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Experimental Thermal Performance Assessment of a Prefabricated External Insulation System for Building Retrofitting

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Abstract

External Thermal Insulation Composite Systems (ETICS) are increasingly used for the energy-efficient retrofit of buildings. This paper evaluates the in-situ thermal performance of a prefabricated composite panel made of PIR and concrete, by full scale testing of a prototype installed at the KUBIK test facility. Experimental results from measurement show a reduction in the thermal resistance of the ETICS assembly compared to theoretical design values. A number of phenomena have been identified causing multidimensional heat flow of conductive and convective nature, such as thermal bridges at floor slabs and anchors, and thermal bypass of the insulation causing airflow behind the ETICS.

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Keywords: building envelope; energy efficiency; retrofit; ETICS; heat transfer; thermal resistance; experimentation; performance gap

1. Introduction

According to the Sustainable Building and Climate Initiative of the UN[1], buildings are responsible for 40% of the global energy needs, yet commercially available technologies can provide energy saving potentials between 30% and 80%. In a European context, considering its large building stock relative to demographic projections, the burden of reducing the energy demand of the built environment will largely lie in the energy efficient retrofit of existing buildings. This is recognised and supported by EU-level legislation such as directives on Energy Performance (EPBD)[2] and Energy Efficiency (EED)[3] of buildings, a harmonised Construction Products Regulation (CPR)[4], and funding granted by the Horizon 2020 Framework Programme for Research and Innovation initiatives.

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Heat losses through the building envelope (walls, roofs, floors and glazed areas) account for over 60% of the energy use of conventional buildings. Many of these losses occur through uninsulated walls, thus the addition of thermal insulation is one of the most robust and efficient solutions for improving their energy efficiency. External Thermal Insulation Composite Systems (ETICS) are increasingly favoured over internal insulation approaches, due to a number of advantages like (a) lower disruption to occupants, (b) no loss of internal space, (c) lower risk of surface or interstitial condensation as the existing substrate is kept close to internal temperature, and (d) more efficient thermal performance allowed by a continuous insulation layer that prevents thermal bridges at junctions with intermediate floors and walls.

However, there is increased awareness of a ‘performance gap’[5] resulting in a mismatch between predicted and measured energy use in buildings, which is often attributed to a combination of causes like occupant behaviour, defective workmanship and unrealistic design assumptions. This issue poses clear implication for strategic EU targets, especially considering that the underperformance tends to grow as the technology becomes more complex[6]. In order to find solutions for these shortcomings and improve our knowledge of their underlying causes, there is a critical need for in-situ tests of construction systems, as built and in service conditions.

This study evaluates the thermal performance of a prefabricated ETICS assembly in a retrofit application, by means of a prototype that was designed and built to be representative of a solution as implemented in the market. The thermal resistance expected from theoretical design values is compared to data from the experimental assessment, discussing possible causes for the variance between these.

2. Case study

This study measures in-situ thermal performance of a prefabricated ETICS solution that is mechanically anchored to existing floor slabs. The ETICS product, developed within the ETIXc project[7], is a composite panel comprised of PIR thermal insulation and a photocatalytic concrete external finish.

Fig. 1. Test area at first floor of west-facing façade in KUBIK facility: (a) original brick wall before installation; (b) ETIXc prototype installed.

The test was carried out over a portion of the west-facing façade of the KUBIK test facility in Derio, Spain (43° 17′ N 2° 52'W). KUBIK by Tecnalia[8] is a full scale experimental infrastructure focussed on research and development of new energy efficient products and systems. It has a total floor area of 500 m² distributed over basement, ground floor and two upper levels. The main distinctive feature of KUBIK is its capacity to create realistic scenarios for the quantitative determination of energy efficiency and energy savings resulting from the interplay of construction solutions, intelligent management of HVAC and lighting systems, and non-renewable and renewable energy sources.

A prototype of the ETIXc assembly was installed over a wall made of two brick layers with an uninsulated air layer in-between, representing a common Spanish construction from the 1970s (Fig. 1). This wall, erected in 2011, has since been used for testing a number of different thermal insulation systems.

3. Methodology

The experimental set-up and the data analysis were designed to obtain the thermal resistance of (a) the whole wall integrating the ETIXc solution and (b) the ETIXc component in itself.

3.1. Measurement method and materials

Pt100 temperature sensors by Thermo Sensor GmbH (precision ≤ ± 0.1 °C) and Phymeas heat flux sensors (precision ≤ ± 0.1 % of FSV) were used in the experiment, connected to a Beckhoff Automation PLC system, where data from measurements was recorded at 1 minute intervals.

In order to gather the data required for obtaining thermal resistance values for the different layers of the component, the sensors were placed over relevant points of the assembly:

- Layer 1, external surface of ETIXc panel: temperature sensor only
- Layer 2, internal surface of ETIXc panel: temperature sensor only
- Layer 3, external surface of existing brick wall: temperature and heat flux sensors
- Layer 4, internal surface of existing brick wall: temperature and heat flux sensors

These sensors give sufficient information for obtaining the following thermal resistance values:

- R_{4-1}, thermal resistance of the retrofitted wall
- R_{4-3}, thermal resistance of the original wall
- R_{2-1}, thermal resistance of ETIXc panel

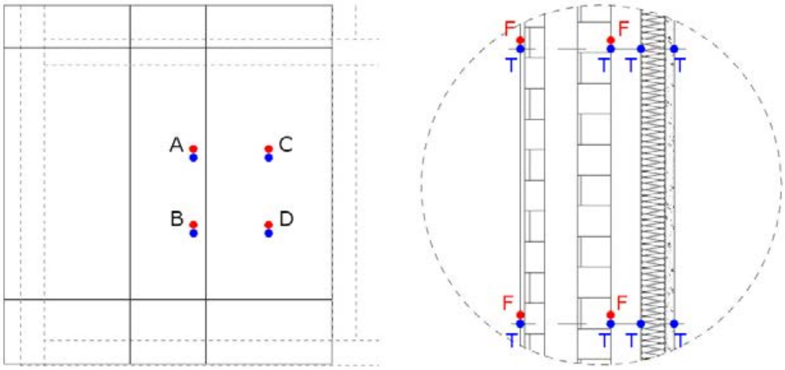


Fig. 2. (a) wall elevation with location of four measurement axes; (b) location of heat flux (F) and temperature (T) sensors through wall section.

This arrangement was replicated along 4 measurement axes, in order to assess the variability of the thermal resistance due to installation defects and thermal stratification conditions. So as to exclude the effect of thermal bridges, these measurement axes were deliberately placed in an intermediate zone between floors.

3.2. Calculation of thermal resistance

The characterization of the thermal properties of the system was performed by means of a procedure where the cumulated mean values of the required variables were computed. For one-dimensional heat transfer, thermal resistance is defined as the ratio of temperature difference and the heat flux between opposite faces of a material. Although thermal resistance is dependent on temperature, this variance is relatively small for applications in the construction sector, and thus is generally assumed to be a constant value.

The input variables (temperature and heat flux) vary over the course of the experiment. Despite a dominant daily cycle, changing weather conditions result in a high variability among different days. Therefore a normalised average method[9] has been used to filter out heat storage effects, where the obtained data is aggregated in order to reduce dynamic oscillations.

$$R = \frac{\sum_{j=1}^{n}(T_{si,j} - T_{se,j})}{\sum_{j=1}^{n} q_j} \tag{1}$$

where:

- R is the surface-to-surface thermal resistance (in m²K/W)
- $T_{si,j}$ is the interior surface temperature (in °C or K) at time step j
- $T_{se,j}$ is the exterior surface temperature (in °C or K) at time step j
- q is the density of heat flow rate through the material (in W/m²) at time step j
- j is each of the time steps of the experimental sequence
- n is the number of time steps of the experimental sequence

When carried over a long enough period of time, there is a convergence to an asymptotical value that is close to the steady-state value. The test procedure requires a minimum duration of 72 h, and a deviation in thermal resistance below 5% when data for the last 24 hours is subtracted. As the experiment has been carried out over 63 days, this criterion is much improved in this particular case.

4. Baseline values

This experiment makes use of a previously experimented brickwork wall[10]. The values obtained by physical measurement are listed in Table 1. Table 2 presents the calculation[11] of the thermal properties of the ETIXc panel, based on design data.

Table 1. Thermal properties of original wall, based on previous measurements.

	Thickness *d* [m]	Thermal resistance *R* [m²K/W]
Original wall	0.295	0.53

Table 2. Thermal properties of ETIXc panel, from theoretical calculations based on design data.

	Thermal conductivity λ [W/mK]	Thickness *d* [m]	Thermal resistance *R* [m²K/W]
PIR insulation	0.03	0.080	2.67
Concrete	1.75	0.030	0.02
ETIXc panel		0.110	2.69

5. Results from experimental campaign

Minutely recorded data in the period from 1 November 2015 to 3 January 2016 was processed for this assessment. The cumulated averaging method was found very stable, furthermore considering that with 63 days of data, daily heat storage can be easily neglected.

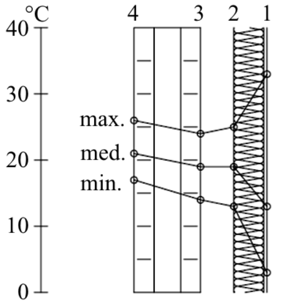
Results were obtained for each of the 4 measurement axes (Fig. 2). In order to achieve a robust and stable surface-surface conductance value, the signals were processed by generated cumulated mean values of each of the signals.

Quantitative results are portrayed in Table 3. A high variance can be observed in temperature and heat flux values recorded, especially for the outer surface of the façade (layer 1). This is due to a higher oscillation in temperatures compared to the internal environment, the effect of solar radiation heating the external surface, and long wave radiation emissions to a clear night sky cooling the surface.

Locations to the inner side of the insulation show lower variances, due to the insulation value of the PIR mitigating external oscillations and the thermal mass of the brickwork. The inner surface of the insulation (layer 2) and the outer surface of the original wall (layer 3) show a very similar performance, as the air layer that separates these locations has poor insulating properties, especially considering the higher relative thermal resistance of the insulation in the panels.

The room surface (layer 4) is also subjected to variances, caused by changes in internal room temperature and the operation of the HVAC system.

Table 3. Statistical distribution of experimental readings for temperature and heat flux density.



	Temperature T [°C]				Heat flux density q [W/m²]	
	T_1	T_2	T_3	T_4	q_3	q_4
Average	13.52	19.25	19.46	21.53	2.67	3.38
Maximum	33.14	25.32	24.62	26.59	9.08	20.14
Third quartile	16.26	20.63	20.69	22.64	4.16	5.07
Median	13.54	19.03	19.23	21.19	2.60	2.35
First quartile	10.24	17.71	17.97	20.22	1.36	1.32
Minimum	2.84	13.28	13.91	16.92	-4.94	-3.53

From the temperature and heat flux density values measured, thermal resistance values have been obtained for both the original wall and the ETIXc panel (Table 4):

- The overall thermal resistance of the insulated assembly has been measured at 2.73–3.00 m²K/W, a significant improvement from the value measured before insulation (0.53 m²K/W)
- The thermal resistance measured for the original wall substrate is increased after the application of insulation (0.53 m²K/W before insulation, 0.61–0.78 m²K/W after insulation)
- The thermal resistance of the ETIXc panel has been measured at 1.70–2.15 m²K/W, lower than its theoretical value (2.69 m²K/W)

Table 4. Overall and partial thermal resistances calculated from temperature and heat flux density.

	Temperature difference ΔT [°C]		Heat flux density q [W/m²]	Thermal resistance R [m²K/W]		
Layer 1	8.01	5.74	2.67–3.38	2.73–3.00	1.70–2.15	ETIXc panel
Layer 2						
Layer 3		2.07			0.61–0.78	Original wall
Layer 4						

6. Conclusions

6.1. Performance of the ETICS assembly

The thermal resistance measured in-situ for the ETICS assembly (1.70–2.15 m²K/W) is lower than its theoretical value from design data (2.68 m²K/W). A number of potential causes are identified below:

- Where the ETICS panels are anchored to the intermediate floor, thermal bridges occur. Reinforced concrete floor slabs are comparatively more conductive than the original wall substrate of perforated brick and air layer, creating a potential for lateral heat flow that is not accounted for by the one-dimensional calculation. While the quantification of their additional heat flow is outside the scope of this study, these could potentially contribute to the increase measured in the test.
- The presence of an air gap between the ETICS assembly and the original wall, in the case where the complete airtightness of this air layer cannot be guaranteed, can potentially result in infiltration of external air by natural or forced (wind-driven) convection. It constitutes a mechanism of open convective loop[12], which is a form of thermal bypass[13]. In the tested assembly, care was taken on site to seal all joints between panels. However, the extent of this phenomenon cannot be detected by conventional air pressure tests, as the air infiltration does not reach the indoor space.
- A high moisture content within the concrete and the PIR insulation could lead to an increase of their thermal conductivity above declared values. In the experimented façade, a water leakage test was carried out in order to prevent the risk of rainwater penetration at joints between concrete panels.
- In addition to the above mentioned factors, there could also be unidentified error sources originating from the experimentation.

6.2. Performance of the original wall substrate

The thermal resistance measured in-situ for the original wall substrate after incorporating the insulation (0.61–0.78 m²K/W) is higher than the previous in-situ measurement of the uninsulated wall (0.53 m²K/W).

- The thermal conductivity of brick has a strong dependence on moisture content. The installation of the ETICS assembly might have resulted in the drying of the original masonry substrate[14], thus lowering its thermal conductivity.
- The ETICS assembly offers additional protection to the wall substrate against weather, wind and air infiltration, which might result on an improvement of its thermal performance.

6.3. Overall conclusions about the assessed retrofit intervention

In general terms, the assessed ETICS assembly constitutes a successful retrofit intervention. As shown by full scale experimental testing, the application of the ETIXc solution results in a 5x increase in the thermal resistance of the wall (from 0.53 m²K/W before insulation up to 2.73–3.00 m²K/W after insulation).

The in-situ thermal performance of the prototype is slightly below the level predicted using design data. This underperformance can be attributed to differences between the theoretical model and the as-built prototype, such as those identified above.

Theoretical calculations assume perfect execution, which is rarely, if ever, possible on site. In order to minimise the gap between predicted and measured values, unrealistic design assumptions should be challenged, and the additional energy loss observed in-situ might need to be estimated and factored in energy calculations.

The authors believe that the workmanship in the tested assembly reflects general construction practice, and the experimental study is representative of the in-situ performance of a typical building, as built and in service conditions, retrofitted with the ETICS assembly studied.

Physical measurements of thermal resistance should be encouraged, which should ultimately lead to a better understanding of the factors that affect in-situ thermal performance by both designers and operatives.

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