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Evaluación de las propiedades térmicas de los muros de piedra en edificios del patrimonio cultural: el hospital real de Granada, España

Assessment of the stone walls' thermal properties in cultural heritage buildings: the royal hospital of Granada, Spain

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Resumen-- **La rehabilitación energética es hoy en día el principal reto de los edificios para conseguir la reducción del consumo de energía final y de las emisiones de CO2, siendo un objetivo que cumplir con las Directivas Europeas y con ayudas directas para la rehabilitación de edificios de los fondos europeos Next Generation. En el caso de la intervención en edificios de patrimonio cultural, su aplicación conlleva la necesidad de estudios específicos que permitan abordar actuaciones de rehabilitación energética, conociendo su comportamiento, al tratarse de casos exclusivos. Este trabajo presenta la evaluación del comportamiento térmico de dos salas del Hospital Real de Granada (España) mediante el estudio de patrones térmicos in situ y simulación por medios computacionales a través de técnicas no destructivas. Los resultados ponen de manifiesto la importancia y mejora que ofrece en el comportamiento de los espacios la existencia de muros gruesos. Asimismo, ofrecen información para abordar una planificación estratégica a escala monumental en el futuro, definiendo las condiciones de confort térmico confirmando la incidencia que reconoce su composición material, sistemas constructivos, así como su estado de conservación.**

Palabras clave— Resistencia térmica in situ; rehabilitación energética; propiedades térmicas de los muros; técnicas no destructivas; patrimonio cultural..

Abstract—**Energy rehabilitation is today the main challenge for buildings to achieve the reduction of final energy consumption and CO2 emissions, being an objective to comply with the European Directives and with direct help for the rehabilitation of buildings of the European Next Generation funds. In the case of intervention in cultural heritage buildings, its implementation entails the need for specific studies that allow addressing energy rehabilitation actions, knowing their behavior, as they are exclusive cases. This work presents the evaluation of the thermal behavior of two rooms of the Royal Hospital of Granada (Spain) through the study of thermal patterns in situ and simulation by computational means through non-destructive techniques. The results highlight the importance and improvement offered in the behavior of the spaces by the existence of thick walls. They also offer information to address strategic planning at the monument scale in the future, defining the conditions of thermal comfort confirming the incidence that recognizes its material composition, construction systems as well as its state of conservation.**

Index Terms— In situ thermal resistance; energy retrofit; wall thermal properties; non-destructive techniques; cultural heritage.

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I. INTRODUCTION

The architectural heritage constitutes an essential part of the cultural heritage, which requires the application of actions that allow its conservation and help to protect the environment, carrying out sustainable interventions. This approach commits all countries, governments and society that seek, among their objectives, to achieve the proposed goals. At present they are framed in the so-called Sustainable Development Goals (SDGs). Its implementation supposes, in addition to generating economic growth, helping the sustainability of the environment in all the actions planned in its different areas. Specifically, the protection of Cultural Heritage is contemplated in the fourth goal of SDG 11, which aims to "redouble efforts to protect and safeguard the world's cultural and natural heritage", being the way to "ensure that cities and human settlements are inclusive, safe, resilient and sustainable".

The application of these objectives, in the context of this study, generates a circular action between economic, social and environmental aspects, contributing to the protection and defence of cultural heritage (Ortega Sánchez et al., 2021; Soler Marchán, 2020). In this sense, the European Union determines as a strategic proposal to achieve the sustainability of architectural heritage buildings during the 21st century (European Commission, 2013).

In addition, the proposal and development of the conservation of cultural heritage and its enhancement contributes directly to the achievement of other SDGs, thereby achieving other achievements related to the safety and sustainability of cities, the slowing down of environmental degradation , and even gender equality, all involved in the promotion of peaceful and inclusive societies (Hosagrahar, 2017). Achieving the objectives in line with the SDGs requires intervention in old buildings with actions that improve their energy efficiency and good conservation. The possibility of guaranteeing the new use, allows their survival over time, giving them utility, and favouring the sustainability of the environment. To this end, along these lines, numerous research teams and scientific committees have developed guides and standards in which intervention in cultural heritage is analysed, including proposals to improve energy efficiency (EN, 2017; Lucchi et al., 2013; AERC, 2023; Lidelöw et al., 2019; De Santoli, 2015; Cool Bricks, 2013).

Most of the proposed approaches focus on reducing the transmittance of the building envelope, working on constructive solutions that prevent the heat inside from being lost, mainly through its facades (Kisilewicz, 2019; Zhou et al., 2018).

The most common proposal consists of placing an element that makes it impossible or reduces the transfer of temperatures. The solution being recurring through an element attached to the outside of the wall. Unfortunately, this solution is very limited when it is proposed in buildings of architectural heritage, whose facades, of great value, are protected (Magrini et al., 2016; Boarin et al., 2019; Buda et al., 2021), being mandatory the conservation of their original state. In these cases, the alternative is based on the placement of insulating material inside the wall.

This circumstance requires that the conservation, restoration or rehabilitation actions carried out on these properties be especially sensitive, so as not to distort their image. To this end, public bodies have been establishing state, regional and local regulations in which actions on these properties are regulated, ensuring the permanence of their original image.

The peculiarity of these interventions causes a dilemma when it comes to addressing the interventions, having to implement, on the one hand, actions for the conservation of cultural heritage and, on the other hand, actions that are appropriate to the requirements of current regulations. Recent studies highlight the importance of maintaining heritage values (Buda et al., 2021; Mazzola et al., 2019; Ruggeri et al., 2020; Siandou et al., 2015) compared to those that address issues of environmental sustainability, focusing mainly on energy efficiency measures (Cornaro et al., 2016).

Obviously, the ideal solution is to be able to achieve both challenges, although, to address the second of them, and reduce energy costs, it is necessary to know the thermal functioning of the envelope and specifically of the facades, since these constitute the largest surface percentage.

In the commented line, on the behavior of buildings and energy needs, the current situation and the increase in energy consumption has generated numerous studies whose main objective is to cover those needs. Furthermore, and as confirmed by (Xu et al., 2022), it corresponds to a significant part of the total energy consumption (Ciardiello et al., 2020; European Parliament, 2018; 2010). Consequently, the development of efficient energy sources, the control of energy consumption and with it the promotion of sustainable development, is increasing.

Climatic conditions and geographical characteristics have been decisive in the design of buildings, even more so in historical constructions, in which construction has focused on satisfying the needs of production and life, adapting to the climate and the characteristics of its environment.

The fundamental environmental thermal conditions are temperature and humidity, coinciding with the determining factors of the so-called thermal comfort. Being the measurement and evaluation systems the key elements for its quantification (Lai et al., 2020).

Being able to quantify the energy necessary to achieve user comfort has a direct consequence on the environment. (De Dear et al., 1998). But also on aspects related to socio-economic impact (Lai et al., 2020), health conditions (Aljawabra et al., 2009) and adaptability at different levels (Nikolopoulou et al., 2018).

With the advancement of construction science, the methodology dedicated to the study of the thermal environment and the characteristics and qualities of buildings have improved considerably. At present, they mainly include software simulation, in situ measurements, and satellite remote sensing (Xu et al., 2022). Its authors indicate that the satellite remote sensing method is considered the most appropriate in locations with similar environmental and climatic characteristics in large-scale studies. On the contrary, to a lesser extent, the most common research is based on simulations and real measurements, solving the problem of authenticity, and reliably showing the changes in the climatic environment, increasing the precision and reliability of the conclusions of the different studies.

In relation to the intervention in the heritage area, it is necessary to consider specific knowledge both about the buildings and about the applicable study and evaluation techniques. In this sense, historical studies are joined by those related to the characterization of their materials, knowing the nature and properties, the state and level of degradation as well as environmental conditions, the state of stress to which they are subjected and their foreseeable evolution. To achieve this, it is necessary to apply experimental techniques, sampling being the system used. However, due to the cultural value, the number of samples is considerably reduced, which requires the use of non-destructive techniques, being in many cases the exclusive way of analyzing the building. As (Menéndez et al., 2016) confirms, the need to preserve the great value of the objects in the most intact way possible has made the use of this type of technique mandatory, even during the construction phase, which allows us to know the suitability of the improvements implemented, as well as compliance with construction and regulatory requirements (Deepak et al., 2021). Added to the above is the limitation of destructive tests and the less representativeness of the results, which need to be contrasted with a greater number of tests that allow an adequate level of knowledge and evaluation, in the shortest possible time (yDiaferio et al., 2022).

In this sense, and on the topic addressed, the materials and construction systems used are decisive when choosing the intervention criteria that improve their thermal behavior and, therefore, the energy efficiency of the building. Therefore, it is necessary to carry out material characterization investigations, as is the case of the works carried out by some of the authors in singular patrimonial locations (Ramos molina et al., 2017; Durán-Suárez et al., 2019; Justicia Muñoz et al., 2021; Rodríguez-Esteban et al., 2014; Sáez-Pérez et al., 2019).

For this reason and taking into account that the studies carried out on them must be differentiated and specific for each type of material and construction system, the present investigation focuses on the study of the thermal behavior of old buildings that were executed with stone material. To carry it out, it must be borne in mind that both the materials and the construction systems used are different from the current ones, and it is necessary to know their behavior and their compliance based on current regulations.

Determining the thermal behavior of Stone Cultural Heritage buildings requires taking into account two aspects, on the one hand, that these walls have been exposed to the weather for decades, and on the other, that the material has certain intrinsic properties, which are determinants in its thermal behavior and whose information is very useful for its analysis and understanding (Umar et al., 2015; Grzyb et al., 2022; el Masri et al., 2020).

Therefore, the first action focuses on analyzing the material, (Sáez-Pérez et al., 2021; 2022), being necessary to consider the geographical factor. A posteriori, once the materials have been characterized and their behavior known, this study allows its application to other similar cases.

Based on the above, in the present investigation the temperature gradient of the facade walls and the thermal behavior of two rooms that are part of one of the most emblematic heritage sites in the city of Granada, a BIC building of special relevance, are analyzed. The Royal Hospital, currently the Rectoral Headquarters of the University of Granada. The present study intends through the use of non-destructive techniques and specific software, to verify and evaluate the thermal behavior of a building with a facade built in stone.

The investigation is carried out in different climatic seasons and orientations to correctly evaluate the behavior of the building throughout the year and thus know the influence of periods of sunshine and the behavior of the material through simulations. For this, two data sources have been used, resorting to two measurement procedures, "in situ" and through the analysis of statistical data.

The study carried out will help to evaluate the conservation interventions that can be proposed as part of the strategic planning at the monument scale, allowing to carry out evaluation, management, protection, and sustainable development actions applied to the built cultural heritage.

In addition, the possibility of extrapolating the results obtained to other buildings, located in different areas with similar material characteristics, construction solutions and environmental conditions, is recognized as of great interest.

II. CASE OF STUDY

A. *Historical study*

The building object of this study is known as The Royal Hospital and currently houses the Headquarters of the Rectorate of the University of Granada. Regarding the category of protection, the building in question enjoys the highest level of legal protection contemplated by Spanish legislation, that is, it has been declared an Asset of Cultural Interest (BIC) since 1931 (Gaceta de Madrid,1931).

The construction of the Royal Hospital of Granada began in 1513 and it was inaugurated unfinished in 1526 with the visit of Carlos V. Despite the fact that the building began to function on that date, the conditioning and finishing works lasted until the eighteenth century, suffering various events in this interval of time. The fire that took place in 1549 stands out as the most important, which forced the reconstruction of the carpentry to assemble and part of the factories in a large part of its rooms, among other deteriorations.

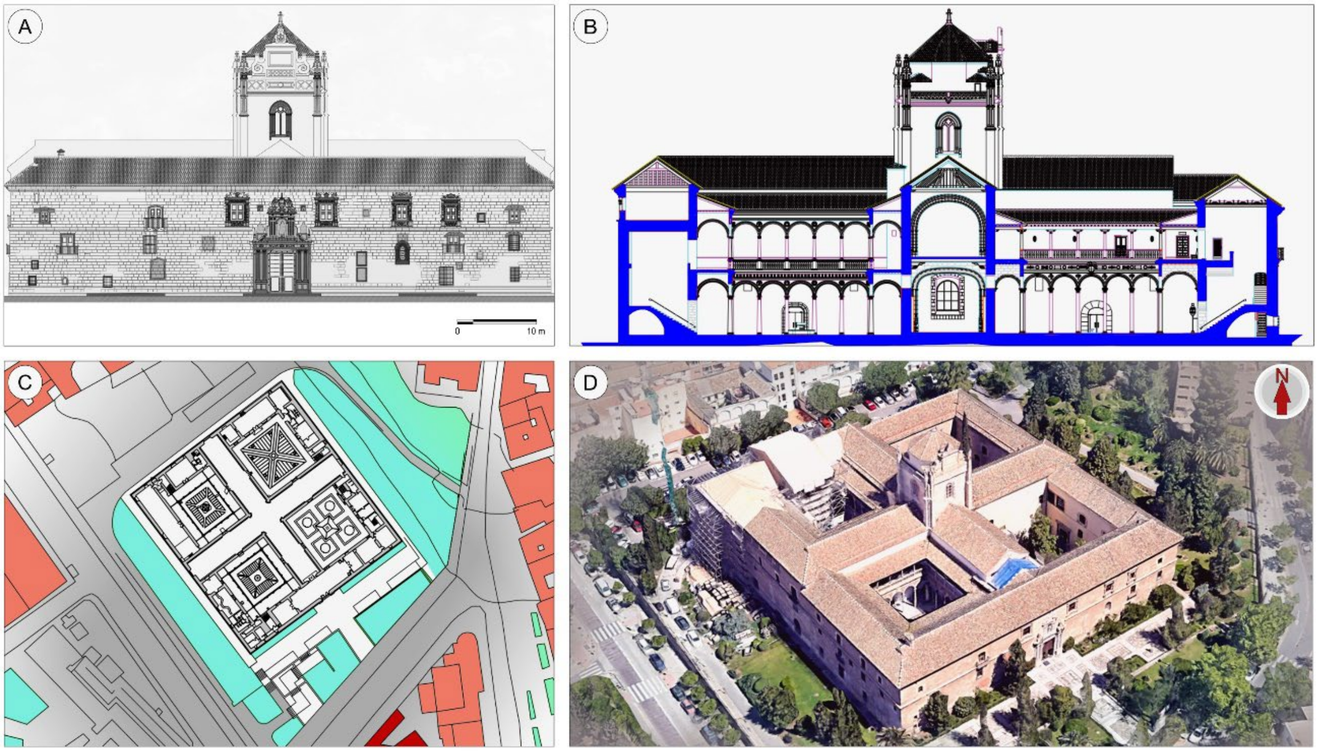

Fig. 1 Elevation plan (a), section plan (b), floor plan (c) and aerial view (d) of the Royal Hospital of Granada building

Formally, it presents a Greek cross floor plan with four symmetrical patios at its corners, built with stone masonry, the galleries being covered with wooden frames. At the intersection between the two main naves is the transept covered with a ribbed or ribbed vault, supported on four pillars adorned with little columns that is culminated in a dome. This type of structure corresponds to a design clearly influenced by Italian hospitals (Gallego Roca,2009). Both around the patios and in the galleries the different rooms are articulated. In elevation it has two floors, except for the southwest corner that exhibits a third floor known as the Gallery of Convalescents. Fig. 1 shows the plan, elevation, and section of the building.

The main façade presents a significant doorway, the work of Alonso de Mena (1632), carved in micritic limestone from native quarries (Sierra Elvira, Granada-Spain) almost entirely, except for some decorative details made of marble from the national quarries of Macael, Almería-Spain. The portal leads to the hallway, rectangular in plan and covered by a paneling like the rest of the naves on the ground floor except for the transept, which is closed with a ribbed vault. On the upper floor, all the naves are covered with wooden armor decorated with lacework and muqarnas, while the enclosure of the upper transept was solved with a wooden dome.

The original project of the building contemplated the erection and ornamentation of the four patios, but only two of them were addressed, partially the Patio de los Mármoles and the entire Patio de la Capilla. In the case of the Patio de los Mármoles, it was left unfinished as only the ground floor, of slender proportions, made up of a gallery of semicircular arches supported by marble columns, was traced. This patio would not be completed until the second half of the 20th century in the intervention carried out by the conservative architect of the Alhambra, Prieto Moreno (Gallego Roca,2009), who, among other things, made the forging of the galleries and the upper floor. On the other hand, the Chapel Courtyard stands out, which was finished in 1536 (as recorded in an inscription) and in which the building's chapel was located, hence its name. Regarding the construction system of said patio, it is made up of two porticoed floors with semicircular arches supported by columns, all carved in bioclastic calcarenite stone, from native quarries in Escuzar, Granada-Spain.

Because of its development over time, the building displays different architectural styles. Recognizing Gothic, Renaissance and Mudejar elements (Félez Lubelza, 2014). This mix of styles added to interventions such as the rehabilitation of the architect Prieto Moreno (mid-20th century), and the repair works and adaptation to various uses justifies the coexistence of different materials, construction systems, thicknesses, heights, etc. (Medina Flórez et al., 2016; Sebastián et al., 1990).

B. Location of rooms for the study. Constructive characterization

Prior to the climatological study, the historical and technical information available in previous studies and existing written and graphic documents on the building, in addition to those cited, were consulted (Romero Gallardo, 2011; Cambil, 2019; 2019; Valenzuela Candelario, 2004; Gijón Jiménez, 2017). The available information was complemented with the visual inspection and the recognition of different phases and construction systems of the complex.

Given the entity of the building and finding the investigation in the phase of previous studies, the thermal evaluation of two rooms, with similar characteristics, located on the ground floor of the Royal Hospital of Granada is addressed. Room 1 has its exterior façade oriented to the Southwest and Room 2 presents its exterior façade oriented to the Northeast. In both cases they are directly exposed to outside air conditions, located on the ground floor and having dividing rooms on the other 3 facades. Fig. 2 below indicates the location of the studied areas.

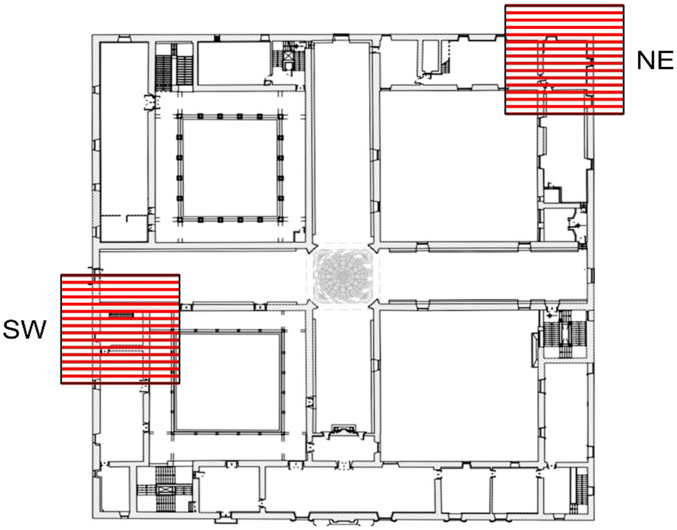

Fig. 2. Location by facades of the rooms in the building. Room 1= NE and Room 2= SW.

Regarding the geometric and constructive characteristics, the two areas present the same composition of materials. The data for each of them is shown in Table 1.

TABLE I
FEATURES OF THE STUDY AREAS

Features	Room 1	Room 2
Geographic orientation (outside wall)	Southwest	Northeast
Area	38.60 m2	29.58 m2
Height of the room	4.50 m	4.50 m
Outside walls (composition and thickness)	Travertine masonry Wall 1.10 m	Travertine masonry 1.10 m
Inside walls (composition and thickness)	Travertine masonry Wall 0.87 m	Travertine masonry Wall 0.87 m
Thermal conductivity	1.10 W/m·K	1.10 W/m·K

C. Climate study

The climatic conditions during the thermographic survey were monitored from the AEMET Cartuja Weather Station (AEMET, 2023). Data on temperature, air humidity, wind speed, pressure and precipitation were recorded.

The city has a mixed Mediterranean and continental climate according to the updated Köppen-Geiger Climate Classification (Kottek et al., 2006). In addition, Granada has the particularity of having Atlantic influences, with its average annual temperatures between 0°C and 34°C. The average annual temperature is higher than 18°C (UAH., 2012; Cara et al., 2008; Mühr, 2022). The city belongs to the C3 climatic area, according to the Spanish CTE regulations (CTE, 2006). This unique location makes it possible for the temperature variations recorded on the same day to exceed a 20º difference.

In 2020, Wang et.al. (2021) investigated the interlayer reinforcement of 3DCP by the in-process deposition of U-nails. A robotic 3D concrete printer was developed with a horizontal working space of 1.73 m. to see the effect of U-nail reinforcement different specimens with different U-nails thicknesses and intervals were tested. In the interface shear tests, they observed that the tensile strength was increased by increase in U-nail thicknesses and was decreased by in U-nails spacing. The U-nail which were used in the experimental study of Wang et.al was steel.

III. METHODOLOGY

A. Thermographic study

In a first phase, the thermographic study was carried out during the two most representative months of the maximum and minimum temperatures (January and July) in which the exterior and interior walls of the building were inspected with a HIKMICRO M20W thermographic camera. The camera has a spectral band between 7.5 μm to 14 μm, a resolution of ±2°C, and simultaneously records infrared and visible spectrum images. Post-processing of the infrared images was performed with the Hikmicro Analyzer thermal imaging software (Hikmicro, 2023).

The thermographic survey was carried out in different time slots to allow the recognition of the walls without insolation and after the warming of the day due to solar radiation, which allowed recognition of the temperature variation through thermographic detection.

The choice of spaces was determined for those locations in which both the constructive and dimensional component could be identified and corresponded to different and opposite orientations, one being directly exposed to solar radiation, (Stay 1, > 6 h) and the other totally protected from solar radiation (Stay 2, = 0 h). During the study, the two rooms were without air conditioning.

In the second phase, to carry out the study of gradients and isotherms of the selected facades, the study of temperatures was carried out using a Raytek Inc. PM5 DLM (Data Logger Model) infrared emissivity thermometer with laser pointer was used for the thermographic test. The main features of the non-contact temperature measurement device are as follows: temperature range from -18°C to 870°C; digitally adjustable emissivity from 0.1 to 1.0; accuracy of ± 1 %; repeatability of ± 0.5%; spectral response from 8 to 14 μm, and working temperature from 0 to 50°C.

The work system consisted of measuring the surface temperature of part of the exterior travertine stone wall from local quarries in Alfacar, Granada-Spain, on the northeast façade of the Royal Hospital of the Catholic Monarchs in Granada-Spain (16th century) and part of the exterior wall of the southwest façade of the same Cultural Heritage Site. Both have an approximate area of 5 m2. The measurements taken, both on the northeast and southwest sides, were carried out once the total or partial direct solar radiation had been removed.

For this purpose, a grid was drawn up with nodes at a distance of 10 cm from each other where the temperatures were taken. For this grid and its corresponding sampling points, laser levels with crossed lines were used to ensure the highest precision between each node at 10 cm.

All measurements were included in a calculation software to compose a longitudinal thermal gradient, from the bottom of the wall to the top, as well as a distribution of isotherm areas. T

A total of 513 measurements were taken in each area of travertine wall and mortar joint of aerial lime mortar and river sand aggregate (granular fragments of marble, silica sand, schist, quartzite, and/or serpentinite), whose sizes range from 1.5 mm to 4 mm.

The environmental values for the location of the north-facing wall at 13:00 on 25 February 2022 were as follows: temperature 17.0 ºC and relative humidity 63%. In the case of the measurement of the south-facing wall at 15:00 on 25 February 2022, its ambient values are: temperature 15.6°C and relative humidity 62% (AEMET, 2023).

B. *Energy simulation. Numerical study*

The chosen areas were subjected to an energy simulation, with the objective of evaluating the thermal behavior in a state of "free floating" (free floating), that is, without the support of artificial air conditioning, ventilation, heating or cooling systems.

In this study, the EnergyPlus tool (EnergyPlus, 2023) is used through the OpenStudio application for SketchUp (OpenStudio, 2023) because it is a software that offers reliable results, as demonstrated in their research (Sakiyama et al., 2021; Ciardiello et al., 2020; Balaji et al., 2019).

Regarding the time interval chosen for data collection, the lowest criterion allowed by the program is adopted, that is, obtaining numerical results every hour whenever possible. The total simulation time spans a full year.

The procedure is carried out in 6 stages:

- Stage 1. Geometry survey. Definition of envelopes.
- Stage 2. Definition of the thermal areas that make up the construction.
- Stage 3. Definition of the boundary conditions of the construction (differentiation between interior and exterior areas and those in contact with the ground).
- Stage 4. Introduction of holes and their characteristics for the elements that make up the envelope.
- Stage 5. Configuration of the climatology data according to the location of the building.
- Stage 6. Carrying out the energy simulation. Verification of the thermal behavior of the building (studied rooms) without the influence of any air conditioning, heating, refrigeration, or ventilation system

IV. RESULTS AND DISCUSSION

A. *Longitudinal gradient and distribution of isotherms*

The results are shown in the corresponding Fig. s 3 and 4 where the longitudinal thermal gradient has been represented, from the point 0-0 to 0-27 (x-y profile of temperature (°C) vs length (m).

In the same way, the isothermal areas of each area measured in an X-Y (distance between nodes of 10 cm over the entire surface) and Z (representative of the temperature values in ºC) arrangement have been represented with colour scales in the corresponding intervals. This arrangement corresponds to points 0-0 to 19-27 (total of 513 temperature values). Finally, the real image of the wall under study has been combined with an insertion of the isothermal areas filled with coloured bars.

In relation to the northeast wall, a relative homogeneity in the profile of the thermal gradient is detected, ranging from 0-0 to 0-27 slightly more than 2°C in an upward direction. This represents thermal differences in the longitudinal thermal gradient of approximately 11%. On the other hand, the surface thermal gradient oscillates from 0-0 to 19-27, where there are thermal variations with superficially heterogeneous isothermal areas, of about 4°C, a factor that represents a variation of 18.5%. All this in an increasing and oblique direction from lower to higher temperature. The coloured bar inset graph reiterates the results and discussions indicated in the isotherm area graph.

Regarding to the southwest wall, the profile of the thermal gradient is very heterogeneous (like saw peaks), oscillating from 0-0 to 0-27 almost 10°C upwards. This represents thermal differences in the longitudinal thermal gradient greater than 35%. On the other hand, the surface thermal gradient oscillates

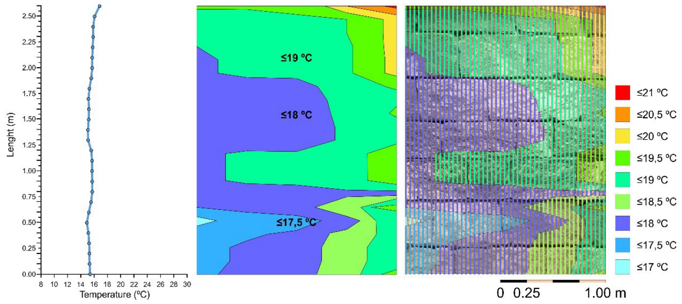

Fig.3. Exterior northeast wall of the Royal Hospital in Granada-Spain (16th century). From left to right. Thermal gradient profile relating temperature vs longitudinal direction (points 0-0 to 0-27). Graph of x-y isotherms (surface positioning at 10 cm intervals) and Z (°C) from point 0.0 to 19-27. Superimposed graph of isotherm areas with coloured bars on the image of the north wall. The coloured squares represent the resulting isothermal intervals-areas

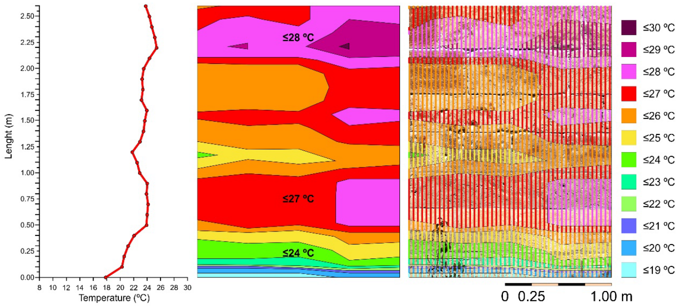

Fig. 4. Exterior southwest wall of the Royal Hospital in Granada-Spain (16th century). From left to right. Thermal gradient profile relating temperature vs longitudinal direction (points 0-0 to 0-27). Graph of x-y isotherms (surface positioning at 10 cm intervals) and Z (°C) from point 0.0 to 19-27. Superimposed graph of isotherm areas with coloured bars on the image of th southeast wall. The coloured squares represent the resulting isothermal intervals-areas

from the 0-0 point to 19-27, where thermal variations occur, with superficially heterogeneous isothermal areas, of around 11°C, a factor that represents a variation of approximately 40%. All this in an increasing and slightly oblique direction from lower to higher temperature. However, the thermal radiation of this area of the southwest wall has generated greater heterogeneities in the areas of thermal equality, probably due to the heterogeneity of the native travertine stone, to the loss of joints between the stone ashlars, to both causes, and even to the selective factors of alteration that proliferate in this type of construction materials.

B. Simulation results

After the simulation, the analysis of the results presented below determines the potential benefits of the rooms that allow mitigating the negative effects of high and low temperatures.

First, the thermal sensation data obtained in the simulation are compared with the thermal data of the two rooms (Room 1 and Room 2). Secondly, the two rooms defined in section 2 are analyzed. Case Study, comparing the percentage of hours of thermal comfort.

C. Evaluation of the orientation of the rooms

Fig. 5 compares the data obtained in the simulation in relation to the average temperature ranges inside the two rooms, with their façades oriented in Room 1 to the Northeast and in Room 2 to the Southwest.

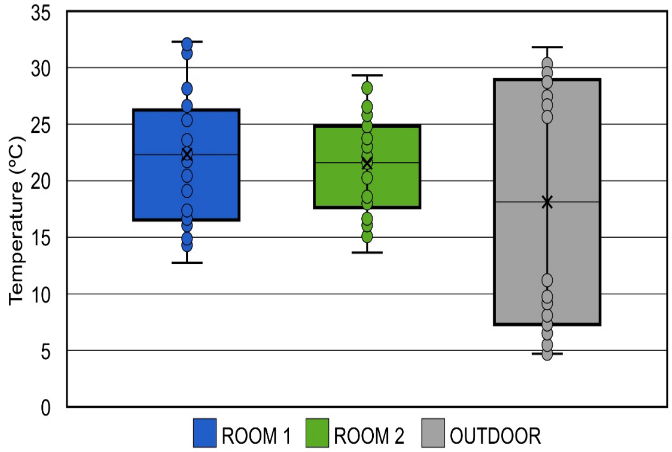

Fig. 5. Graph of average temperature ranges inside the two rooms and outside during the study period (1 year). The colored rectangles represent the distribution of the data. The horizontal lines represent the maximum, average and minimum temperature values.

The comparison of these data shows that Room 2 presents higher temperatures than Room 1. In addition, the minimum temperatures are higher in Room 1. On the other hand, the thermal oscillation is noticeably wider in Room 1, up to 14 .3°C, being 12.7°C in Room 2, resulting in a difference between the two of 1.6°C.

Fig. 6 and 7 illustrate the evolution of the maximum and minimum daily interior temperatures for the coldest and hottest months of the year, which allows a better understanding of the thermal behavior of each room.

The results for the month with minimum temperatures (January) are shown in Fig. 6. The coldest days are between January 15 and 21, with minimum temperatures of 14.7 and 18.6°C for rooms 1 and 2 respectively.

It can be seen how the data in Room 1 show lower temperatures during the coldest month, (≈15°C) with a difference of 10.8°C compared to the outside temperature. For its part, Room 2 offers slightly milder temperatures for that same period, with the minimum temperature being 16.1°C and presenting a difference with respect to the outside temperature of 11.9°C.

In the case of the hottest month, with maximum temperatures (July), Fig. 7 shows the results obtained. In this period the hottest days are between July 22 and 30, with maximum temperatures of 22.8°C for Room 1 and 30°C for Room 2.

Likewise, it can be seen how the data for Room 1 show milder temperatures during the hottest month, reaching 29°C and presenting a difference with respect to the outside temperature of 2.5°C (See Fig. s 5 and 7). In addition, it is confirmed that the data for Room 2 show higher temperatures during the hottest month, reaching 30°C and presenting a difference with respect to the outside temperature of 1.5°C (See Fig. 5 and 7).

D. Impact of geometry on the operation of rooms

This section compares the internal thermal sensation of the two rooms in "free-running" conditions (without any air conditioning system). With this it is possible to evaluate the comfort time inside generated by the constructive and geometric conditions for each room.

Fig. 5 shows the average temperature distribution inside the two rooms under "free-running" conditions. Despite both having a substantially square plan, Room 1 reaches the most extreme interior temperatures between 15 and 20.2°C, and more

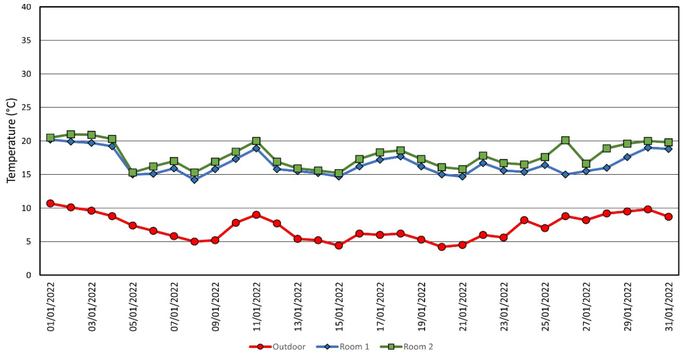

Fig. 6. Average daily temperature of the study areas during the coldest month (January)

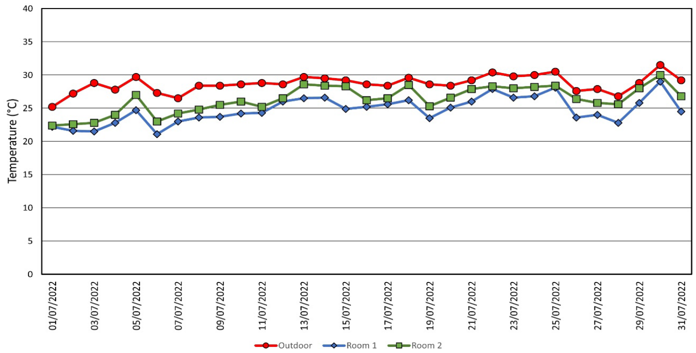

Fig. 7. Average daily temperature of the study areas during the hottest montl (July)

moderate warm average temperatures, between 21.4 and 29°C.

In contrast, Room 2 reaches more moderate cold interior temperatures, between 16.1 and 21°C, and more extreme warm average temperatures, between 22.4 and 30°C. Between the two rooms, there is an average temperature difference of 1.1 ºC in the coldest month and an average temperature difference of 1°C in the hottest month.

E. Optimal climate-resilient configuration of the rooms

Table 3 shows the benefits of Ranch 1 and Ranch 2 in mitigating the impact of extreme temperatures. In the cold month, Room 1 can offer thermal comfort for 94% of the time of the analyzed period, by managing to maintain the average temperature above the comfort level established by ASHRAE (ASHRAE, 2019), which stands at 17.6°C. In the case of Room 2, the percentage increases slightly, until reaching 95% of hours of comfort, which represents an improvement of 1% compared to Room 1.

For the hottest month, Room 1 can offer thermal comfort for 97% of the time of the analyzed period, that is, keeping the average temperature below the level established by ASHRAE (ASHRAE, 2019), being 26.7°C. For its part, Room 2 ensures 99% of hours of comfort, improving 2% compared to Room 1.

TABLE I

FEATURES OF THE STUDY AREAS

Annual thermal comfort		Comfort difference between rooms 1 and 2
Cold month		
Room 1	343 days = 94%	1%
Room 2	348 days = 95%	
Hot month		
Room 1	353 days = 97%	2%
Room 2	360 days = 99%	

V. DISCUSSION

Regarding the gradient and the distribution of isotherms, it is confirmed that the thermal radiation of the area of the southwest wall studied involves greater heterogeneities throughout the studied surface, probably due to the heterogeneity of the autochthonous travertine stone, to the loss of jointing between the ashlars of stone, or even both causes at the same time, also having to consider possible selective factors of alteration that proliferate in this type of construction materials.

On the other hand, regarding the geographical orientation, the data obtained show the thermal benefits of orienting the most permeable façade towards the Northeast orientation compared to the Southwest orientation.

In relation to the simulation, the data obtained show the thermal benefits derived from the recognized orientation for each room. In the case studied, the most permeable façade corresponds to the Southwest orientation compared to the Northeast orientation. As shown in Fig. s 5 and 6, in the period with minimum temperatures, façade 2 is capable of mitigating the temperature up to a maximum of 11.9°C. On the other hand, it is observed that during the hottest period, Room 1 with a northeast orientation mitigates heat more efficiently, while Room 2 with a southwest orientation offers greater heat filtration in the winter month.

The influence of geometry in the parallel operation between Rooms 1 and 2 highlights the potential to mitigate extreme temperatures in the building. The mitigation of the maximum temperatures in the building has a positive impact on the interior rooms, reducing heat gains by transmission, infiltration and ventilation during daylight hours. As indicated in the Impact of geometry section, the results for Room 1 show an average temperature in the cold month that is 1.1°C colder compared to Room 2.

Finally, the climatic-resilient analysis of the rooms studied indicates that the thermal oscillation that is created in Room 1 presents a better efficiency in the hot month by 1°C, which represents an improvement of 3% with respect to Room 2. In contrast, Room 2 presents a better behavior in the cold month by 1.1°C, which represents an improvement of 6.8% with respect to Room 1. This means that, using different geometries and locations of transition spaces between the exterior and interior passive cooling strategies can be designed and planned to increase indoor comfort hours and cooling demand (Galán-Marín et al., 2018; López Cabeza et al., 2020; 2018).

6. CONCLUSIONS

The research carried out tries to provide an estimate of the thermal performance of the locations chosen in the building under study, through the study of its envelope, largely responsible for the regulation of the internal thermal environment in response to the external environment. This article presents for the first time a complete simulation of two rooms that encompass the casuistry of the Royal Hospital of Granada (16th century) to consider the potential benefits of its orientation in the climatic conditions of its location. The results demonstrate and quantify that considering the geometry, situation, orientation and inclusion of transition areas between the exterior and the interior, the improvement in thermal comfort is obtained. It is worth noting the need for future studies with different construction typologies and orientations, existing in the building, as well as the impact on the behavior of open spaces (patios) and extreme hot and cold conditions.

For the study addressed, the climatological study and the analysis of the thermographic images are considered key information required for the simulation that, as it has been revealed, determines the thermal behavior of the building.

Analyzing the behavior of the façade walls, it is confirmed that the thermal characteristics of the existing thick masonry walls are suitable for climates with high thermal amplitudes, as is the case of Granada, together with a high percentage porosity with respect to the volume of the stone material. , because the thermal mass offers benefits as a consequence of its thermal inertia and insulating capacity in line with (Balaji et al., 2014; Flores Larsen et al., 2021).

The study allows us to confirm the incidence of the construction components in the thermal behavior and in the scope of thermal comfort inside the rooms, being more relevant in high temperatures, proving greater benefit through the microclimate created inside the spaces. This reflects the attenuation capacity of the materials that make up the envelope, managing to reduce the increase in temperature.

It is therefore concluded by confirming that the study carried out and the methodology used are adequate for determining the thermal behavior of thick walls in heritage buildings. Its reliability allows these investigations to be carried out in other locations, both in the same building and in other heritage buildings, in which different formal, constructive, material and environmental conditions can be considered.

The use of non-destructive study methods offer valuable scientific support through the results obtained, for decision-making in future energy rehabilitation strategies in the context of the restoration of heritage buildings

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