Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Energy, technical – constructive and economic optimization of retrofit solutions for single-family houses and multi – storey buildings: analytical and experimental evaluation

Curriculum: Architectures, Buildings and Structures

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Date: 30-01-2014

Abstract. The existing building energy restoration provides a great energy saving potential for our country. According to Directive 2012/27/EU the aim of this study is to identify the most suitable thermal insulation technique in a Mediterranean climate and define the relative constructive and economic details for both single-family houses and multi-storey buildings.

In the first case, the study involved an experimental investigation on a single-family house (characterized by walls with different thermal inertia) and analytical dynamic thermal simulations to compare different retrofit measures and extend the study to new building envelopes. The different solutions were compared from the point of view of comfort, energy savings and global cost. The study shows that the most suitable intervention is the introduction of an insulation layer on the external side of the building envelope leaving an adjacent air gap alternatively sealed in wintertime and ventilated during the summer thus allowing the existing massive envelope to maintain its seasonal dynamic behaviour. This technology could be advantageously adopted on both walls and roof.

In the second case, the study was carried out on an apartments block constructed in the 1982s adopting a vertical envelope made by precast concrete panels with glass wool insulation placed on the room side. The research included laboratory tests on insulation samples, detailed on-site

monitoring and dynamic thermal simulations to assess the impact of different retrofit scenarios by comparing from the point of view of comfort, energy savings and global cost. The results show that the glass fibres has a partial crystallization and aging resulting in worsening of 5 – 10% of the wall thermal transmittance. The preferable retrofit was found to be the introduction of an insulation layer on the external side of the walls leaving an adjacent air gap ventilated during the summer and the maintenance of the existing inner insulation layer.
In both cases, details of the preferable retrofit solution are presented.

Keywords. Actual envelope performance, Dynamic thermal insulation, Experimental study and parametric analyses, Integrated evaluation of energy saving comfort and global cost, Most effective energy retrofit solutions.

1 Problem statement and objectives

The existing building energy restoration provides a great energy saving potential for our country where most of building envelopes are lacking of thermal insulation or with small insulation thicknesses.

The energy saving regulations developed on the last years have focused their attention on the problem of heating consumption reduction without considering that in Mediterranean climates, characterized by considerable climatic variability, the predominant need is to guarantee comfort during the warm period. So, even in such climates, considerable thicknesses of insulation layer were adopted, both in new construction and in buildings retrofit, regardless of the relative position between mass and thermal insulation.

However many authors have already shown that the insulation position and the thermal mass has a great effect both on heating and cooling consumptions [1, 2] and on indoor comfort [3-5] with a different and often opposite effect on the various aspects. So that the better choice identification is still an open question and it could result to be with internal insulation (in studies focused on winter performance [6, 7]), external insulation (in studies focused on summer performance [8 – 10]), insulation placed on both sides of the wall [11 – 13]. Very rarely studies were performed on a multidisciplinary simultaneous evaluation of the different aspects (consumptions, comfort and costs).

During hot seasons, the considerable thickness of insulating material (imposed by energy savings standards) creates a thermos effect leading the problem of internal spaces overheating [14]. In such period, building envelopes with heavy "storing" masses that dynamically adapt to seasonal variations was found to be preferable either with not insulated configurations [15 – 16] or with seasonal deactivation of the insulation layer [17, 18].

Recently the European regulations on energy saving [19, 20] have faced the comfort issue stressing the importance of referring to representative buildings of the local climatic conditions and typical in terms of geometry, systems and energy performance.

The *single-family architectures*, belonging to the Italian regional tradition, are an example of a very close relationship with the specific climate and many authors have demonstrated their ability to provide interior comfort through passive strategies [21 – 23]. It is therefore important to analyse and quantify the effects on comfort and consumption of traditional building systems, in order to identify the most suitable retrofit intervention on the existing non-insulated buildings belonging to local tradition.

On the other hand, there are *multi storey buildings* owned by public bodies characterized by low insulation level. For this kind of buildings, it is important to assess the state of conservation and the actual performance of the existing insulating materials to identify the most effective retrofit intervention. In recent years, several experimental studies were carried out on the hygro-thermal performance of fibrous insulation materials. Most of these studies are focused on laboratory measurements [24 – 26]. Much less numerous are the studies aimed at the long term assessment of the building behaviour in on-site conditions (over a 2-year [27] or 4-year [28] period). Very few are the studies about the assessments of insulated enclosures with a longer duration [29, 30]. Besides there are no multidisciplinary studies that combine different approaches, also including comfort and costs evaluation, and that take into account the actual enclosure performance to identify the most suitable retrofit intervention.

The main aim of the present study is to contribute to the debate by identifying the most suitable envelope stratigraphy in a Mediterranean climate by combining (differently from the other studies) the sustainability with comfort issues. To reach this goal two multidisciplinary studies were performed:

– an experimental investigation on a traditional detached building; analytical simulations of comfort level and energy consumptions to define the most beneficial mutual position between mass and insulation;
– an on-site evaluation of the building envelope performance in a *multi-storey building* after a service life of about 30 years, through a simultaneous assessment of the state of conservation of the actual inner insulating layer and of the energy and comfort conditions. In this way, it will be possible to identify more consciously the preferable retrofit solution.

Moreover, in both cases it was checked the effect of the introduction of a new recently patented insulation system to avoid overheating risk. The system thanks to the summer ventilation of the inner layers simultaneously exploits the dynamic behavior of the mass and the thermal barrier effect of a thick insulating layer thus ensuring summer comfort while verifying the strict limits imposed by regulations. The benefits of adopting that system in comparison with other traditional solutions are quantified.

2 Research planning and activities

2.1 Traditional single family house

The research on the traditional single family house has focused on a detached building located in the central Italy characterized by high thermal inertia solid brick masonry at the ground floor and semisolid brick walls with low thermal inertia on the first floor.

2.1.1 Experimental methods

Two monitoring campaigns were conducted from July 27 to August 2 and September 9 to 19, in order to compare the influence of two different levels of wall thermal inertia on thermal comfort during the summer and intermediate season.

Both monitoring activities involved the following investigations according to ISO 7726:2002:

– outdoor environmental conditions: a weather station with a global radiometer, a combined sensor for wind speed and direction and a thermo-hygrometer with a double screen anti-radiation was used;
– indoor climate conditions: two indoor microclimate stations that included a thermo-hygrometer and thermo-resistors were used;
– Envelope performance: dataloggers coupled to thermo-resistances were used to measure the internal and external surface temperatures of the walls.

2.1.2 Analytical methods

Analytical simulations of the thermal behavior were carried out using EnergyPlus dynamic software to evaluate walls thermo-physical parameters, internal comfort conditions and energy consumptions. The model was calibrated through comparison with monitored values.

Using the calibrated model parametric variations were carried out by changing the insulation layer position (external or internal) within the horizontal and vertical envelope stratigraphy in order to provide the same stationary and periodic thermal transmittance [31] but a different internal areal heat capacity (High capacity for external insulation and Low capacity for internal insulation layer).

The retrofit measures were combined according to the following scenarios:

– *as built scenario*: ground floor, roof, walls and windows as in the "as built" situation.
– *SCHEME 0*: glass-frame system performance is improved.
– *SCHEME 1*: a retrofit on the ground floor and roof was implemented by placing the insulation material on the external face or on the internal face.
– *SCHEME 2*: the insulation layer was also applied on the external walls by placing it in the outer side or on the inner side of the vertical envelope. The former scenario is characterized by an insulation material either positioned adjacent to the existing wall or leaving a cavity (High Capacity vented building) that could be alternatively closed (in the cold period) or vented (in the hot period through openable vents).
– *SCHEME 3*: new lightweight wooden building envelope.

Finally, an economic analysis according to UNI EN 15459 by using the global cost methodology was carried out.

In order to evaluate the cost related to the innovative vented solution the price was obtained from market companies by considering the system as if it was industrially produced rather than handcrafted.

2.2 Multi-storey building

The research on the multi-storey building has focused on an apartment block constructed in the 1982s adopting a vertical envelope made by precast concrete panels with glass wool insulation placed on the room side.

2.2.1 Experimental methods

A series of laboratory tests and on-site investigations were conducted to evaluate the state of conservation and the actual performance of the existing envelope after a service life of about 30 years. The experimental activities included the following phases:

– laboratory tests on samples of glass wool extracted from the walls to quantify any changes of morphological, chemical and physical proprieties of the material;
– on site evaluation of the actual condition of the building envelope through thermograpic survey to identify thermal bridges, monitoring of the in situ thermal trasmittance of the external walls, blower door test to evaluate the air tightness;
– a detailed analysis of the thermo-physical behavior of the building envelope and of the interior thermal comfort conditions in both winter (December 5 to 13 and February 6 to 28) and summer (July 25 to August 4) season. The surveys were conducted on 5 apartments characterized by different typologies, floor position and adjacency to the outside.

2.2.2 Analytical methods

The different apartments were reconstructed as virtual models using EnergyPlus dynamic software. The models were calibrated through comparison with monitored values. The calibrated models were then used to carry out an in depth study of the as built condition and for the retrofit scenarios assessment.

The thermal performance of each component of the enclosure (roof, external floor, walls, and windows) was improved according to three levels of thermal transmittance:

– *Low* (D.lgs. 192/05): U_{wall} = 0.36 W/m^{2}K, U_{roof} = 0.32 W/m^{2}K, U_{floor} = 0.36 W/m^{2}K, U_{window} = 2.4 W/m^{2}K.;
– *Medium* (DM 26/01/2010): U_{wall} = 0.29 W/m^{2}K, U_{roof} = 0.26 W/m^{2}K, U_{floor} = 0.34 W/m^{2}K, U_{window} = 2.0 W/m^{2}K;
– *High* (standard passivhaus): U_{wall} = 0.20 W/m^{2}K, U_{roof} = 0.20 W/m^{2}K, U_{floor} = 0.20 W/m^{2}K, U_{window} = 1.3 W/m^{2}K.

A more detailed assessment involved the walls insulation system, by applying the insulation layer on the outer side of the vertical envelope either positioned adjacent to the existing wall or leaving a cavity (closed in winter and vented in summer) thus defining a dynamic insulation system. Furthermore, both cases are evaluated by assuming either the removal or the conservation of the existing insulating layer on the room side.

Each configuration (single retrofit or combination of multiple interventions) was evaluated through dynamic simulation in both winter and summer, by assessing thermal comfort, consumptions and global cost. The three aspects were combined in an integrated analysis to identify the preferable scenario.

3 Analysis and discussion of main results

3.1 Traditional single family house

Thanks to the real data collected during the experimental activity, it was possible to demonstrate that the walls have a very different behavior due both to different inertia and specific exposure/occupancy conditions of the room at the two levels. Even if the two walls have different boundary conditions, it is nevertheless possible to highlight a strong relationship between the surface temperature trends and the thermal inertia level. Indeed the heavy wall works as a heat storage requiring more energy to activate the heat conduction process thus ensuring smaller fluctuations than the lighter wall.

It was also founded a double trend inversion between walls with different inertia at the two extremities of the hot season that determines a continuously lower performance for the lightweight solution.

Energy retrofitting solutions were compared through an integrated evaluation of different aspects (comfort, energy saving and global cost). The results proved that the introduction of an insulation layer on the internal side is the worst intervention but, having to necessarily choose it to maintain the external aesthetic wall appearance, it is important to adopt a massive finishing panel on the internal side.

Moreover, the results highlighted that the better solution envisages the adoption of a dynamic envelope in order to maximize alternatively the thermal barrier effect and the heat loss. In this way, it is possible to resolve the conflicting requirements that are typical of climates with both seasonal and daily high temperature ranges. For that reason an innovative (recently patented) system, characterized by an external super insulation layer spaced from the internal wall by an air gap, was proposed. The thermal barrier effect that is effective in the winter season is than deactivated in the summer through the cavity ventilation and the mass dynamically interacts with the environment. Thanks to these performances, the system ensures optimum comfort conditions during the summer (improving by approximately 20% the levels of comfort than the worst outcome solution), winter and summer energy saving (respectively reduced up to 17% and up to 43% respect to the worst case) and a lower global cost despite the higher initial investment.

3.2 Multy-storey building

Thanks to real data recorded during the winter it was possible to verify that the glass wool insulation shows a partial crystallization process with a consequent susceptibility to pulverization. Besides, the in situ monitoring of the thermal trasmittance showed the aging of the insulation material resulting in a worsening of the initial value of about 5–10%. The thermographic and air tightness investigations, and the surface temperatures monitoring, have allowed us to verify and quantify the presence of a strongly dispersing enclosure. Finally, monitoring data showed that the apartments placed in extreme position (first floor above the porch, head position, adjacent to the roof) have the greatest heat loss which leads to a different use of the heating system (with more frequent ignitions in such apartments). In this way, the apartments at the different floors have the same operative temperature but very different heating consumptions.

The floors surface temperatures recorded during the summer allowed to prove the presence of an overheating condition both on the third and on the fifth floor. It was also examined as the specific usage conditions (presence or not of natural ventilation) influence the internal environmental conditions both for temperature and humidity values. Under the same usage conditions, a different level of indoor thermal comfort and consumptions was highlighted for the different floors showing a more difficult condition for the intermediate apartments and the ones on the top floor.

To combine the different needs, various retrofit strategies were assessed using a methodology that integrate energy saving, comfort and global cost evaluation. The overall analysis showed that the preferable intervention is a single retrofit strategy (combined interventions were not cost-effective for the high initial investment) by installing an external dynamic insulation system to the walls and the maintenance of the existing insulation layer on the room side. This solution was the best as it is able to combine both the thermal barrier effect, effective in the cold season, and the heat dissipation through the ventilation of the cavity in the summer season. Such a scenario was preferable especially with respect to floors thermal insulation or to external traditional insulation of the walls (solutions found to be preferable from a winter evaluation) because, despite a higher initial investment, it guarantees optimal comfort conditions. It was also found to be preferable the maintenance of the internal existing insulation layer because the interior comfort conditions are guaranteed anyway, thus the required investment for removal is not justified.

4 Conclusion

The results about an experimental and numerical study on both single-family house and multi-storey building were presented. The aims of this research are to evaluate the building envelope real behavior and to define the most suitable retrofit scenario.

The experimental activities carried out on the single-family house allowed us to stress and quantify the influence of thermal inertia on both summer and intermediate seasons.

While the measured data recorded by multi-storey building monitoring allowed us to demonstrate the presence of a high heat loss through the building envelope during winter and of overheating phenomena during the summer.

The results obtained from the parametrical analysis demonstrated that the adoption of a dynamic insulation was found to be the preferable solution in both cases because it is able to resolve the conflicting requirements that are typical of climates with both seasonal and daily high temperature ranges. Thus, an innovative (recently patented) system was proposed. It is characterized by an external super insulation layer spaced from the internal wall by an air gap that can be alternatively sealed in winter and ventilated in summer. Thanks to these performances, the system ensures optimum comfort conditions during the summer, winter and summer energy saving and a lower global cost despite the higher initial investment.

References

[1] Ferrari S. Building envelope and heat capacity: re-discovering the thermal mass for winter energy saving. In: Conference proceedings: “building low energy cooling and advanced ventilation technologies in the 21st century”, September, 2007, Crete island, Greece. p.346-351.
[2] Aste N, Angelotti A, Buzzetti M. The influence of external walls thermal inertia on the Energy performance of well insulated buildings. Energy Build 2009; 41: 1181-1187.
[3] Ogoli DM. Predicting indoor temperatures in closed buildings with high thermal mass. Energy Build 2003; 35: 851-862.
[4] Balaras CA. The role of thermal mass on the cooling load of buildings. An overview of computational methods. Energy Build 1996; 24: 1-10.
[5] Cheng V, Ng E, Givoni B. Effect of envelope color and thermal mass on indoor temperatures in hot humid climate. Sol Energy 2005. 78: 528-534.
[6] Bojić M Lj, Loveday DL. The influence on building thermal behaviour of the insulation/masonry distribution in a three-layered construction. Energy Build 1997; 26: 153-157.
[7] Tsilingiris PT. Wall heat loss from intermittently conditioned spaces – The dynamic influence of structural and operational parameters. Energy Build 2006; 38: 1022-1031.
[8] Kossecka E, Kosny J. Influence of insulation configuration on heating and cooling loads in a continuously used building. Energy Build 2002; 34: 321-331.
[9] Al-Sanea SA, Zedan MF. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. App Energy 2012; 89: 430-442.
[10] Gregory K, Moghtaderi B, Sugo H, Page A. Effect of thermal mass on the thermal performance of various Australian residential constructions systems. Energy Build 2008; 40: 459-465.
[11] Al-Sanea SA, Zedan MF. Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. App Energy 2011; 88: 3113-3124.
[12] Asan H. Effects of Wall’s insulation thickness and position on time lag and decrement factor. Energy Build 1998; 28: 299-305.
[13] Kontoleon KJ, Bikas DK. The effect of south wall’s outdoor absorption coefficient on time lag, decrement factor and temperature variations. Energy Build 2007; 39: 1011-1018.
[14] Di Perna C, Stazi F, Ursini Casalena A, D’Orazio M. Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy Build 2011; 43: 200-206.
[15] Bojic M, Yik F, Wan K, Burnett J. Influence of envelope and partition characteristics on the space cooling of high-rise residential buildings in Hong Kong. Build Environ 2002; 37: 347-

355.
[16] Martin S, Mazarron FR, Canas I. Study of thermal environment inside rural houses of Navapalos (Spain): the advantages of reuse buildings of high thermal inertia. Costr Build Mat 2010; 24: 666-676.
[17] Stazi F, Vegliò A, Di Perna C, Munafò P. Experimental comparison between 3 different traditional wall constructions and dynamic simulations to identify optimal thermal insulation strategies. Energy Build 2013; 60: 429-441.
[18] Imbabi MSE. A passive–active dynamic insulation system for all climates. International Journal of Sustainable Built Environ 2012; 1: 247-258.
[19] Directive 2012/27/UE of the European Parliament and of the Council of 25 October 2012 on the energy performance of buildings.
[20] European standard UNI EN 15251:2008, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
[21] Dili AS, Naseer MA, Zacharia Varghese T. Passive control methods of Kerala traditional architecture for a comfortable indoor environment: A comparative investigation during winter and summer. Build Environ 2010; 45: 1134-1143.
[22] Rijal HB, Yoshida H. Comparison of summer and winter thermal environment in traditional vernacular houses in several areas of Nepal. Proceedings of the International Conference on Advances in Building Technology 4–6 December 2002, Hong Kong, China; Volume II: 1359-1366.
[23] Yilmaz Z. Evaluation of Energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate. Energy Build 2007; 39: 306-316.
[24] Pavlík Z, Černý R. Experimental assessment of hygrothermal performance of an interior thermal insulation system using a laboratory technique simulating on –site conditions. Energy Build 2008; 40: 673-678.
[25] Peuhkuri R, Rode C, Hansen KK. Non-isothermal moisture transport through insulation materials. Build Environ 2008; 43: 811-822.
[26] Björk F, Enochsson T. Properties of thermal insulation materials during extreme environment changes. Construction Build Mater 2009; 23: 2189-2195.
[27] Rasmussen TV, Nicolajsen A. Assessment of the performance of organic and mineral-based insulation products used in exterior walls and attics in dwellings. Build Environ 2007; 42: 829-839.
[28] Toman J, Vimmrová A, Černý R. Long-term on-site assessment of hygrothermal performance of interior thermal insulation system without water vapour barrier. Energy Build 2009; 41: 51-55.
[29] Stazi F, Di Perna C, Munafò P. Durability of 20-year-old external insulation and assessment of various types of retrofitting to meet new energy regulations. Energy Build 2009; 41: 721-731.
[30] Stazi F, Tittarelli F, Politi G, Di Perna C, Munafò P. Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls. Energy Build 2014; 68: 292-304.
[31] Decreto Legislativo 19 agosto 2005, n.192, Attuazione della direttiva 2003/91/CE relativa al rendimento energetico nell'edilizia.