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Extended summary

Experimental and analytical study of high energy efficient envelopes in Mediterranean climate

Curriculum: Architettura, Costruzioni e Strutture

Author

Elisa Tomassoni

Tutor

Prof. Alessandro Stazi

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Abstract. This research is focused on the study of the behavior of several envelopes with high energy performance in a Mediterranean climate, in terms of energy saving, thermal comfort and sustainability.

The high energy efficient buildings attracts considerable attention since the recent Directives 2010/31/EU and 2012/27/EU set as an objective the standard of *nearly zero-energy building* for new constructions. The German *Passivhaus* standards (characterized by super-insulated wooden envelopes) represent a good model to be followed in cold climates while the adoption of this model in Mediterranean climates causes summer overheating problems. The new Directives recently highlighted the importance to consider the specific climate, however the development of constructive techniques for energy efficient envelopes suitable for a Mediterranean climate still remains an open question.

Therefore the aim of the study is to verify, analytically and experimentally, the performance of super-insulated wooden envelopes in residential buildings located in hot-summer temperate climates and to compare them with different types of construction techniques characterized by higher thermal inertia, commonly adopted in the Mediterranean area. Moreover it was possible to evaluate the behavior of a mixed-weight technique identified as a possible solution to the summer overheating problem since, on the inner side of the lightweight envelope, a massive panel was adopted.

The method adopted set up an integrated strategy between monitoring and calibrated simulations on experimental data and involved the simultaneous analysis of several aspects such as energy performance, comfort and environmental-economic sustainability through a multidisciplinary approach. The study is also carried out by means of the adoption of different evaluation methods for each analyzed aspect as well through a series of parametric analyses to generalize the results to various climate zones, use patterns of plants and passive cooling techniques.

The study allowed to verify the presence of overheating phenomena in lightweight envelopes and to demonstrate that such problem can be solved or reduced through the adoption of appropriate passive strategies, such as the increase of the thermal inertia on the inner side and the night ventilation of the environments.

Keywords. energy saving, environmental sustainability, experimental study, internal thermal inertia, thermal comfort.

1 Problem statement and objectives

The high energy efficient buildings attract considerable attention since the recent European Directives 2010/31/EU and 2012/27/EU [1-2] on the energy performance of buildings set as an objective the standard of *nearly zero-energy building* for new constructions, making the experimental study on real cases an interesting issue. The German *Passivhaus* standards, developed in Germany since the early 90's, generally characterized by very well insulated and airtight wooden envelopes, whilst providing the constructive tendency implemented in Italy in response to the EU regulations on energy saving (Directive 2002/91/EC [3]), represent a good model to achieve these new requirements of high energy efficiency. However these standards focus on winter heating consumptions and they are mainly applicable in cold climates like those of Northern Europe. In Italy the adoption of these standards (D.Lgs.192/2005 [4] and subsequent decrees) led to the construction of buildings with super-insulated envelopes and with super-glass that act as thermal barriers with respect to the external climate and that behave as "thermos" preventing, regardless of the indoor climate, the dispersion of heat flow. For that reason, in many cases, these envelopes have caused discomfort problems due to summer overheating of the environments leading to the consequent need to attribute the regulation of indoor comfort to expensive conditioning systems.

The new European Directives [1-2] and the standard EN 15251 [5] recently highlighted the importance to consider both specific local climate and indoor comfort in the building envelope design, enhancing the summer thermal performance. However the development of constructive techniques for energy efficient envelopes suitable for a hot-summer Mediterranean climate still remains an open question. The daily and seasonal temperature variations typical of the Mediterranean climate infact makes it difficult the choice of design strategies and envelopes techniques.

In international literature the most common studies on the theme are generally analytical and aimed at the definition of project specifications [6-7] or evaluation methodologies [8-9], or focused on the determination of the performance of case studies [10]. Moreover most of the research working about passive houses focuses on the optimization of winter energy performance, as this building was originally conceived for cold climate with the winter heating priority. Few studies focus on summer behavior, and in particular on indoor thermal comfort condition highlighting the summer overheating phenomena in Mediterranean climates [11-12]. Nevertheless experimental studies and real data on the overheating problem, investigated only analytically by the aforesaid researchers, are very rare.

Experimental studies mainly concern passive buildings with the aim to verify in-situ consumptions and comfort in cold North-American and North-European climates [13-14] or in extreme arid climates [15-16], but only rarely these identified studies are based on complex simulations that are calibrated on experimental data [15]. The lack of experimental studies in hot-summer Mediterranean climates (characterized by considerable seasonal climate variability and high diurnal temperature variation) is probably due to the fact that, as learned from the historic traditional architecture and demonstrated from international studies [17-19], appropriate levels of comfort inside the buildings can be reached only through the use of massive envelopes that adapt their behavior to the environment in a dynamic way (with a deep relation with the specific climate). In the case of current envelopes in which these masses must be necessarily combined with considerable insulation thicknesses, to optimize comfort the mass should be placed on the inner side, as demonstrated by several authors [20-23].

The studies carried out on these high energy efficient buildings, as well as being generally based on analytical assessment to verify the energy consumption, usually do not consider the aspects related to the life cycle of buildings. Because of this, as demonstrated by several studies in literature [24], in some cases it could be generated the contradiction to obtain a better energy performance while more emissions in global terms are produced due to the increase in energy costs of building construction. This creates the need to focus not only on energy savings but also on aspects related to the life cycle of material and construction techniques adopted. The importance of an integrated approach of this type is also underlined by the recent EU regulations [1, 2] and by the program Horizon 2020.

There are several studies on the life cycle assessment and economic evaluation of different buildings or constructive systems [25-35] that generally demonstrate that lightweight solutions should be preferred [27-31]. Nevertheless this type of envelope, even if ensuring a low environmental impact, could not have a positive incidence on energy saving and on other aspects such as comfort [36] or cost effectiveness. For that reason the integrated study of the impact on different and conflicting aspects, such as energy saving, comfort, environmental sustainability and cost-effectiveness, requires a multidisciplinary approach addressed by numerous authors [29, 32-35] but very rarely studies have been performed on the simultaneous investigation of all the highlighted aspects.

The aim of the following research is to evaluate, analytically and experimentally, the performance of super-insulated wooden envelopes in high energy efficient residential buildings located in a Mediterranean hot-summer climate, in terms of energy performance, thermal comfort and sustainability. These envelopes are compared with different types of construction techniques characterized by higher thermal inertia commonly adopted in the Mediterranean area. Moreover it was possible to evaluate the behavior of a mixed-weight technique, identified as a possible solution to the summer overheating problem since on the inner side of the lightweight envelope a massive panel was adopted. The methodology combines experimental analysis (in various seasons) on different case studies and numerical simulations on calibrated models, involving a multidisciplinary approach that integrates simultaneously energetic, comfort, environmental and economic aspects.

2 Research planning and activities

The research developed in analytical and experimental phases on various case studies located in a hot-summer Mediterranean climate (type *Csa*, Köppen classification).

case study 1. 3 low-energy multi-family residential buildings with different external opaque envelopes (masonry, wood-cement and wood) to be constructed in Ancona:

- energy performance through analytical models in semi-stationary and dynamic regime;
- comfort through dynamic simulations using different comfort models;
- environmental sustainability through Life Cycle Assessment and Life Cycle Cost.

An in-depth study of the worst case (wood) was performed. The following activities involved experimental studies on 2 wooden envelopes and further numerical simulations on calibrated virtual models to individuate optimization strategies.

case study 2. 1 Passivhaus located in Porto Sant' Elpidio, Fermo:
– summer monitoring;
– energy performance through calibrated models in semi-stationary and dynamic regime;
– comfort through dynamic simulations using different comfort models;
– environmental sustainability through Life Cycle Assessment and environmental cost.

case study 3. 1 energy-efficient semi-detached house, optimized thanks to the introduction of a massive panel on the inner side, located in Falconara M., Ancona:
– winter monitoring and simultaneous summer monitoring with a masonry building;
– energy performance through calibrated models in semi-stationary and dynamic regime;
– comfort through dynamic simulations using different comfort models.

Each activity has been developed in detail according to the following methods:

2.1 Experimental methods

Experimental analyses consisted of a series of monitoring campaigns on the case studies. The surveys were carried out during summer and winter (30th July - 3rd September 2012 for case study 2; 24th February - 3rd March and 11st - 21st July 2011 for case study 3) comparing different exposure and building levels and various use patterns of the systems (continuous/intermittent heating, natural/mechanical ventilation).

The measurements were performed according to ISO 7726:

– outdoor environmental conditions through a weather station with a global radiometer, a thermohygrometer and a combined sensor for wind speed and direction;
– indoor climate conditions through indoor microclimate stations including a globe thermometer, a psychrometer and hot-wire anemometers;
– envelope thermo-physical behavior through dataloggers coupled to thermoresistances and heat flux meters;
– specific tests on the envelope as blower door test (EN 13829) to quantify the airtightness, thermo-graphic survey (EN 13187) to identify the thermal bridges, in-situ measurement of thermal transmittance (ISO 9869).

The experimental activities included also the evaluation of perceived comfort by occupants on a subjective scale of thermal sensation at fixed time intervals according to EN 15251. The detected experimental data made it possible to obtain real informations on the performance of the case studies, to collect data useful for calibration of the analytical calculation models and to evaluate the thermal comfort according to ISO 7730 and EN 15251.

2.2 Analytical methods

Numerical simulations were performed in dynamic state (EnergyPlus software) on virtual models of the case studies calibrated with experimental data or, for the buildings still to be constructed, on models set up with the semi-stationary one, complying with UNI/TS 11300. Calculations were run to compare the super-insulated lightweight envelopes with construction techniques characterized by higher thermal inertia (masonry with external insulation layer, wood-cement hollow block with insulation in the cavity). The analyses involved all the construction components (external walls, floors, internal partitions) and subsequently they focused on the external vertical opaque envelope considering increasing levels of thermal inertia on the inner side placed adjacent to the living areas, using thickness and materials which provided the same stationary thermal transmittance. The study is also carried out through the adoption of different evaluation methods for each analyzed aspect (semi-stationary and dynamic energy analysis; different comfort models; various LCA methods; financial and environmental costs) and it involved a series of parametric analyses to generalize the results to various seasons, climate zones, use patterns of heating/cooling plants (continuous operation/intermittent use with different time slots) and passive cooling techniques.

2.2.1 Energy performance

The energy performance has been studied using analytical models both in semi-stationary and dynamic conditions (Termo and EnergyPlus programs, UNI/TS 11300) and the detailed analysis of thermal bridges (Therm software, ISO 14683).

2.2.2 Thermal comfort

Indoor thermal comfort conditions were calculated for the different cases considered thanks to the analysis in dynamic conditions (EnergyPlus software) and using appropriate methods (Fanger's PMV - ISO 7730 and adaptive comfort model - EN 15251). The summer comfort was also detailed with an in-depth study of different apartments (in multi-residential buildings) and rooms analyzing also different levels and exposition to study the relative impact of their specific features and the influence of various cooling strategies.

2.2.3 Environmental sustainability

The environmental sustainability has been performed by means of the Life Cycle Assessment (SimaPro software, ISO 14040 and ISO 14044) with Eco-indicator 99, CED, EPS 2000 and IPCC 2001 GWP methods, as well through the Life Cycle Cost considering financial and economic costs (Net Present Value calculation).

The *environmental analysis* of buildings was carried out to compare the environmental burdens in envelopes characterized by different construction techniques in terms of environmental impacts, energy demand, environmental costs and CO_2 emissions throughout their 75 year life-span. The unit processes examined involves three life cycle phases: pre-use (construction, transport), use (maintenance, heating/cooling energy) and end-of-life (recycling, final disposal).

The *financial costs* were calculated through the analysis of Financial Net Present Value (NPV^f) during 75-year service life considering construction costs, maintenance and replacement costs, operation costs for heating and cooling. The *economic costs* were calculated through the analysis of Economic Net Present Value (NPV^e) considering, in addition to the costs necessary to calculate the NPV^f, the environmental cost assessed by EPS 2000 and Eco-indicator 99 methods, made comparable through appropriate conversion factors.

3 Analysis and discussion of main results

The comparison among different construction techniques, lightweight and massive, through a multidisciplinary study, has shown that there is not an absolute optimal solution, depending on what issue the designers consider to be most relevant among different and often conflicting aspects such as winter and summer consumptions, comfort conditions in winter, in intermediate seasons and in summer, environmental impacts and cost effectiveness. The choice among the different prospects should depends on the specific case study (building shape factor, building energy efficiency level, heating/cooling operating conditions, etc.) and on the specific climatic location. Also the choice of the calculation method adopted to approach the study could influence the result, so the adoption of multiple methods for each analyzed aspect (semi-stationary and dynamic analysis; PMV and adaptive models; Eco-indicator 99, CED, EPS 2000 and GWP methods; financial and environmental costs) could be useful to analyze various implications on energetic, comfort and sustainable balance of the building.

3.1 Energy performance

In high energy efficient buildings the small difference between consumptions of lightweight and massive envelopes, both in winter and in summer and both with continuous and intermittent operation, determines that the comfort and environmental aspects prevail on energy issue.

3.2 Thermal comfort

In *winter* the experimental analyses on the wooden envelope with an inner massive layer showed the efficacy of the internal inertia mostly with an intermittent pattern of the heating system, since the heat stored during switch-on times is released gradually during the day.

The numerical analyses of lightweight techniques compared with massive ones showed similar indoor comfort conditions even if the wooden envelopes responds more quickly to the external variations producing greater fluctuations of inside temperatures and causing slightly less comfort.

In *summer* the experimental analyses on passive building showed that the presence of a lightweight and super-insulated envelope together with the use of high-performance and sealed windows determines a considerable overheating of the indoor environments, manly at the upper levels. The very low heat fluxes of walls and roof with constant daily fluctuations and the steady inside temperatures respect to the variations of the outdoor dry bulb temperature demonstrated the "thermal barrier" effect of the envelope. The only heat dispersions of this envelope are through the ground floor that determines a noticeable air stratification on the lower level. The measurements on a lightweight envelope optimized thanks to the introduction of an internal massive finish panel showed a reduced percentage of overheating hours with small temperature fluctuations and low heat fluxes.

The numerical analyses demonstrated that in all climates the best or worst technique varies according to the considered period, the central days of the summer or the end of the hot season, making it possible to identify a day of trend inversion. In the central days of the summer lightweight techniques present higher and less stable temperatures, and consequently worst comfort conditions, while at the end of hot season the wooden envelope cooling itself more rapidly respect to the solutions that have a greater seasonal inertia. Nevertheless in *extreme climates*, with high temperatures and high diurnal temperature variation, the difference between lightweight and massive envelopes is reduced, demonstrating the lower importance of adopting a high-inertia technique. In *Mediterranean climate*, instead, the efficacy of high-inertia becomes more relevant making the optimization of lightweight envelopes possible thanks to the introduction of a massive layer (clay board, wood-cement panel, brick, ...) in the inner side. The internal inertia allows the heat, stored during the hot-test hours, not to be released instantaneously towards the internal environment keeping indoor temperatures lower. The adoption of a night-time ventilation further reduces the temperatures, ensuring good comfort conditions.

3.3 Environmental sustainability

The LCA analysis applied to the buildings with high energy performance in Mediterranean climate and extended over a 75 years lifetime showed the importance of the "construction" phase and, consequently, the great contribution of the impacts resulting from the choice of materials and construction techniques. In these buildings the higher embodied burdens, mainly due to the super-insulation of the envelope, were compensated by the remarkable operational energy saving. The adoption of lightweight envelopes, rather than massive ones, ensures lower environmental impacts and economic costs throughout the entire life cycle thanks to the adoption of ecological materials and dry techniques that reduce the use of the concrete and the consequent release in the environments of toxic substances and inorganic particles, harmful for the human health. The transport from distant places (since the wood is not a locally available material) doesn't seem a great problem for its low incidence respect to the entire life cycle. However the vast use of wood threatens the ecosystem quality highlighting the importance of recycling potential and making an intelligent wood resources policy necessary to favor the regeneration of the environment.

4 Conclusions

This research has provided a detailed analysis of lightweight and super-insulated envelopes in high energy efficient residential buildings located in a hot-summer Mediterranean climate. The study was carried out by means of thermal monitoring on real buildings as well through numerical simulations in dynamic state to generalize the results. Thermal behavior and energy performance of the envelopes, indoor thermal comfort levels, environmental impacts and costs were investigated, comparing the lightweight solution with different types of construction techniques characterized by higher thermal inertia and adopting multiple assessment methods for each analyzed aspect.

The study allowed to verify the presence of overheating phenomena in lightweight and super-insulated envelopes and to demonstrate that such problem can be solved or reduced through the adoption of appropriate passive strategies, such as the increase of the thermal inertia on the inner side by means of the introduction of an internal massive layer such as brick counter-walls or dry clay interior finish panels and the use of the night natural ventilation of the indoor environments. The combination of these strategies enables a considerable reduction in consumptions, bringing the passive buildings near to *nearly zero energy* standard required by the EPBD. The lower environmental impacts and economic costs of super-insulated lightweight envelopes, respect to massive ones, through the entire life cycle also contribute to achieve these new requirements of high energy efficiency and environmental-economic sustainability, even if in the construction phase the super-insulation of the envelope, while minimizing costs during the winter use, could lead to an increase in energy costs of building construction.

References

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