Petter Jelle B. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. Energy and Buildings 2011;43:2549–63.

[70] Hoes P, Trcka M, Hensen JLM, Bonnema BH. Investigating the potential of a novel low-energy house concept with hybrid adaptable thermal storage. Energy Conversion and Management 2011;52(6):2442–7.

[71] Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering 2003;23(3):251–83.

[72] Farid MM, Khudhair AM, Ali S, Razack K. A review on phase change energy storage: materials and applications. Energy Conversion and Management 2004;45:1597–615.

[73] Kuznik F, David D, Johannes K, Roux J-J. A review on phase change materials integrated in building walls. Renewable and Sustainable Energy Reviews 2011;15(1):379–91.

[74] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: state-of-the-art and outlook. Building and Environment 2007;42(6):2197–209.

[75] Pasupathy A, Velraj R, Seeniraj RV. Phase change material-based building architecture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews 2008;12(1):39–64.

[76] Rodriguez-Ubinas E, Ruiz-Valero L, Vega S, Neila J. Applications of phase change material in highly energy-efficient houses. Energy and Buildings 2012;50:49–62.

[77] Wang X, Zhang Y, Xiao W, Zeng R, Zhang Q, Di H. Review on thermal performance of phase change energy storage building envelope. Chinese Science Bulletin 2009;54(6):920–8.

[78] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009;13(2):318–45.

[79] Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. Renewable and Sustainable Energy Reviews 2011;15(3):1675–95.

[80] Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renewable and Sustainable Energy Reviews 2007;11(6):1146–66.

[81] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renewable and Sustainable Energy Reviews 2007;11(9):1913–65.

[82] Zhou D, Zhao CY, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Applied Energy 2012;92:593–605.

[83] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews 2010;14(2):615–28.

[84] Baetens R, Jelle BP, Gustavsen A. Phase change materials for building applications: a state-of-the-art review. Energy and Buildings 2010;42(9):1361–8.

[85] Osterman E, Tyagi VV, Butala V, Rahim NA, Stritih U. Review of PCM based cooling technologies for buildings. Energy and Buildings 2012;49:37–49.

[86] Sharma RK, Ganesan P, Tyagi VV, Metselaar HSC, Sandaran SC. Developments in organic solid–liquid phase change materials and their applications in thermal energy storage. Energy Conversion and Management 2015;95:193-228.

[87] Hawes DW, Feldman D, Banu D. Latent heat storage in building materials. Energy and Buildings 1993;20(1):77–86.

[88] Fang G, Tang F, Cao L. Preparation, thermal properties and applications of shape-stabilized thermal energy storage materials. Renewable and Sustainable Energy Reviews 2014;40:237–59.

[89] Kuznik F, Virgone J, Noel J. Optimization of a phase change material wallboard for building use. Applied Thermal Engineering 2008;28(11–12):1291–8.

[90] Heim D, Clarke JA. Numerical modelling and thermal simulation of PCM-gypsum composites with ESP-r. Energy and Buildings 2004;36(8):795–805.

[91] Heim D. Isothermal storage of solar energy in building construction. Renewable Energy 2012;35(4):788–96.

[92] Zhang Y, Lin K, Jiang Y, Zhou G. Thermal storage and nonlinear heat-transfer characteristics of PCM wallboard. Energy and Buildings 2008;40(9):1771–9.

[93] Neeper DA. Thermal dynamics of wallboard with latent heat storage. Solar Energy 2000;68(5):393–403.

[94] Zhou D, Shire GSF, Tian Y. Parametric analysis of influencing factors in phase change material wallboard (PCMW). Applied Energy 2014;119:33–42.

[95] Bastani A, Haghighat F, Kozinski J. Designing building envelope with PCM wallboards: design tool development. Renewable and Sustainable Energy Reviews 2014;31:554–62.

[96] Shilei L, Guohui F, Neng Z, Li D. Experimental study and evaluation of latent heat storage in phase change materials wallboards. Energy and Buildings 2007;39(10):1088–91.

[97] Kuznik F, Virgone J, Johannes K. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renewable Energy 2011;36(5):1458–62.

[98] Zhou T, Darkwa J, Kokogiannakis G. Thermal evaluation of laminated composite phase change material gypsum board under dynamic conditions. Renewable Energy 2015;78:448–56.

[99] Schossig P, Henning H-M, Gschwander S, Haussmann T. Micro-encapsulated phase-change materials integrated into construction materials. Solar Energy Materials and Solar Cells 2005;89(2–3):297–306.

[100] Koo J, So H, Hong SW, Hong H. Effects of wallboard design parameters on the thermal storage in buildings. Energy and Buildings 2011;43(8):1947–51.

[101] Kuznik F, Virgone J. Experimental investigation of wallboard containing phase change material: data for validation of numerical modeling. Energy and Buildings 2009;41(5):561–70.

[102] Kuznik F, Virgone J, Roux J-J. Energetic efficiency of room wall containing PCM wallboard: a full-scale experimental investigation. Energy and Buildings 2008;40(2):148–56.

[103] Borreguero AM, Sánchez ML, Valverde JL, Carmona M, Rodríguez JF. Thermal testing and numerical simulation of gypsum wallboards incorporated with different PCMs content. Applied Energy 2011;88(3):930–7.

[104] Chen C, Guo H, Liu Y, Yue H, Wang C. A new kind of phase change material (PCM) for energy-storing wallboard. Energy and Buildings 2008;40(5):882–90.

[105] Zhu N, Wang S, Xu X, Ma Z. A simplified dynamic model of building structures integrated with shaped-stabilized phase change materials. International Journal of Thermal Sciences 2010;49(9):1722–31.

[106] Xiao M, Feng B, Gong K. Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity. Energy Conversion and Management 2002;43(1):103–8.

[107] Xiao M, Feng B, Gong K. Thermal performance of a high conductive shape-stabilized thermal storage material. Heat and Mass Transfer 2001;69:293–6.

[108] Zhou G, Yang Y, Xu H. Energy performance of a hybrid space-cooling system in an office building using SSPCM thermal storage and night ventilation. Solar Energy 2011;85:477–85.

[109] Zhu N, Wang S, Ma Z, Sun Y. Energy performance and optimal control of air-conditioned buildings with envelopes enhanced by phase change materials. Energy Conversion and Management 2011;52:3197–205.

[110] Zhou G, Yang Y, Xu H. Performance of shape-stabilized phase change material wallboard with periodical outside heat flux waves. Applied Energy 2011;88:2113–21.

[111] Zhou G, Yang Y, Wang X, Cheng J. Thermal characteristics of shape-stabilized phase change material wallboard with periodical outside temperature waves. Applied Energy 2010;87:2666–72.

[112] Zhou G, Zhang Y, Wang X, Lin K, Xiao W. An assessment of mixed type PCM-gypsum and shape-stabilized PCM plates in a building for passive solar heating. Solar Energy 2007;81:1351–60.

[113] Zhou G, Zhang Y, Lin K, Xiao W. Thermal analysis of a direct-gain room with shape-stabilized PCM plates. Renewable Energy 2008;33(6):1228–36.

[114] Zhou G, Yang Y, Wang X, Zhou S. Numerical analysis of effect of shape-stabilized phase change material plates in a building combined with night ventilation. Applied Energy 2009;86:52–9.

[115] Zhang YP, Lin KP, Yang R, Di HF, Jiang Y. Preparation, thermal performance and application of shape-stabilized PCM in energy efficient buildings. Energy and Buildings 2006;38(10):1262–9.

[116] Zhu N, Hu P, Xu L. A simplified dynamic model of double layers shape-stabilized phase change materials wallboards. Energy and Buildings 2013;67:508–16.

[117] Xiao W, Wang X, Zhang Y. Analytical optimization of interior PCM for energy storage in a lightweight passive solar room. Applied Energy 2009;86(10):2013–8.

[118] Xu X, Zhang Y, Lin K, Di H, Yang R. Modeling and simulation on the thermal performance of shape-stabilized phase change material floor used in passive solar buildings. Energy and Buildings 2005;37:1084–91.

[119] Ye H, Long L, Zhang H, Zou R. The performance evaluation of shape-stabilized phase change materials in building applications using energy saving index. Applied Energy 2014;113:1118–26.

[120] Cheng W, Xie B, Zhang R, Xu Z, Xia Y. Effect of thermal conductivities of shape stabilized PCM on under-floor heating system. Applied Energy 2015;144:10–8.

[121] Diarce G, Urresti A, García-Romero A, Delgado A, Erkoreka A, Escudero C, Campos-Celador Á. Ventilated active façades with PCM. Applied Energy 2013;109:530–7.

[122] de Gracia A, Navarro L, Castell A, Cabeza LF. Energy performance of a ventilated double skin facade with PCM under different climates. Energy and Buildings 2015;91:37–42.

[123] Álvarez S, Cabeza LF, Ruiz-Pardo A, Castell A, Tenorio JA. Building integration of PCM for natural cooling of buildings. Applied Energy 2013;109:514–22.

[124] Diarce G, Campos-Celador Á, Martin K, Urresti A, García-Romero A, Sala JM. A comparative study of the CFD modeling of a ventilated active façade including phase change materials. Applied Energy 2014;126:307–17.

[125] de Gracia A, Navarro L, Castell A, Ruiz-Pardo Á, Alvárez S, Cabeza LF. Experimental study of a ventilated facade with PCM during winter period. Energy and Buildings 2013;58:324–32.

[126] de Gracia A, Navarro L, Castell A, Ruiz-Pardo Á, Álvarez S, Cabeza LF. Thermal analysis of a ventilated facade with PCM for cooling applications. Energy and Buildings 2013;65:508–15.

[127] Soares N, Samagaio A, Vicente R, Costa J. Numerical simulation of a PCM shutter for buildings space heating during the winter, in: Proceedings of WREC – World Renewable Energy Congress 2011, Linköping, Sweden, 8–13 May, 2011.

[128] Soares N, Costa JJ, Samagaio A, Vicente R. Numerical evaluation of a phase change material-shutter using solar energy for winter nighttime indoor heating. Journal of Building Physics 2014;37(4):367–94.

[129] Silva T, Vicente R, Rodrigues F, Samagaio A, Cardoso C. Performance of a window shutter with phase change material under summer Mediterranean climate conditions. Applied Thermal Engineering 2015;84:246–56.

[130] Silva T, Vicente R, Rodrigues F, Samagaio A, Cardoso C. Development of a window shutter with phase change materials: full scale outdoor experimental approach. Energy and Buildings 2015;88:110–21.

[131] Alawadhi EM. Using phase change materials in window shutter to reduce the solar heat gain. Energy and Buildings 2012;47:421–9.

[132] Weinlaeder H, Koerner W, Heidenfelder M. Monitoring results of an interior sun protection system with integrated latent heat storage. Energy and Buildings 2011;43(9):2468–75.

[133] Wang Q, Zhao CY. Parametric investigations of using a PCM curtain for energy efficient buildings. Energy and Buildings 2015;94:33–42.

[134] Manz H, Egolf PW, Suter P, Goetzberger A. TIM-PCM, external wall system for solar space heating and daylight. Solar Energy 1997;61(6):369–79.

[135] Bontemps A, Ahmad M, Johannès K, Sallée H. Experimental and modelling study of twin cells with latent heat storage walls. Energy and Buildings 2011;43(9):2456–61.

[136] Weinläder H, Beck A, Fricke J. PCM-facade-panel for daylighting and room heating. Solar Energy 2005;78(2):177–86.

[137] Goia F, Zinzi M, Carnielo E, Serra V. Spectral and angular solar properties of a PCM-filled double glazing unit. Energy and Buildings 2015;87:302–12.

[138] Goia F, Perino M, Serra V. Experimental analysis of the energy performance of a full-scale PCM glazing prototype. Solar Energy 2014;100:217–33.

[139] Silva T, Vicente R, Soares N, Ferreira V. Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: a passive construction solution. Energy and Buildings 2012;49:235–45.

[140] Vicente R, Silva T. Brick masonry walls with PCM macrocapsules: an experimental approach. Applied Thermal Engineering 2014;67:24-34.

[141] Alawadhi EM. Thermal analysis of a building brick containing phase change material. Energy and Buildings 2008;40(3):351–7.

[142] Zhang C, Chen Y, Wu L, Shi M. Thermal response of brick wall filled with phase change materials (PCM) under fluctuating outdoor temperatures. Energy and Buildings 2011;43(12):3514–20.

[143] Lai C-M, Chiang C-M. How phase change materials affect thermal performance: hollow bricks. Building Research and Information 2006;34(2):118–30.

[144] Cheng R, Pomianowski M, Wang X, Heiselberg P, Zhang Y. A new method to determine thermophysical properties of PCM-concrete brick. Applied Energy 2013;112:988–98.

[145] Kheradmand M, Azenha M, de Aguiar JLB, Krakowiak KJ. Thermal behavior of cement based plastering mortar containing hybrid microencapsulated phase change materials. Energy and Buildings 2014;84:526–36.

[146] Sá AV, Azenha M, de Sousa H, Samagaio A. Thermal enhancement of plastering mortars with phase change materials: experimental and numerical approach. Energy and Buildings 2012;49:16–27.

[147] Joulin A, Zalewski L, Lassue S, Naji H. Experimental investigation of thermal characteristics of a mortar with or without a micro-encapsulated phase change material. Applied Thermal Engineering 2014;66:171–80.

[148] Franquet E, Gibout S, Tittelein P, Zalewski L, Dumas J-P. Experimental and theoretical analysis of a cement mortar containing microencapsulated PCM. Applied Thermal Engineering 2014;73:32–40.

[149] Tittelein P, Gibout S, Franquet E, Johannes K, Zalewski L, Kuznik F, Dumas J-P, Lassue S, Bédécarrats J-P, David D. Simulation of the thermal and energy behaviour of a composite material containing encapsulated-PCM: influence of the thermodynamical modelling. Applied Energy 2015;140:269–74.

[150] Ventolà L, Vendrell M, Giraldez P. Newly-designed traditional lime mortar with a phase change material as an additive. Construction and Building Materials 2013;47:1210–6.

[151] Zhang Z, Shi G, Wang S, Fang X, Liu X. Thermal energy storage cement mortar containing n-octadecane expanded graphite composite phase change material. Renewable Energy 2013;50:670–5.

[152] Li Y, Liu S. Numerical study on thermal behaviors of a solar chimney incorporated with PCM. Energy and Buildings 2014;80:406–14.

[153] Liu S, Li Y. Heating performance of a solar chimney combined PCM: a numerical case study. Energy and Buildings 2015;99:117–30.

[154] Joulin A, Younsi Z, Zalewski L, Lassue S, Rousse DR, Cavrot J-P. Experimental and numerical investigation of a phase change material: thermal-energy storage and release. Applied Energy 2011;88(7):2454–62.

[155] Medina M, King J, Zhang M. On the heat transfer rate reduction of structural insulated panels (SIPs) outfitted with phase change materials (PCMs). Energy 2008;33(4):667–78.

[156] Evers AC, Medina MA, Fang Y. Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. Building and Environment 2010;45(8):1762–8.

[157] Carbonari A, de Grassi M, Di Perna C, Principi P. Numerical and experimental analyses of PCM containing sandwich panels for prefabricated walls. Energy and Buildings 2006;38:472–83.

[158] Halford CK, Boehm RF. Modeling of phase change material peak load shifting. Energy and Buildings 2007;39(3):298–305.

[159] Mathieu-Potvin F, Gosselin L. Thermal shielding of multilayer walls with phase change materials under different transient boundary conditions. International Journal of Thermal Sciences 2009;48(9):1707–17.

[160] Huang M, Eames P, Hewitt N. The application of a validated numerical model to predict the energy conservation potential of using phase change materials in the fabric of a building. Solar Energy Materials and Solar Cells 2006;90(13):1951–60.

[161] Jin X, Medina MA, Zhang X. On the placement of a phase change material thermal shield within the cavity of buildings walls for heat transfer rate reduction. Energy 2014;73:780–6.

[162] Darkwa K, O'Callaghan PW. Simulation of phase change drywalls in a passive solar building. Applied Thermal Engineering 2006;26(8-9):853–8.

[163] Lai C-m, Hokoi S. Thermal performance of an aluminum honeycomb wallboard incorporating microencapsulated PCM. Energy and Buildings 2014;73:37–47.

[164] Biswas K, Abhari R. Low-cost phase change material as an energy storage medium in building envelopes: experimental and numerical analyses. Energy Conversion and Management 2014;88:1020–31.

[165] Kong X, Lu S, Li Y, Huang J, Liu S. Numerical study on the thermal performance of building wall and roof incorporating phase change material panel for passive cooling application. Energy and Buildings 2014;81:404–15.

[166] Zhao CY, Zhang GH. Review on microencapsulated phase change materials (MEPCMs): fabrication, characterization and applications. Renewable and Sustainable Energy Reviews 2011;15(8):3813–32.

[167] Riffat S, Mempouo B, Fang W. Phase change material developments: a review. International Journal of Ambient Energy 2015;36(3):102–15.

[168] Diakaki C, Grigoroudis E, Kolokotsa D. Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy and Buildings 2008;40:1747–54.

[169] Pielichowski K. Phase change materials for thermal energy storage. Progress in Materials Science 2014;65:67–123.

[170] Dutil Y, Rousse D, Lassue S, Zalewski L, Joulin A, Virgone J, Kuznik F, Johannes K, Dumas J-P, Bédécarrats J-P, Castell A, Cabeza LF. Modeling phase change materials behavior in building applications: Comments on material characterization and model validation. Renewable Energy 2014;61:132–5.

[171] Khudhair AM, Farid MM. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. Energy Conversion and Management 2004;45(2):263–75.

[172] Zhu N, Ma Z, Wang S. Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Conversion and Management 2009;50(12):3169–81.

[173] Parameshwaran R, Kalaiselvam S, Harikrishnan S, Elayaperumal A. Sustainable thermal energy storage technologies for buildings: a review. Renewable and Sustainable Energy Reviews 2012;16(5):2394–433.

[174] Whiffen TR, Riffat SB. A review of PCM technology for thermal energy storage in the built environment: part II. International Journal of Low-Carbon Technologies 2013;8:159–164.

[175] Jeon J, Lee J-H, Seo J, Jeong S-G, Kim S. Application of PCM thermal energy storage system to reduce building energy consumption. Journal of Thermal Analysis and Calorimetry 2013;111:279–88.

[176] Kalnaes SE, Jelle BP. Phase change materials and products for building applications: a state-of-the-art review and future research opportunities. Energy and Buildings 2015;94:150–76.

[177] Raj VAA, Velraj R. Review on free cooling of buildings using phase change materials. Renewable and Sustainable Energy Reviews 2010;14(9):2819–29.

[178] Cheng R, Wang X, Zhang Y. Energy-efficient building envelopes with phase-change materials: new understanding and related research. Heat Transfer Engineering 2014;35(11-12):970–84.

[179] de Gracia A, Cabeza LF. Phase change materials and thermal energy storage for buildings. Energy and Buildings 2015;103:414–9.

[180] Fokaides PA, Kylili A, Kalogirou SA. Phase change materials (PCMs) integrated into transparent building elements: a review. Materials for Renewable and Sustainable Energy 2015;4(6):1–13.

[181] Cuce E, Riffat SB. A state-of-the-art review on innovative glazing technologies. Renewable and Sustainable Energy Reviews 2015;41:695–714.

[182] Hee WJ, Alghoul MA, Bakhtyar B, Elayeb O, Shameri MA, Alrubaih MS, Sopian K. The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews 2015;42:323–43.

[183] Lai C-M, Hokoi S. Solar façades: a review. Building and Environment 2015;91:152–65.

[184] Silva T, Vicente R, Rodrigues F. Literature review on the use of phase change materials in glazing and shading solutions. Renewable and Sustainable Energy Reviews 2016;53:515–35.

[185] Soares N. Thermal energy storage with Phase Change Materials (PCMs) for the improvement of the energy performance of buildings. PhD Dissertation in Sustainable Energy Systems, Department of Mechanical Engineering, Faculty of Sciences and Technology of the University of Coimbra. 2015.

[186] Mehling H, Cabeza LF. Heat and cold storage with PCM: an up to date introduction into basics and applications, Springer, 2008.

[187] Soares N, Gaspar AR, Santos P, Costa JJ. Experimental study of the heat transfer through a vertical stack of rectangular cavities filled with phase change materials. Applied Energy 2015;142:192–205.

[188] Soares N, Gaspar AR, Santos P, Costa JJ. Experimental evaluation of the heat transfer through small PCM-based thermal energy storage units for building applications. Energy and Buildings 2016;116:18–34.

[189] Sun X, Zhang Q, Medina MA, Lee KO, Experimental observations on the heat transfer enhancement caused by natural convection during melting of solid–liquid phase change materials (PCMs). Applied energy 2016;162:1453–61.

[190] Kylili A, Fokaides PA. Numerical simulation of phase change materials for building applications: a review. Advances in Building Energy Research 2015.

[191] Rathod MK, Banerjee J. Thermal stability of phase change materials used in latent heat energy storage systems: a review. Renewable and Sustainable Energy Reviews 2013;18:246–58.

[192] Pomianowski M, Heiselberg P, Zhang Y. Review of thermal energy storage technologies based on PCM application in buildings. Energy and Buildings 2013;67:56–69.

[193] Jegadheeswaran S, Pohekar SD. Performance enhancement in latent heat thermal storage system: a review. Renewable and Sustainable Energy Reviews 2009;13:2225–44.

[194] Fan L, Khodadadi JM. Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renewable and Sustainable Energy Reviews 2011;15(1):24–46.

[195] Kosny J. PCM-enhanced building components: an application of phase change materials in building envelopes and internal structures. Springer International Publishing Switzerland, 2015.

[196] Website "AlbaBalance PCM solid plasterboards": www.rigips.ch.

[197] Website "ebb PCM Clay Boards": http://ecobuildingboards.weebly.com.

[198] Website "Knauf ComfortBoard Phase Change plasterboard": www.knauf.co.uk.

[199] Website "ThermaCool Phase Change Technology": http://therma.cool.

[200] Website "ThermalCORE PCM Panel": www.thermalcore.info.

[201] "Website "Glauber-lamell AB": www.glauber-lamell.se.

[202] Website "GlassX AG": www.glassx.ch.

[203] Saffari M, de Gracia A, Ushak S, Cabeza LF. Economic impact of integrating PCM as passive system in buildings using Fanger comfort model. Energy and Buildings 2016;112:159–72.

[204] Evola G, Marletta L. The effectiveness of PCM wallboards for the energy refurbishment of lightweight buildings. Energy Procedia 2014;62:13–21.

[205] Al-Saadi SN, Zhai Z(J). A new validated TRNSYS module for simulating latent heat storage walls. Energy and Buildings 2015;109:274–90.

[206] Gomes AP, de Souza HA, Tribess A. Impact of thermal bridging on the performance of buildings using Light Steel Framing in Brazil. Applied Thermal Engineering 2013;52(1):84–9.

[207] Gaterell MR, Mcevoy ME. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. Energy and Buildings 2005;37:982–95.

[208] Christenson M, Manz H, Gyalistras D. Climate warming impact on degree-days and building energy demand in Switzerland. Energy Conversion and Management 2006;47:671–86.

[209] Bill Dunster Architects, UK Housing and Climate Change. Heavyweight vs. lightweight construction. London: Arup Research and Development. 2005.

[210] Santos P, Gervásio H, Simões da Silva L, Lopes AG. Influence of climate change on the energy efficiency of light-weight steel residential buildings. Civil Engineering and Environmental Systems 2011;28(4):325–52.

[211] Kendrick C, Ogden R, Wang X, Baiche B. Thermal mass in new build UK housing: a comparison of structural systems in a future weather scenario. Energy and Buildings 2012;48:40–9.

[212] Rodrigues LT, Gillott M, Tetlow D. Summer overheating potential in a low-energy steel frame house in future climate scenarios. Sustainable Cities and Society 2013;7:1–15.

[213] Gosling J, Sassi P, Naim M, Lark R. Adaptable buildings: a systems approach. Sustainable Cities and Society 2013;7:44–51.

[214] Hoes P, Hensen JLM. The potential of lightweight low-energy houses with hybrid adaptable thermal storage: comparing the performance of promising concepts. Energy and Buildings 2016;110:79–93.

[215] Dubina D, Ungureanu V, Landolfo R. Design of Cold-formed Steel Structures. ECCS and Ernst & Sohn 2012.

[216] ISO 14040:2006. Environmental management – Life Cycle Assessment – Principles and Framework. 2006.

[217] ISO 14044:2006. Environmental management – Life Cycle Assessment – Requirements and Guidelines. 2006.

[218] EN 15643-1:2010. Sustainability of construction works. Sustainability assessment of buildings. General framework. 2010.

[219] EN 15804:2012+A1:2013. Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. 2013.

[220] EN 15978:2011. Sustainability of construction works. Assessment of environmental performance of buildings, calculation method. 2011.

[221] Gervásio H, Santos P, Martins R, Simões da Silva L. A macro-component approach for the assessment of building sustainability in early stages of design. Building and Environment 2014;73:256–70.

[222] Santos P, Martins R, Gervásio H, Simões da Silva L. Assessment of building operational energy at early stages of design – a monthly quasi-steady-state approach. Energy and Buildings 2014;79:58–73.

[223] Gervásio H. Eco-structural efficiency in natural hazard events. Safesust Workshop - A roadmap for the improvement of earthquake resistance and eco-efficiency of existing building and cities, JRC, Ispra, 2015.

[224] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and Buildings 2010;42:869–80.

[225] Citherlet S, Defaux T. Energy and environmental comparison of three variants of a family house during its whole life span. Building and Environment 2007;42(2):591–8.

[226] Thormark C. A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential. Building and Environment 2001;37:429–35.

[227] Rodrigues C, Freire F. Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. Building and Environment 2014;81:204–15.

[228] Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Hischier R, Hellweg S, Nemecek T, Rebitzer G, Spielmann M. Overview and Methodology. Final report ecoinvent 2000 No. 1, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2007.

[229] Recchioni M, Mathieux F, Goralczyk M, Schau E. ILCD Data Network and ELCD Database: current use and further needs for supporting Environmental Footprint and Life Cycle Indicator Projects. JRC Technical reports. Report EUR 25744 EN.2012

[230] ISO 14025:2006. Environmental labels and declarations – Type III environmental declarations – Principles and Procedures. 2006.

[231] Intini F, Kühtz S. Recycling in buildings: an LCA case study of a thermal insulation panel made of polyester fiber, recycled from post-consumer PET bottles. The International Journal of Life Cycle Assessment 2011;16:306–315.

[232] Asdrubali F, D'Alessandro F, Schiavoni S. A review of unconventional sustainable building insulation materials. Sustainable Materials and Technologies 2015;4:1–17.

[233] Kylili A, Fokaides PA. Life cycle assessment (LCA) of phase change materials (PCMs) for building applications: a review. Journal of Building Engineering 2016;6:133–143.