The 4th international Symposium on HVAC
Beijing, China, October 9-11, 2003

HIGH ENERGY-EFFICIENCY BUILDINGS

Ettore Zambelli*, Marco Imperadori, Gabriele Masera

Department of Built Environment Science and Technology (BEST)
Politecnico di Milano, via Bonardi 15, 20133 Milano - Italy
e-mail: ettore.zambelli@polimi.it, atelier2@arcoquattro.it, gabriele.masera@polimi.it

Massimo Lemma

Istituto di Disegno e Architettura Urbanistica (IDAU)
Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona - Italy
e-mail: lemma@idau.unian.it

ABSTRACT

In cold, central European climates, hyper-insulated, heat-conserving buildings have proven a very effective way to reduce current energy consumption to 1/10th of a traditional house. Using dry, stratified building techniques (Str/En) allows to obtain quite easily the required thermal and acoustical performances, also enhancing the construction process and allowing for the final recycling of the components. In a warmer climate – such as the Italian one – a heat-conserving strategy has to be balanced against the potential overheating problems. Among the possible solutions, the use of building-integrated Phase Change Materials, which could create a "light thermal inertia" (that is, without heavy mass), was also investigated.

1. INTRODUCTION

Designing the building of the future has become the real challenge of today. This means, in general, not only designing high-tech, expensive and glazing rich buildings, but trying and give even popular buildings, low-costs housing, new technological practices to save energy and therefore to reduce air pollution. To assure to our cities and to our planet (the only one where we could live!) a future, we have to act today with real alternative solutions to sink down energy consumption of all our houses.

For the first time in Italy, the "*Passivhaus*" concept has been introduced for a building of four flats, realised in the North of Italy. The concept is based on hyper-insulation, which creates an adiabatic behaviour of the living box: this means no heat flows from inside to outside, except for the hygienic necessary air exchange. State-of-the-art building technologies and installations were introduced, such as heat pumps fed by photovoltaic energy and domotic control of all the devices. The house will be monitored from summer 2003 to summer 2004, in order to evaluate the actual performance of the building: outsource energy consumption will be almost reduced to zero.

The construction of the building is based on steel primary frames with independent interior and exterior envelopes. Between them, installations run freely and the whole gap is filled by mineral wool as acoustic and thermal insulation.

The *Passivhaus* concept – and in general the intelligent use of energy – could be even more suited to warmer climates (such as central and southern Italy), but these situation could require the presence of thermal inertia. This is possible without adding significant weight to the construction by using PCM's (Phase Change Materials) as an artificial inertial shield. Using the latent energy heat of PCM's (salts or paraffins) protects from overheating the outside lightweight cladding and the interior living spaces.

An evaluation campaign of these performances has been set parallel to the monitoring of the *Passivhaus* façade without PCM's. In these experiments, will be used Climsel 32 salt (32°C melting point) packaged in aluminium small bags. Future development of PCM's in building industry will need shaped-form PCM's to ease their application to the existing construction products.

Figure 1: the South front of the house: left, in its final appearance; right, during construction.

Figure 2: erecting one of the light portal frames.

2. FUNCTIONAL MODELS FOR SUPER-EFFICIENT ENERGY BUILDINGS

Designing a highly-efficient energy building requires a correct relationship to the local climate, which should be considered as a resource for the well being of the users instead of a hostile element.

The envelope of the building becomes an efficient filter between external and internal conditions, and has its own, intrinsic aptness for climatic control: this is the only way to reduce significantly the energetic consumption for winter heating and summer cooling, leaving to mechanical installations a role of fine-tuning the internal climate. The relationship with the local climate being so close, every climate-sensitive building has to be specifically designed. There are no general rules valid in every situation.

One of the most interesting experiences with respect to minimising energy consumption for winter heating is the German one: here, a ten-year practice shows that it is possible, with limited technological and economical investment, to achieve a reduction in current energy consumption as large as 90% in comparison with a traditional building. When the energy requirements for winter space heating are lower than 15 kWh/m² per year, the building is called a *Passivhaus*. The strategies adopted in Germany are mainly conservative, as in that climate the main issue is keeping heat inside the building.

On the contrary, the case study in Chignolo – the **first example** of such a low-energy building in Italy – was confronted with a milder winter and a hot and humid summer. The energetic strategy which was adopted was therefore more articulated:

- the **winter** strategy is based on the conservation of heat inside the building, by a very performing envelope (high thermal resistance of opaque and transparent parts + air-tightness) and mechanical ventilation with heat recovery, which is anyway needed to maintain a good indoor air quality. These strategies allow for the full exploitation of internal heat gains (coming from people, luminaries, appliances and so on) and solar direct gains, which are allowed inside the building through south-facing windows. The energy which may still be required to keep the interior comfortable can be supplied by heating the ventilation air through a small fan coil unit for each flat. These are fed with warm water produced by heat pumps for space heating and sanitary use;
- in **summer**, overheating is prevented by the effective shading of south-facing windows and by natural cross-ventilation. PV panels act as fixed overhang and protect the south side by direct solar radiation, while each window has a louvre system that can be adjusted by the users. In the event of high outside temperatures, fan coil units can be fed with cold water produced by the heat pumps. The roof is also naturally ventilated to prevent heat from being transmitted to the attic.

Figure 3: all the building components rely on Str/En light, layered technologies.

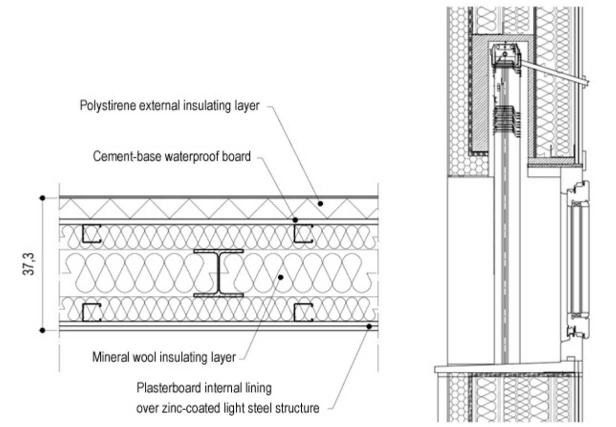

Figure 4: details of the hyper-insulated external envelope.

3. THE 1ST SUPER-EFFICIENT ENERGY BUILDING IN ITALY: THE CASE STUDY OF CHIGNOLO D'ISOLA

The building of Chignolo d'Isola stands in a residential area and is composed of four flats, two 60 m² and two 120 m² large. Besides addressing the question of running energy needs, the building in Chignolo was realised with an eye on its performance all over the life cycle and on the well-being of its users: this is why it makes large use of dry building techniques (Structure/Envelope, Str/En). This allows, first of all, for a very high internal comfort, as each apartment is a kind of independent "box" inside a larger "box" which is the external envelope of the building. Moreover, Str/En techniques present other different advantages. First of all, the construction operations are quicker, safer and cleaner than with traditional techniques, as the components are light, easy to work and there are no delays due to wet operations. The energy needed for construction, which contributes significantly to the overall embodied energy, is much lower in comparison with a traditional building (the house in Chignolo is eight times lighter than a comparable, massive one). Maintenance operations will also be greatly facilitated, as the building elements have reversible connections that allow for the substitution of parts and the inspection of plants running in the walls. At the end of its life, the building will be easily dismantled, with a selective, low-energy process, which will allow for the reuse, or the recycling, of its components.

Structure

The structure of the building is composed by rolled-steel HEA 140 columns, which all but one stand on the perimeter of the building in order to allow the future flexibility of the internal distribution. The border beams of the intermediate floors and of the roof are made of cold-formed, C-shaped elements (350×70×35 mm, 7 mm thickness), where the joists of the floors and the sandwich panels of the roof are fixed. The structure (columns and beams) was assembled on the ground and subsequently erected with a small crane. The wind bracing of the structure in the vertical plane is realised through steel elements (60×8 mm flat ones, or L-shaped 50×75×7 mm ones), while in the horizontal direction it relies on the plate behaviour of the dry floors.

Technological system

As regards building technology, it is interesting to stress that Str/En technologies allow designing the components for every single situation, by adding layers where higher performances are needed.

Vertical enclosures: perimeter walls are made up of two independent shells, which completely enclose the columns. Both envelopes stand on a zinc-coated steel stud structure, 75×50×0.6 mm large – the technique derives from the well-consolidated one of plasterboard walls. The external board is made with a fibre-reinforced, light cement board, 12.5 mm thick, waterproof and shock-resistant. A continuous layer in expanded polystyrene was put on its external face and finished in render. The internal shell is a standard plasterboard wall on a steel sub-structure, including a vapour barrier layer in aluminium. The resulting cavity was filled with mineral wool: the total thickness of the insulating layer reaches 37 cm, with a thermal transmittance U lower than 0.1 W/m²K. The external envelope is thus practically adiabatic and the energetic flow is concentrated on the transparent components, with a U-value of 1.1 W/m²K.

Intermediate floors: the structure of the floors is composed of C-shaped, cold-formed steel joists, 250×50×20 mm in dimension and 2 mm in thickness, which are bolted to the border beams by steel plates in order to have a reversible connection. The load-bearing part of the floor is completed by waterproof wooden panels, 28 mm thick, screwed on the joists in order to take part in the horizontal wind bracing of the floor. The resistance to residential loads is thus guaranteed with a weight of just 40 kg/m². Over the load-bearing components, the other layers – required to meet design performances – were simply laid by gravity, without a single drop of water being used. These layers are an insulating one in polystyrene 20 mm thick, an acoustic one in mineral wool 10 mm thick, and two mineral boards which constitute the rigid layer where the flooring is laid. Even though the floor is extremely light (100 kg/m²), the in-situ acoustical proofs have shown an insulation of 72 dB to aerial sound and a level of impact sound lower than 42 dB.

Roof: the copper-finished, ventilated roof was built by combining existing industrial products in innovative ways: in particular, water-proofing and ventilation were obtained by directly fixing a corrugated sandwich panel to the structural elements. The ridges create the space where air can flow by convection, and constitute the surface for fixing the wooden boarding where copper sheets are laid. A suspended plasterboard ceiling was installed below the insulated sandwich panels: the wide resulting cavity was filled with 34 cm of rockwool, in order to dramatically reduce winter heat losses and the incoming heat flow in summer. The rooms in the attic get their natural light from two couples of windows in the north and south façades and from eight skylights, with triple glass and U = 0.80 W/m²K.

Figure 5: Str/En technologies allow for the easy flowing of ducts in the cavities of walls and floors.

Figure 6: the tecnological installations at the underground level: above, the ventilation unit with heat recovery from exhaust air.

4. INSTALLATIONS

A high energy-efficiency building requires the technological installation design to be strictly integrated to the architectural and constructional issues, as it is only a holistic process that can take to a building which is in harmony with the environment and its users. The dramatic reduction of current energy needs, which is obtained through simple, passive techniques, allows the use of small-scale, advanced system, using to large extents renewable energy.

In Chignolo, the production of hot water, for both heating and domestic use, and of cold water, for summer-time cooling, completely relies on a couple of heat pumps, working with low temperatures and small power. The combined use of super-insulation and heat pumps, doing completely away with traditional combustion plants, avoids the emission to the atmosphere of some 13,000 kg CO_2 with respect to a comparable, traditional building.

Ducts and runs flow easily in the central wall of the building, and are finally distributed to the various flats through the cavities in walls and false ceilings. No pipes are installed between the layers of the floor, in order to maintain a high acoustical performance. Thanks to the use of Str/En building techniques, all the technical installations are easy to inspect, maintain and substitute.

Table 1 – Design data.

Shape factor	0.576	Degree days	2,395
Winter internal temperature	+20°C (+1°C)	External minimum temperature	-6°C
Winter internal HR	Optional control	Winter external HR	90%
Temperature of water for heating	+45/40°C	Temperature of water for DHW	+60/50°C
Working time	14 h/day		
Thermal power for heat losses	5.5 kW	Thermal power for natural air change	1.6 kW
Total thermal power	7.1 kW	Thermal power for summer cooling	16.5 kW
DHW production	600 l/day	Ventilation exchange rate	0.6 volumes/h

The functional scheme of the integrated ventilation and climatisation plant includes mechanical ventilation with central heat recovery from stale air, which allow the hygienic air change rate inside the flat without losing heat in the process. Local temperature in each flat can be adjusted by a small fan-coil unit, which heats or cool the internal air, according to the season.

These units are fed by water – both hot and cold – produced by the two reversible, air-to-water heat pumps, which also produce domestic hot water (DHW) on a separate circuit. This is possible also during the summer, when the condensation heat from the chiller is completely re-used for DHW production. The use of heat pumps, thanks to the very low energy needs, completely eliminates the need for fuel-consuming traditional installations. The pumps use propane gas as cooling fluid, so avoiding the use of harmful, ozone-depleting CFC gases. Every heat pump has a thermal power of 9.9 kW in winter and 12.5 kW in summer, while the overall electric power used by the two pumps together is 9,000 kWh per year.

Table 2 – Heat pump characteristics.

Thermal power with external temperature –5°C	2 × 9.9 kW
Maximum cooling power with external temperature 35°C	2 × 12.5 kW
Nominal absorbed electrical power	2 × 3.9 kW
COP in heating or DHW working mode	3.6
COP in heating and DHW working mode	3.8
EER in cooling only working mode	3.2
EER in cooling and DHW working mode	6.8

The mechanical ventilation system of the flats is based on a central unit for air recirculation, with a heat recovery system with an efficiency of 74%. This unit takes fresh air outside the building, filters it, drives it through the heat exchanger – where it acquires the sensible heat of the outgoing stale air – and distributes it to the different flats. The total quantity of treated air is 600 m^3/h. In summer, the ventilation unit can by-pass the heat exchanger to improve the night cooling of the flats by using fresh external air (only when its temperature is lower than the internal one). Exhaust internal air is extracted from kitchens and bathrooms, so that unpleasant smells are eliminated before they diffuse in the nearby rooms.

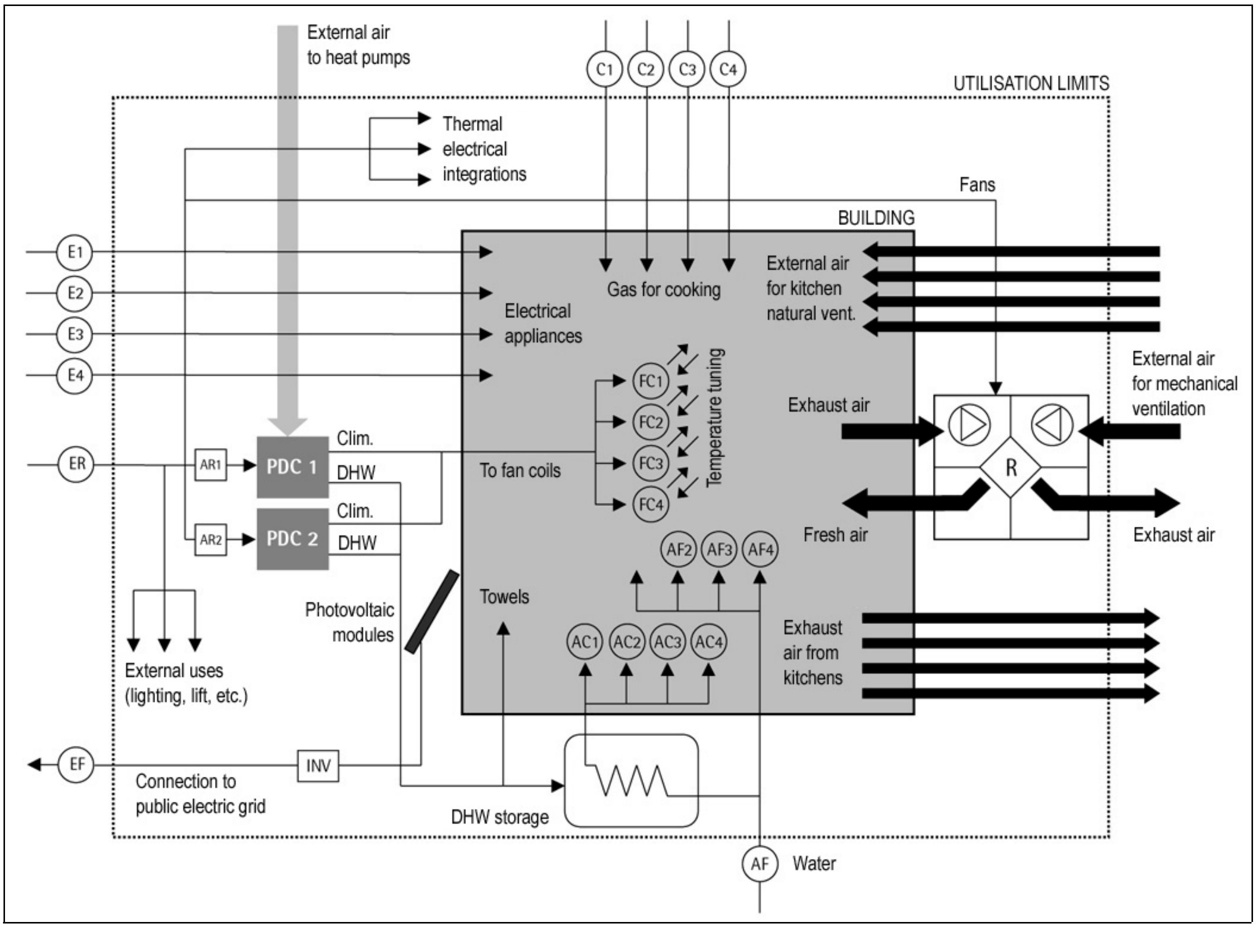

Figure 7: Functional model of the technological installations in Chignolo.

Inside each flat, a very advanced domotic system was installed. This links and co-ordinates all the systems of the house, such as artificial lighting, external shading, internal air thermostat, security, and so on. On the one hand, this system allows for an automatic management of the house in different situations, tuning the internal climate even when the inhabitants are not present; on the other, it allows to remote control the various components. The system, which is modular and can be expanded and upgraded, can also link domestic and telecommunication appliances.

Clean energy

A high energy-efficiency building allows for the effective exploitation of renewable energy sources, which are available in limited quantities and, in a traditional building, cannot contribute significantly to the overall energetic balance.

In Chignolo, a grid-connected photovoltaic (PV) system produces electricity. It is composed by a field of 36 modules (31 m²) which give a nominal power of 3.96 kW_p. PV panels are installed on the south façade, which receives direct solar radiation for most of the day, without obstructions, and are tilted 35° on the horizontal by a system of aluminium elements cantilevering from the building. Every single-crystalline solar cell module (0.87 m²) guarantees a peak power of 110 W_p, with a nominal efficiency of 14.6%. As the expected production is 3,600 kWh per year, 40% of the total energy for climatisation and DHW production (that is, the energy required by the heat pumps) derives from a completely renewable and non-polluting source.

5. PCM'S IN OUTSIDE WALLS

Stratified layer lightweight building systems, based on Structure/Envelope (Str/En) construction techniques, proved highly performing in continental climates (in general, hyper-insulated buildings are very suitable for mainly cold climates but could suffer from overheating in warmer contexts).

The lack of inertia, due to the light weight of the building components, has brought to Phase Change Materials (PCM) in outside cladding, in order to give artificial thermal inertia to the building. PCM's allow to sink down the temperature of the outside walls by melting and using their own latent heat to store energy and delay heat transmission.

This solution is all the more interesting for climates where the winter insulation should not be so high, and where in summer the light weight wall would need a thermal inertial shield, to protect itself from overheating and sun irradiation. Following this inputs, a parallel campaign of testing and monitoring has been set up both on the wall of the house realised in Chignolo d'Isola and on a number of test boxes with walls mixed by PCM.

This operation is a EU-funded research called **C-TIDE** (Changeable Thermal Inertia Dry Enclosures) and is a *Craft* project inside the Fifth European Framework Program (FP5) aimed at fostering practical solutions for sustainable development. Partners of the research are PCQ, formed by Politecnico di Milano (BEST Department), University of Ancona (IDAU Department) and Politecnico di Torino, University of Gävle (Sweden) and 3 SME (Small and Medium Enterprises): Vanoncini (I), Poggi (I) and Climator (S).

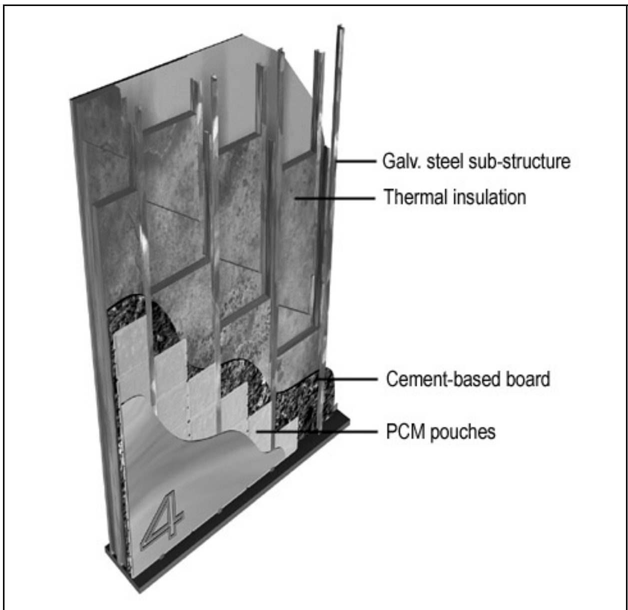

Figure 8: Rendered view of the reference PCM wall to be tested in Ancona.

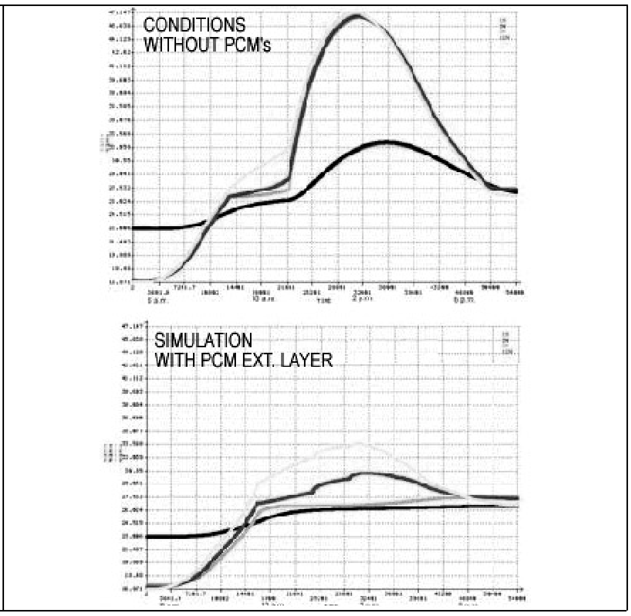

Figure 9: Theoretical simulation show that an external PCM layer helps smooth internal temperature swing in the reference box.

As one of the partners (Climator) is a producer of PCM's based on eutectic salts, these will be used for the test campaign. This, starting 1st May 2003 and ending 15th September 2003, will evaluate the optimal position and quantity of ClimSel 32 salts (melting temperature 32°C) as outside shield in ventilated façade, in comparison to the one realised in Chignolo's *Passivhaus*, through a series of different reference boxes. The experimental field will be in Ancona, in central Italy, where the summer climate will create heavy overheating situations on the external face of the envelope components.

During the experimental campaign, samples of sandwich metal panels with PCM layers will also be tested, to provide artificial thermal inertia also to these components. For this case, shape-formed PCM's will be suitable and contacts with Tsinghua University (China) will allow testing this new solution.

After evaluating all these performances for summer protection, a wintertime experimental campaign on the same boxes will start to see the effects of the heat storage properties of PCM's during the heating season (2003-2004). In this case, PCM's will be placed both on the external façade (connected to heat vectors like water running in transmission tubes) and in the internal layers, to use renewable energy or low-cost energy during the night (which is off-peak time). The application of shaped-form PCM's in floors, ceilings or internal walls would be suggested and suitable.

CONCLUSIONS

Building the first *Passivhaus* represented a big step forward in the Italian construction sector. In fact, it shows how it is possible to practically tackle the problem of energy consumption through hyper-insulated skins, high-performance windows and integration of installations (heat pumps) with renewable energy sources (solar PV panels).

The design of building technologies – based on the Structure-Envelope concept – and installations ran parallel, were followed by scientists right from the beginning and will be evaluated during the next 1-year monitoring campaign.

A further development of intelligent energy use in houses is foreseen with the introduction of layers integrating PCM's in dry, stratified building technologies. This could help both to delay overheating in façade and roofs and also to store energy in internal partitions (floor or walls) during the winter.

A great potential for this application, which will be tested in an experimental monitoring campaign, is seen in shaped-form PCM's, which could more easily fit together with the ordinary building construction elements now on the market.

REFERENCES

[1] Zambelli, E.; Imperadori, M.; Vanoncini, P.A. – *Costruzione stratificata a secco*, Maggioli editore, Rimini 1998.

[2] Imperadori, M. – *Le procedure Struttura / Rivestimento per l'edilizia sostenibile*, Maggioli editore, Rimini 1999.

[3] Imperadori, M. – *Stratified layer building systems*, Proceedings of CIB World Building Congress, Gävle, 1998.

[4] Lemma, M.; Imperadori, M. – *Phase Change Materials in concrete building elements: performance characterisation*, Proceedings of XXX IAHS World Housing Congress, Coimbra, 2002.

[5] Zambelli, E.; Masera, G. – *Sustainable settlement in Mondovì: new standards for Italian housing*, Proceedings of XIX International Conference PLEA – Design with the environment, Toulouse, 2002.

[6] Feist, W. – *Das Niedrigenergiehaus*, C. F. Müller, Heidelberg 1998.

[7] Feist, W. – *Das Passivhaus*, C. F. Müller, Heidelberg 2000.

[8] Graf, A. – *Das Passivhaus: wohnen ohne Heizung*, Callwey, München 2000.

[9] *Sommerliches Innenklima im Passivhaus-Geschoßwohnungsbau*, CEPHEUS report no. 42, Passivhaus Institut, Darmstadt 2001.

[10] Feustel, H; Stetiu, C. – *Thermal performance of Phase-Change Wallboard for residential cooling*, published in CBS Newsletter, Fall 1997.

[11] Rudd, A. F. – *Phase Change Material Wallboard for distributed thermal storage in buildings*, published in the ASHRAE Transactions: Research, Volume 99, Part 2, paper #3724, Atlanta 1993.