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HIGH ENERGY EFFICIENT BUILDINGS: SUSTAINABLE STRATEGIES BASED ON STRUCTURE/ENVELOPE TECHNIQUES WITH ARTIFICIAL THERMAL INERTIA

M. IMPERADORI
Professor, PhD, Engineer, Dipartimento BEST, Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italy Co-Director Atelier 2 (Gallotti e Imperadori Associati), via P. Custodi 16, 20136, Milano, Italia
marco.imperadori@polimi.it

G. MASERA
Senior Researcher, PhD, Engineer, Dipartimento BEST, Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italia - gabriele.masera@polimi.it

G. IANNACCONE
PhD, Architect, Dipartimento BEST, Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italia
g.iannaccone@archiworld.it

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Abstract

The big amount of energy requested by buildings has shown the necessity of proposing new technologies in building construction and services. Saving energy has become a primary issue nowadays. An integration during the design phase among Architecture, Building Technology and Services, is very recommended in order to obtain a more sophisticated “living-environment” using relatively simple strategies avoiding extra-costs. Industrialized systems of construction, based on assembled stratified layers over a bearing frame structure, seem to offer a lot of advantages in a sustainable approach. Through the exploitation of renewable sources and the optimization of the building thermal behavior it is possible to reduce considerably the energy consumption. Thermal inertia appears to be one of the fundamental characteristics of buildings (combined to high levels of thermal insulation). New materials can be investigated to enhance the performances of lightweight building systems. Among these, PCM (Phase Change Materials) can be integrated into lightweight building components, providing an artificial inertial effect. They can be used for storing heat during winter days and releasing energy during the night, reducing overheating risks in summer, especially in Structure / Envelope constructions (S/E) and storing off-peak energy in order to have a warm/cool surface that contributes to irradiative comfort by day. An extensive experimental campaign was set up to understand the potential for integration of hydrated salt PCM’s in lightweight floors and internal partitions. Some recent examples are shown to underline the possible strategies and their effective results. The residential projects illustrated demonstrate how to design high energy efficient buildings using ordinary technology and performing a pleasant contemporary architecture: sustainable buildings don’t mean to be aesthetically unsustainable.

1 Introduction

The issue of realizing a better energy-performing building should today be primary and each designer has to take it in serious consideration. Saving energy has become a primary issue nowadays. As a matter of fact the amount of energy requested for living (preserving requested comfort levels) is very high and must drastically be reduced to match the request of Kyoto protocol. The EU Directive 93/76 - regarding the emission of CO_2 - estimates that over 40% of the global energy consumption can be attributed to the Building Construction sector. Through the exploitation of renewable sources and the optimization of the buildings' thermal behavior the same Directive maintains that it is possible to reduce this consumption level to 22%. In the last years, the building sector has been undergoing significant changes as concerns both building techniques and energetic strategies. The positive aspect is that there is wide scope for improving its energetic performances, simply using technologies that are already available on the market, such as thermal insulation, efficient glazing, ventilation systems with heat recovery, and so on. Integration during the design phase among Architecture, Building Technology and Services, is very recommended in order to obtain a more sophisticated "living-environment" using relatively simple strategies avoiding extra-costs. Industrialized systems of construction, based on assembled stratified layers (Structure/Envelope techniques) over a bearing frame structure, seem to offer a lot of advantages in a sustainable approach. On the other hand, performance requirements are growing higher because of both more stringent regulations and higher comfort requirements by the users – the spreading use of air conditioning systems, also in houses, is just an example of this trend. These two issues mean that a deep reconsideration of how buildings are designed and built is required, in order to provide high performance levels with a limited environmental impact – which is simply the definition of *sustainable development* applied to buildings.

Figures 1-2: On the left, high energy-efficient building in Colognola (BG), Italy. On the right, L'Armadillo, a new industrialized system for light, energy-efficient, permanent and temporary buildings (Atelier2, Milano).

2 Winter strategy: high-insulated envelope

Different concepts have been proposed by architects, engineers and by scientists in the whole life cycle of the building, from materials production, through design phase, the building phase, the operating phase to the eventual disassembling and recycling phase. Structure-Envelope (StrEn) systems have a lower embodied energy compared with massive buildings. The goal is now to make StrEn buildings evolve by giving them the relevant amount of natural or artificial inertia, as it will be shown later on in this paper. It is possible to tackle the problem of energy consumption with stratified lightweight skins and layers, high performance materials and integration of installations, like heat pumps for example or wind turbines, and enhancing the use of renewable energy sources by using devices like solar photovoltaic panels or solar thermal exchanger or simply by favouring natural ventilation and natural shading or re-interpreting low processing materials and using them in a clever way. Results expected are to re-interpret good vernacular approaches to construction or introducing a new generation of buildings, also using new materials, that seem to be very revolutionary and could easily be almost totally served by clean energy sources (sun, wind, earth energy or other clean sources) and become non-oil houses or non-oil towns. Several recent sustainable projects are characterized by high-insulated envelopes, light structures integrating solar panels and ventilation systems. The bearing structure is dry-assembled as a Meccano. It is characterized by a steel or timber frame with concrete floors and staircases acting as bracing systems. Therefore we have a well-insulated and ventilated "skin" and a core endowed with massive and inertial elements. Architecture, shape and orientation of building allow the whole systems to work well. Precise seasonal strategies maximize the winter energy contributions from both natural sources (sun) and interior gains stored in the massive parts and retained because of insulation. In the middle seasons and in summertime, the natural ventilation could be exploited thanks to temperature differentials between opposite walls and the "stack effect" of massive floors acting as "cooling sheets". These buildings (we don't call them "passive" because it's an adjective misread by customers and common people) work following the environment conditions and the seasons, unlike the conservative strategies (in summer and in winter) of adiabatic hyper-insulated construction. The hybrid strategy (insulated shell – inertial core) seems a logical passage in buildings, a smart evolution rather than a traumatic revolution in a slow market. In Italy, we could imagine high energy-efficient buildings characterized by a concrete bearing frame and concrete slabs, and a dry assembled insulated envelope. A recent study, commissioned by Knauf Italia and carried out by ANIT (Thermo-acoustical Insulators manufacturers National Association), has valued the performance of light envelopes in stratified dry-assembled buildings in all Italian Regions. Thermal transmittance and attenuation, and then phase shift, or the delay of the peak temperature between inner and outer side of a wall, are valued together. The minimum permissible phase shift for an external wall is 8 hours. A wall made up of Knauf Aquapanel (19 mm), wood wool (100mm+75mm) and 2 gypsum plasterboards (25 mm) has a thermal phase shift of 12h 35' and U value 0.434 W/m^2K (total thickness 22 cm). If we replace 75mm of wood wool with 30 mm of mineral wall, U value became 0,4313 W/m^2K and the thermal phase shift 8 h 35' (total thickness 16 cm). In conclusion, light stratified envelopes ($25\div30$ cm thick) have good insulating (and acoustical) performance and also good thermal phase shift. It's recommended a mix of mineral wool (inner wall, density: 15 Kg/m^3 – outer wall, density $60\div70$ kg/m^3), wood wool (best performing for thermal attenuation) and insulating board (EPS and polyurethane, good thermal insulators but not for the phase shift).

Figure 3: Examples of high-insulated envelope: the last one shows a mix of mineral and wood wool.

3 Artificial thermal inertia and summer cooling

A basic strategy required to save energy for cooling is the reduction of overheating inside the building. Apart from efficient shading of the glazed areas, the use of thermal mass is critical in order to control temperature peaks and the cycle of temperature during the day, so reducing the load on the cooling system.

A possible way to use thermal mass in a building is that of an internal mass that contributes to the storage of energy during the day (also in winter) and releases it during the night, when the air temperatures are supposed to be lower. In well-insulated buildings, this is the most important issue about thermal inertia as the wall is almost adiabatic and the heat flow through it is practically eliminated. The required storage capacity is low, as energetic inputs are relatively small.

The EU-funded CRAFT research called C-TIDE (*Changeable Thermal Inertia Dry Envelopes*) moved in 2002 from the consideration of the opposite requirements deriving from the advantages of thermal mass (which is obtained, in general, through heavy elements) and from those of light Str/En construction. The basic idea was the integration in light buildings of *Phase Change Materials* (PCM), that are salts or paraffins that undergo a phase change process (that is, a reordering of the microstructure) involving the storage, or release, of latent heat.

PCM’s could then be used in order to obtain thermal storage elements that do not add unnecessary weight to the construction and that – what is more – can be *tuned* to have a melting temperature coherent with the human comfort necessities. If the PCM is made to store heat at a useful temperature (both from the sun or from a vector fluid, such as hot water), this means that it will maintain *that temperature level* until the whole phase change process has taken place, so reducing overheating (in summer) or cooling (in winter) of the interior environment. A sort of “programmable inertia” can thus be obtained by regulating the melting temperature and the quantity of PCM’s in the building.

C-TIDE research was two years long (November 2002 to November 2004) and involved some building component and PCM manufacturers (Vanoncini S.p.A. and Impresa Pietro Poggi from Italy, Climator S.A. from Sweden) and, as academic partners, Politecnico di Milano and Polytechnic University of Marche from Italy and BMG Gävle from Sweden.

The output of this research was a “PCM blanket”, that is a series of pouches containing PCM, of limited thickness to improve heat exchange with nearby elements, welded in series in order to obtain a continuous element (figure 1). Each pouch is some 8 x 4 cm wide, while the blanket is to be produced in a modular size of about 100 x 50 cm. The main advantage of using small-size pouches, besides *limiting the effects* of a damaged element, is that the blanket can be *easily cut* to the required dimensions following the welding lines, without the use of any special tools – apart from a cutter.

3.1 The PCM blanket

3.1.1 Application in a radiant floor

One of the possible uses that was imagined for the PCM blanket is an underfloor application, integrated to a radiant heating or cooling system (figure 2). In this sense, the blanket would replace the thermal mass traditionally obtained through concrete elements, giving the added benefit of being able to design both the operating temperature of the system and its thermal capacity according to the specific situation.

The technical solution is composed by two layers of the PCM blanket with the water pipes embedded between them in order to enhance heat exchange between the surface of the pipes and the PCM contained in the pouches. The upper surface is then made smooth trough a thin self-levelling screed, where the floor material can be laid.

The basic idea was to maintain the floor at a more or less *constant temperature*: that of the melting point of PCM contained in the blanket. In summer, the floor heats up, because of the radiation from the sun entering the windows, but when it reaches the melting temperature the phase change process begins. Then, the energy gained from the sun is used in latent form, while the temperature of the PCM layer remains constant.

If the melting temperature is accurately chosen, during the phase change process the floor *works as a radiant surface at a comfortable temperature* for the users of the building. Most of the energy coming from the sun is thus used for PCM melting instead of increasing the air temperature inside the building. When PCM's are completely melted, or night has fallen, cool water circulating in the floor is used to activate the inverse process of solidification (discharging of the PCM layer by taking latent heat away). In this way, the PCM element is ready for another storage cycle, be it the same day or the next morning.

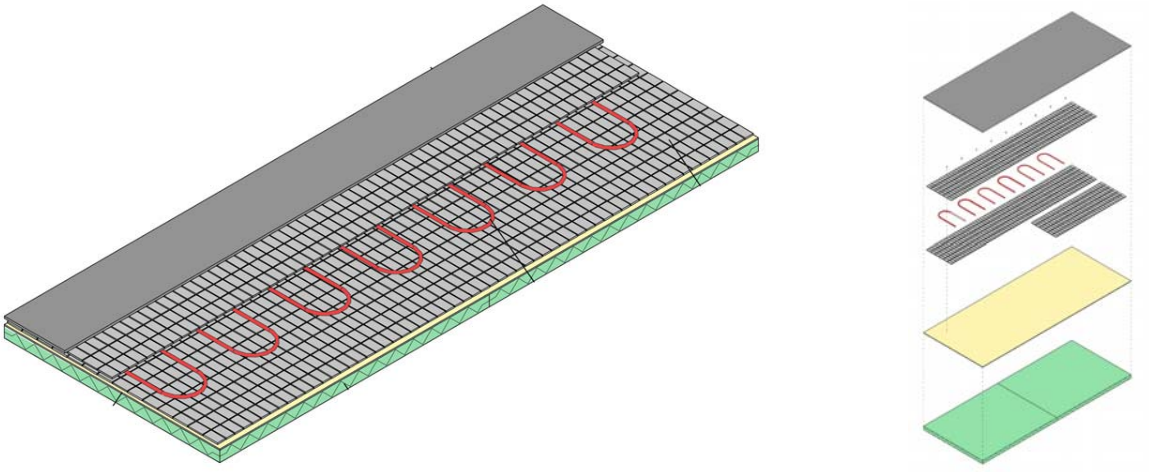

Figure 4: The PCM blanket applied to a radiant floor

3.1.2 Application in internal wall

Another use for PCM blanket is a wallboard application, integrated between two plasterboard layers fixed to a metal sub-structure, with the same aim of the blanket in the floor.

The integrated wallboard could be simply assembled by ordinary workers, without changing the assembly process of a normal plasterboard wall.

During the experimental campaign of the C-TIDE research, a sample of internal wall board was tested applying layers packaged in blankets containing PCM to provide artificial thermal inertia.

All the tests showed the good performances of the internal wall blanket allowing its installation .

At the end of test campaign, a part of the plasterboard, close to the floor, was removed in order to evaluate possible straining of melted salts. Test showed that PCM inside the wallboard were perfectly placed inside the pouches and perforations on these induced a light halo confined to the damaged.

Several load tests were also carried out to verify the performance of the internal wall blanket compared to a normal one.

3 Theorical simulations

3.1 The Passivhaus in Chignolo d'Isola (BG)

The first Italian Passivhaus (space heating less than 15 kWh/m² /year) was built in 2003 in Chignolo d'Isola, close to Bergamo.

Low energy consumption was achieved through efficient enclosures (hyper-insulated envelopes and low-emissivity windows) and ensured a high standard of thermal comfort in winter. Conversely, a HVAC system was required to maintain desired summer time indoor environmental conditions.

In order to study the effects of the PCM-based enclosures and partitions on the indoor climate, a dynamic numerical simulation was performed on this building.

An explicit finite difference method was used for the simulation. The building was divided into elements of finite dimensions. The heat balance for each element was calculated by hypothesizing that the thermal capacity of the element is condensed into one point and the heat transfer with the adjacent element is linearly dependent on the temperature difference between the two nodes. The building model is therefore composed by a network of resistances and capacitances.

In order to accurately determine the transition phase the specific heat capacity of the phase change material node was expressed as function of the temperature. Still the shape of the curve was manually determined as there is no $c_p(T)$ curve available at the moment. The thermal conductivity, instead, was supposed to be constant over the temperature interval. A carefully determined time step was used to ensure the stability of the simulation.

Calculations showed that PCM walls allow for energy savings through reducing HVAC operational time. However if used in a passive way, PCM only facilitates desirable thermal comfort conditions for short periods of time.

Figure 5: Sample of internal wall board, tested applying layers packaged in blankets containing PCM to provide artificial thermal inertia.

3.2 Ongoing experiments

A prototipe of a PCM Blanket in a EFTE greenhouse has been tested in Carate Brianza (MI) in cooperation with the Italian Industry Brianza Plastica.

The outputs of the test could be transferred by the agricultural field to the architectonical one.

The most interesting outcome is the discovery of “turbo effect”, that is the PCM performing as catalyst of greenhouse effect when exposed to the sun inside a solar greenhouse.

The experimental campaign has valued the turbo effect phenomenon (consisting of a substantial increase of temperature inside the greenhouse because of PCM) on several days during the year.

The phenomenon is joined with the reaching, inside the greenhouse, of the temperature that brings about phase changing of the salt. The solar radiation is fundamental for the “turbo effect”.

This effect could be very useful in architecture and agriculture if controlled and used when necessary.

High temperature reached during the experiment can’t be used for direct conditioning of environments or greenhouses. A good idea could be to use the surplus of produced heat, to store it during the hours when it exceeds and to release it when necessary, by means of an heat exchanger.

Figure 6: The greenhouse prototype built up in Carate Brianza.

A dynamic numerical simulation was performed on a box built in Verona in the Velux Italia factory using Structure/Envelope techniques. The aim of the experiment was to use PCM as heat source during the winter, increasing the inner temperature and making possible savings for the heating.

The box was divided into two parts: one room with a roof window containing a PCM blanket, one room without PCM blanket. The analysis on the prototype performed on March, April and December, pointed that the inner temperature of the room with the PCM-integrated roof window increases in some degrees, so the PCM could performs as alternative heat sources.

Figure 7 – The box built in Verona with roof windows containing PCM.

4. Conclusions

The issue of realising a better energy-performing residential building should be primary and each designer has to take it in serious consideration because being a designer - Architect or Engineer . nowadays contains strong ethics responsibilities.

Results expected are to re-interpretate good vernacular approaches to construction or introducing a new generation of buildings, also using new materials, that seem to be very revolutionary and could easily be almost totally served by clean energy sources (sun, wind, earth energy or other clean sources). This will allow to sink down drastically pollution and energy costs and respects in reality the demands of Kyoto protocol. A big field of extension of the concept is also possible in retrofit operation adding performances to the existing buildings and adapting them to present requests, without demolish them (of course if their condition is still good). In Italy, and Center-South Europe, high energy-efficient buildings need a good balance between the above mentioned strategies: insulation and thermal inertia. A great potential comes also from the application of new materials, like in example PCM for artificial thermal inertia, with interesting performances of energy savings.

Designers have to imagine a dynamical and active behaviour of buildings rather than passive according to the Darmstadt Protocol (thus energetically iper-conservative) or passive meaning obsolete and dispersive (as most of Italian buildings). The residential projects illustrated demonstrate how to design high energy efficient buildings using ordinary technology and performing a pleasant contemporary architecture: sustainable buildings don't mean to be aesthetically unsustainable.

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