Methodology for diagnosis of real condition of a listed building envelope for its refurbishment

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ABSTRACT: This paper presenst a methodology for the diagnosis of the energy performance of envelopes of listed buildings. In refurbishment, the energy improvement of the building and the preservation of its architectural value have usually been considered as opposed approaches. Nevertheless even minor interventions can generate significant results in terms of level of comfort and energy consumption in buildings of this type.

For this reason, the starting point must be the diagnosis of the real condition of the building envelope based on an exhaustive knowledge and quantification of its thermal properties and its state of preservation. This study includes thermograph analysis, thermofluxometry, blower door test and analysis of the indoor conditions of temperature and humidity according to occupant behaviour. Using this procedure we can determinate the critical points on which focus the efforts for its energy improvement. A case study of a multi-residential building registered as Modern Movement architecture is presented.

Keywords: Energy retrofit, building envelope, in-situ measurement, comfort, listed buildings

INTRODUCTION

The refurbishment of the existing building stock is a priority for EU's countries in order to move towards a Low-Carbon economy in 2050 [1]. Nonetheless a large number of buildings is exempt from any requirement of energy efficiency due to its historical or architectural value.

The energy optimization of existing building stock is a complex issue and, when talking about listed Modern Movement buildings, there are more constraints to take into account: their architectural, historical, aesthetic and patrimonial value have to be maintained.

Modern Movement buildings are characterized by the use of industrially produced materials, the visual expression of structure, the simplicity and clarity of forms and the attention for detail among others features. These formal attributes have an impact on its energy behaviour and their thermal deficiencies are common in most of them.

In this kind of buildings a huge amount of energy is used to maintain comfortable indoor temperatures. Nevertheless when their owners decide to renovate them, the local authorities don't allow to alter their appearance and, thence, the effort focuses on repair and maintenance works. On other occasions, they make changes without the approval of the institutions and, as a consequence, the cultural value is modified.

Hence, the goal of this paper is to establish a methodology to study the performance of the building envelope of a listed building. This way it is possible to assess different interventions in order to improve the thermal performance and indoor comfort of the building by means of minimum and non-invasive interventions based on an exhaustive knowledge of the building.

METHODOLOGY

The complexity of the thermal behaviour of buildings makes it difficult to establish standard interventions that are cost-effective without the previous through study of the actual condition of the building. The different subsystems of a building are highly interactive and therefore different retrofit measures may have different impact on associated building subsystems.

The understanding of the building allows to know how to make it work as efficiently as possible and to establish the limits and potentials of a refurbishment. For this reason, field work measurements, tests and monitoring allow us to figure out the behaviour of the building depending on the weather conditions and the occupancy patterns.

The methodology consists of four phases being the analysis of the performance the main part of the work. The following table (Table 1) resumes the procedure to follow.

Identification of the historical features of the building

First of all, the building has to be analysed in terms of its architectural value, historical context and actual relevance. The first step will be to proceed to the collection of the information available in the historical documentation, city files, cultural associations, documentary collection of the architects… and to carry out a visual inspection to examine the integrity of the original building, its preservation condition and to check if the building has undergone works that have modified these elements.

This study allow us to establish the cultural value of the building and its features and to determinate what elements should be preserved and which ones can be modified and in which grade.

Table 1: Structure of the methodology.

1. Identification of the historical features of the building	
Building	Historical context
Features	Historical/architectural value Preservation state
2. Analysis of the performance of the envelope	
Climate	Study of weather data and surroundings
Building	Documentation Visual inspection Layout drawing
Opaque envelope	Thickness measurement Thermographic inspection Thermofluxometry test Monitoring (T, RH, CO_2 sensors) Sonic trials
Thermal bridges	Thermographic inspection
Translucent envelope	Thermographic inspection Blowerdoor test + thermography
Infiltration	Blowerdoor test + thermography
Comfort	Monitoring (T, RH, CO_2 sensors) Surveys
3. Establishment of the diagnosis of the envelope	
Opaque envelope	
Thermal bridges	Low/standard/high efficiency
Translucent envelope	Very damaged/damaged/good preservation
Infiltration	
4. Pre-assessment of proposals of intervention	
Level of intervention	Feasibility Energy efficiency Cost effectiveness Priority of the intervention

Analysis of the performance of the envelope

Following we proceed to the analysis of the performance of the building. The understanding of the local climate and surroundings: maximum, minimum and average daily temperatures through the year, solar incident radiation, wind direction and intensity, presence of elements that can obstruct the solar radiation, street width … let us to identify the elements from which the building should protect and the possible advantages as free solar gains, night cooling… Both the climatic conditions and the surroundings determine largely the performance of the building so that the refurbishment proposals must consider these requirements when defining the objectives of the intervention.

The collected documentation of the building gives information about the year of construction, construction systems and materials. Most of the times the project lacks of detailed information about construction solutions; in this case it is necessary to resort to literature on construction systems of that time.

Once all the information has been studied we can proceed with an initial visual inspection in which we should check if the executed works match with what was planned. Therefore, it is convenient to take the dimensions of at least a representative part of the building and to measure the thickness of different construction elements. At the same time other preservation aspects will be evaluated: decay, dampness, cracks, flaws…

The elements that have a higher impact on the energy demand of the building are opaque and translucent envelopes, thermal bridges and infiltration. Thus, to determine accurately the energy savings derived from the refurbishment of the envelope is necessary to quantify their thermal properties with precision through different methods.

For the field study we select the most representative stays for monitoring. It is necessary to monitor more than one stay/dwelling since the occupant's activity has a great influence on the pattern of use recorded. In the same way it is important to select rooms with different thermal behaviour: in different position in the building (first, intermediate and last floor perform differently), in different orientation or with different obstacles or boundaries.

To determine the state of the opaque envelope we conduct an infrared inspection. Thermography is a tool that detects the infrared radiation that is emitted by all objects above absolute zero and transforms the intensity into a colour scale which allows visualize the temperature distribution of a surface. Its application to the detection of thermal irregularities in building envelopes is regulated by regulated by the ISO 6781:1993 MOD [2]. This tool allows a fast way of visualising insulation defects or thermal bridges (hot spots), humidity (cold spots) or air leaks among other applications.

The thermal conductance of the opaque envelope is quantified by a thermofluxometer. This instrument can determine the heat flow through a component at steady-state conditions and it is regulated by ISO 9869:1994

[3]. The test consists on logging the air and superficial temperatures, both exterior and interior, of the construction under study and the thermal flow that passes through it, a posterior mathematical analysis is conducted to calculate the U-value of the component.

Sonic trials give the physical and mechanical configuration of the element: density, dimensions, porosity or grain size of its components. Nevertheless to determine more accurately the composition and thickness of the different materials that constitute the envelope there are invasive tests such as coring and endoscopy. These methods also characterize the mechanical behaviour. However since they are destructive they should be performed only when it is absolutely necessary.

On the other hand, thermal bridges shouldn't be neglected. According to literature their impact on the heating requirements can be around 16% in poorly insulated buildings and 30% in better insulated buildings [4]. An infrared inspection allows to locate them but its quantitative study should be performed by heat-transfer modelling software.

The characterization of the translucent components is difficult to perform in-situ, therefore the visual inspection and collection of the technical documents or year of replacement is the only information source that we can get. In any case, a detailed study of the solar incident radiation should be carried out to study the potential of free heating gains and determinate when it is necessary to protect from it.

The permeability of the envelope and its components can be characterized by the blower door test in combination with thermograph inspection to determinate the origin of the air leaks. It is regulated by ISO 9972:1996 [5].

The indoor comfort is evaluated through the monitoring of the air temperature and relative humidity, superficial temperatures of the envelope and CO_2 concentration. To make surveys to the occupants and facilities managers gives first-hand information about the comfort both in winter and summer of different areas of the building and its main deficiencies. To study the results of the indoor measurements it is necessary to take into account the influence of the heating or cooling systems, the occupant and the individual characteristics of the room/dwelling. Therefore the information concerning temperature set points, schedules, ventilation time, additional heating systems… has to be collected.

Establishment of the diagnosis of the envelope

The analysis of the results allows us to identify the critical points and their extend in the building and establish a diagnosis of the actual condition of the envelope in terms of energy efficiency and state of preservation.

At the same time, these values will be used for the building simulation in other to model accurately the building and calibrate it with the data recorded. A calibrated model will allow us to quantify the energy savings of different retrofit scenarios and along with the technical and economic assessment to choose the optimal solution.

Pre-assessment of proposals of intervention

Once the critical points have been determined we can propose different interventions to solve them. These interventions will be ranked according to the feasibility, the energy efficiency, cost-effectiveness and priority.

The technical feasibility of the intervention is assessed taking into account the architectural value of the building. The energy efficiency is graded depending on the reduction of the energy demand associated to the element that is the target of improvement and not to the total building demand since most of the interventions are only applicable to certain extent in the building (e.g. the replacement of single glazing by double glazing has an important impact on the performance of the element, nevertheless the impact on the whole energy demand is minimum if the number of these kind of windows is small). The cost effectiveness depends on the energy savings and the economic investment and the priority is established according to the preservation state of the element as well as its energy efficiency.

With this listing we can proceed to the detailed study of the different measures and to develop retrofit scenarios that will be evaluated in the same terms as aforesaid in order to decide the cost-optimal proposal.

CASE STUDY

The building under study is registered by DOCOMOMO (Documentation and Conservation of buildings, sites and neighbourhoods of the Modern Movement) and is listed by Local Authorities with a grade 3 of protection for its architectural value as it is one of the best examples of the Modern Movement in the city.

Figure 1: Plan and photography of the current appearance of the building under study.

The building, located in Pamplona (Fig. 1), was built in 1965. It is composed by two residential towers joined at one side. They have 13 floors (ground floor plus twelve with four dwellings per floor each tower. The plant is raised diagonally to get the best orientation and an optimal exploitation of the plot.

The building is characterized by the essential use of geometric shapes and volumes, repetition of windows, asymmetrical composition of plan and facade, lack of decoration and distinction between structure and envelope. The element to preserve is the facade which involves that its composition and the arrangement and size of windows must be maintained. Regarding finishing materials apart from their conservation the normative only allows its replacement by the same material. In the same way the closure of terraces and balconies is forbidden, nevertheless most of them were already closed before the building was listed in December of 2002.

The building originally lacks of insulation. It has a double brick wall, flat roof and wood windows with single glass. However over the years the building has undergone several works: in 2003 the roof was retrofitted with a double bituminous membrane, 5 cm of XPS and finishing of gravel, the concrete structure in the facade was repaired and the bricks cleaned. Each tower has its own oil boiler for all the dwellings and the flats have radiators without any system for its regulation.

During the visual inspection we can annotate all the changes that have been made in the building and study its preservation state. This allow us to ascertain that most of the windows have been replaced regardless the original design (most of the owners have replaced them by PVC or aluminium with thermal break ones and double glazing or they have installed an additional window on the outside) or maintaining a common approach to the entire building. Part of its architectural value has been lost by the closure of the terraces of the living room and the courtyard of the kitchen, turning these spaces into heated ones. At the same time, a new window has been opened in most of the flats when the courtyard of the kitchen was closed since a room had its window faced to this space. However the character of its structure and the composition of the facade should be preserved in any case.

Taking measurements of one of the flats was useful for realizing that the construction of the building wasn't executed as defined in the plans. In the documentation the thickness of the facade was constant except for in the spaces to house the radiators; however, the thickness of the air cavity varies depending on the room to create recessed shelves in the bedrooms. To define properly the thickness of the walls will be crucial to evaluate retrofit proposals in the case of opting for injected insulation since the effectiveness of the intervention depends on the thickness of the camera and the lack of internal elements that hinder the proper injection of the insulation.

Following we perform a thermographic inspection (Fig. 2). The different qualities of the windows are identified and the thermal bridges detected. There are some panels of the facade that present an uneven behaviour; they look like to be more insulated than the others. After talking with the owners of these flats we can conclude that these parts of the facade were insulated by injection of polyurethane foam in the cavity wall. Thermal bridges together with the windows constitute an important source of heat loss as well as the slab between the heated terraces and the open ones.

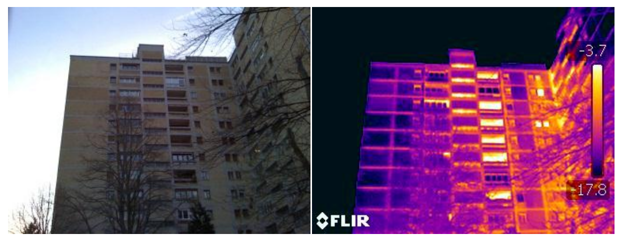

Figure 2: Photography and thermography of the east facade of Tower3.

To determinate the U-value of the facade a thermofluxometer was installed during 9 days and the average U value was calculated according to ISO 9869:1994[6] with the values recorded during the last 72 hours. The final U-value has a deviation lower than 5% with regard to the value obtained 24 hours before. The result was 1,39 W/m^2, this value is consistent with what was expected (1,43 W/m^2 is the value calculated for double brick wall with air cavity of 4 centimetres).

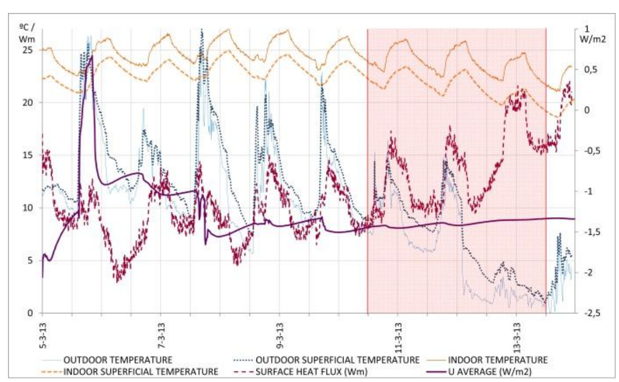

Figure 3: Temperatures, heat flux and U average value (calculated) recorded during the thermofluxometer test.

In this graph (Fig. 3) we can also check the indoor superficial temperature of the wall where it was performed. Its oscillation is linked to the indoor mean air temperature with a difference of 2,6ºC during the day. This difference is reduced during the night, when the heating is turned off, until 1,5ºC. It keeps usually between 21ºC and 24ºC but decreases as the outdoor temperature drops (as the indoor temperature does) registering a minimum temperature of 18,6ºC when the exterior temperature was -1.3ºC. Therefore we can say that the cold wall effect is small and the thermal mass of the building contributes to keep the indoor temperature during the night when the heating is turned off.

As showed in the thermograph (Fig. 2), the building under study presents a high proportion of thermal bridges in relation to the facade area. A thermal bridge is characterized by its linear heat transmission coefficient (Psi) and its length. The following figure (Fig. 4) shows the heat distribution in different thermal bridges and their Psi value calculated in accordance with the ISO 10211:2007 [6] through the two-dimensional building heat-transfer modelling software Therm.

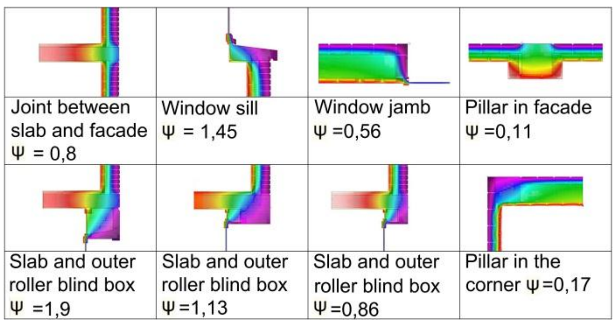

Figure 4: Characterization of some of the thermal bridges by Therm.

The impact of the thermal bridges in the facade is such that involves an increase of the thermal transmittance of the facade of the 30% (from 1,39 W/m^2 to1,8 W/m^2).

The blower door test was conducted in two different dwellings where the windows have been replaced in different times. In the first flat all the windows have been replaced by PVC ones with sun control double glazing two years ago. In the second flat two original windows remain and the others were replaced by aluminium without thermal break and wood frames with double glazing fifteen years ago. The value of n50 obtained was 2,18 1/h (Effective Leakage Area at 4 Pa= 181,6, ±3,4%) and 3,78 1/h (Effective Leakage Area at 4 Pa= 335,9, ±4,1) respectively. The main origin of the air leaks is the inefficient closing of the windows, the join between the window frames and the facade and the head box for the exterior roll shutters as we can see in the thermograph (Fig. 5). According to these results the infiltration can be reduced considerably with airtight windows and their proper installation.

Figure 5: Photography and thermography of one window during the blower door test under depression.

The indoor temperature and humidity was recorded during two weeks in steps of 10 minutes in the living rooms of 8 dwellings, 4 per tower in all orientations (Fig. 6). The temperatures are in general high, around 23,5 ºC. It is remarkable the low temperature of 12A due to the fact that the area of the living room was increased but not the surface of the radiators. The daily temperature oscillation is bigger in the flats faced to south due to the solar gains during the day. The thermal mass of the building is beneficial for maintaining the temperature during the night.

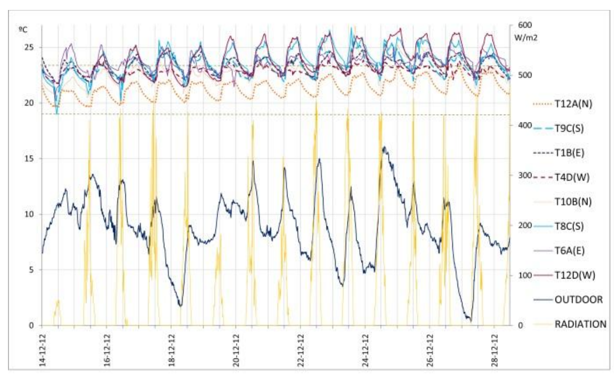

Figure 6: Temperatures recorded during two weeks.

Table 2: Resume of the temperatures recorded.

	TOWER 3				TOWER 5			
	12A N	1B E	9C S	4D W	6A E	10B N	8C S	12D W
Average daily max temp (ºC)	22,4	24,5	24,6	23,5	24,6	24,7	25,8	25,9
Average daily mix temp (ºC)	20,4	22,3	22	22,3	22,5	21,8	22	22,5
Average daily oscillation(ºC)	2	2,2	2,6	1,3	2,1	3	3,8	3,3

The summer monitoring will be carry out during this summer but with the results of the surveys we can notice problems of overheating in the stays faced to south and west, in some cases increased by the closure of the terraces.

Establishment of the diagnosis of the envelope

The state of preservation of the building in general is good, the facade and the roof have been renovated 10 years ago. The opaque envelope has a high thermal transmittance, away from the current standards. The condition of the windows is quite different due to the individual replacement carried out by the occupants. Through the infrared inspection the windows with worst thermal performance have been identified. The airtightness of the envelope is medium-high depending on the state of preservation and installation of the windows. The heat losses through the thermal bridges are high.

Table 3: Pre-assessment of different interventions

		F	EE	CE	P
Level of intervention 1					
TE	Replacement of windows with single glazing and/or metallic frame without thermal break	H	H	M	H
TE I	Improvement of the airtightness of the windows through draught excluders	H	M	H	H
TE TB	Installation of thermal insulation inside the roller blind box	H	M	H	H
TE	Installation of awning in windows oriented to south or west	H	H	H	M
OE TB	Insulation of the ceilings and floors of open terraces	M	H	M	M
OE	Insulation of the facade in the main bedrooms	M	M	M	M
Level of intervention 2					
OE	Internal or cavity insulation of the facade	M	H	M	M
TB	Improvement the thermal bridges by interior insulation	L	H	L	L
OE	Insulation of the partition between the dwellings and the stairwell (unconditioned space)	H	M	L	L
OE	Roof's insulation	H	L	L	L
OE	Insulation of the slab between conditioned and unconditioned	L	L	L	L

F: feasibility EE: energy efficiency CE: cost effectiveness P: priority
OE: opaque envelope TE: translucent envelope TB: thermal bridge I: infiltration
H: high M: medium L: low

This table (Table 3) constitutes a pre-assessment of the possible interventions on the envelope of the building. It has been established two levels of intervention depending on the scope of the measure. The level 1 consists of interventions on specific elements of the envelope that are quite feasible to execute and mean energy savings in the event that they are applied to all the building. The level 2 constitutes global interventions that represent a significant improvement in energy saving and a stronger investment.

Nevertheless it is necessary a detailed energy simulation of the different interventions and its combinations for an accurate quantification of the energy savings. At the same time the interventions have to evaluate in economic, technic, comfort and aesthetic terms in order to prioritize the different interventions and establish an efficient retrofit scenario.

CONCLUSION

The understanding of the real condition and the energy needs of the building is essential to propose an optimized retrofit intervention. A careful assessment of the feasibility of the intervention and its compatibility with the cultural features of the building allows to choose the most suitable proposal according to the cultural value of the building.

The methodology proposed allow us to characterize the main thermal parameters of the building envelope and the thermal behaviour of the building depending on the use pattern and environmental and surrounding factors in order to evaluate accurately the energy savings of the possible interventions.

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