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User Thermal Comfort in Historic Buildings: Evaluation of the Potential of Thermal Mass, Orientation, Evaporative Cooling and Ventilation

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Abstract: The study investigated the level of thermal comfort in historical buildings located at a relatively high altitude in the Arabian Desert of Saudi Arabia. The study focused on the impact of the use of thermal mass and orientation on the level of thermal performance at Shubra and Boqri Palaces. Qualitative and quantitative analyses were used in this study, including a questionnaire interview with architecture experts living at the relatively high altitude of Taif city, to obtain data and information from local experts. The computer software TAS EDSL was used along with on-site equipment, such as thermal imaging cameras and data loggers, to observe the physical conditions of the building in terms of its thermal performance. The study revealed that the experts' age and years of experience were important aspects while collecting data from them during the survey. The use of thermal mass had a slight impact on the indoor air temperature as well as the energy consumption, but it helped in providing thermal comfort. Use of ventilation can improve thermal comfort level. Evaporative cooling technique has a considerable impact on reducing indoor air temperature with 4 °C drop, improving the thermal comfort sensation level. The novelty of this work is that, it links the outcomes of qualitative results of experts with field monitoring as well as computer modelling. This can contribute as method to accurately collect data in similar case studies.

Keywords: historical buildings; thermal mass; orientation; hot regions; evaporative cooling; ventilation

1. Introduction

1.1. Background

Buildings should be constructed with consideration of the local microclimate conditions at a given location, particularly when dealing with thermal comfort, which relies heavily on location and culture [1]. Thus far, many passive strategies have been proposed to improve the energy building performance and comfort, such as thermal mass, window to wall ratio (WWR), SHGC, building geometry, orientation, and layout [2–4]. Several researchers have investigated the influence of low-E glazing, which aids in improving energy consumption as well as internal visual comfort [5]. WWR is a significant element for energy use for cooling, and to a less extent, ventilation and daylight [6]. Solar radiation is a leading factor affected by the solar coefficient as well as WWR [7].

1.2. Impact of Window to Wall Ratio (WWR)

With respect to the hot and dry climate of Saudi Arabia (Figure 1), Alwetaishi [8] explored the impact of WWR in the different climatic zones of Saudi Arabia. The results determined that WWR in hot regions should not exceed 10% in all the directions; however, the impact of this opening size on de-lighting was unclear. Moreover, another study was conducted in a similar climate of Libya [9]. This study revealed that an increase in the WWR on the south-side led to an increase in the energy load in summer and a nearly zero demand of heating in winter. In another study reported in [10], in the hot climate of Libya, an increase in the WWR resulted in an increase in the cooling energy in summer and a reduction to nearly zero carbon energy in winter. However, the amount of cooling energy generated by the increase in the WWR was greater than that of the energy saved in winter, which led to the overall increase in the annual energy consumption. Even in cold climate, there is a significant influence of windows in the form of solar heat gain [11].

Thus, each direction would have a different WWR depending on the local climate (Figure 2 shows different climatic zones in Saudi Arabia), which is very similar to the findings of Alwetaishi [11], where each direction within the same building was designed according to the diversity of the solar radiation exposed to the outer surface of each direction. The study revealed that the south and west orientations should have their glazing minimised as compared to the east and north ones. Similarly, Asfour [12] studied the impact of de-lighting and having a courtyard, considering the hot and dry climate of Saudi Arabia; he recommended that the WWR should be minimised and the usage of external shading devices should be encouraged. In addition, the study also highlighted that increasing the WWR in such a region to more than 50% will only lead to an increase in the cooling demand as well as in the glare, which will ultimately affect human comfort. Alshuhail [13] investigated the influence of orientation on thermal performance in an experimental study performed in the hot and dry climate of the UAE. This study revealed that the south orientation has a 9.4% higher temperature than the north.

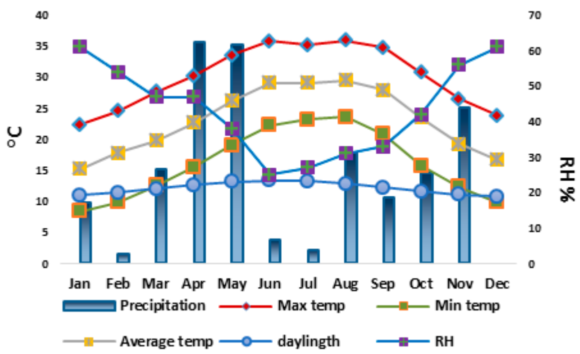


Figure 1. Climate of Taif city, reproduced from the .epw file derived from Alwetaishi [11].

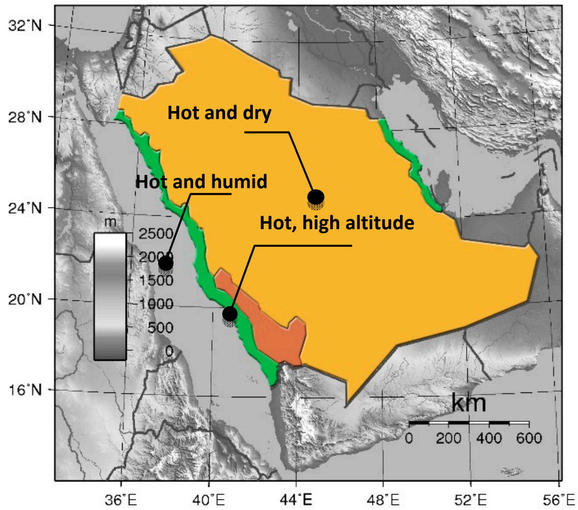


Figure 2. Major climatic zones in Saudi Arabia based on temperature, humidity, and altitude, as introduced by Alwetaishi [8].

In contrast, another study reported in [14] investigated the impact of orientation on the indoor thermal environment in the hot and humid climate of Singapore. This work highlighted that the north and the south orientations are preferred for providing thermal comfort over the east and the west ones. Su [15] stated that a single glazing window models a higher influence on the energy demand than any other aspect, while low-E could considerably improve the lifecycle energy performance of the building. In addition, the WWR should be precisely highlighted, as it increases the energy demand even in regions with a relatively cool climate [16–18]. Note that the type of glazing has a greater impact on the energy demand in hot countries than the orientation, building shape, and storey level [19]. Shahbazi [20] introduced a new tool to optimise the glazing system by using a parametric study. In cold regions, the WWR may affect the solar gain and the daylight in winter when passive solar heat is required; however, it may lead to overheating in summer [21]. As a result, the WWR should be designed carefully even in cold regions (Table 1 highlights recent publications in the topics of thermal mass, orientation and WWR) while Figure 3 present flow chart of study

Table 1. Selection of recent studies on thermal mass, orientation, and WWR.

Ref.	Year	Country	Climate	Method	Major Findings
[22]	2020	Italy	Mediterranean	Review paper	Thermal mass and night ventilation can improve energy consumption in the case of retrofitted heritage buildings
[23]	2020	Spain	Mediterranean	Photovoltaic electrical self-system	It can reduce amount of energy consumption from 60–80%
[24]	2020	Turkey	Black sea	Experimental	Use of night ventilation and thermal mass can reduce energy consumption by 27%
[25]	2020	Germany	Temperate	Model predictive control (algorithm)	The use of thermal mass can reduce the energy demand by 3–7%, and it is considerably linked to the thermal comfort level.
[19]	2020	Saudi Arabia	Hot and dry	AEISS, ECOTECT, BIM, Revit	Window glazing has a considerable impact on the cooling load in hot regions as compared to other aspects such as orientation, building shape, and storey level.

Table 1. *Cont.*

Ref.	Year	Country	Climate	Method	Major Findings
[26]	2019	Australia	Temperate	IDA and ICE computer software	The use of thermal mass through various wall and flooring systems can reduce the energy demand by up to 58%.
[12]	2020	Saudi Arabia	Hot and dry	EnergyPlus, Radiance	• It is recommended to use shading devices, courtyard, and atrium to control the sunlight in hot regions. • The optimum WWR is 30% with the use of a shading device. • Increasing the WWR to a value higher than 50% will impact glare and increase the cooling demand in a hot region.
[13]	2020	UAE	Hot and dry	Measuring equipment	South-facing rooms have 9.5% higher temperatures than the north-facing ones.
[11]	2020	Saudi Arabia	Hot and dry	Measuring equipment, TAS EDSL computer modelling	It is recommended to have a WWR of 35% for north-west-facing rooms, 25% for south-east-facing rooms, and 20% for south-west-facing rooms.
[27]	2019	China	Temperate	Proposed model based on control	The use of thermal mass in this region can save up to 7.23% energy.
[28]	2019	Portugal	Mediterranean	EnergyPlus	• Thermal transmittance (TT) can vary depending on the location of the building. Istanbul for instance, might have a variation of TT of −0.73% to 4.21%), while Casablanca was found to be in the range of −5.66% to 6.96%. • The determination of the impact of thermal mass is very complex, and the amount of TM has to be identified on the basis of TT.
[29]	2019	China	Hot summer and cold winter	State-space model	A high thermal mass has no effect on the energy demand, but it helps to improve the thermal comfort for the users.
[30]	2018	India	Composite	Experimental study	The use of thermal mass can aid to improve the thermal comfort from 40% to 98% in summer and winter, respectively.
[31]	2017	Ireland	Hot and cold climates	Transient energy ratio method	The use of thermal mass is more likely to be effective in hot countries.
[7]	2013	Malaysia	Hot and humid	Measuring equipment	• Reduction of the amount of solar radiation is the leading factor in building heat transfer. • Solar radiation is affected by the WWR and the solar coefficient.

1.3. Significance of Thermal Mass in Buildings

Thermal mass (TM) can be classified into two major groups: internal TM, such as furniture, and external TM, such as walls, roofs, and floors [32]. The use of TM can be effective in reducing the total amount of energy and maintaining the thermal comfort levels for the users [23,26,30–32]. TM is the most functional in hot weather when outdoor temperatures soar sharply [31] or in hot summer in cooler regions [25,26,28,33–35]. Kumar [36] argued that the use of thermal mass is not beneficial only in summer but also in the composite climate of India in winter. Furthermore, Rodrigues [28] investigated the relationship between energy consumption and thermal mass in the Mediterranean climate and found that thermal transmittance varies on the basis of the local climate. For instance, the variation of thermal transmittance was as low as (−0.99% to +3.89%) in Marseille in France and was as high as (−1.81% to 5.44%) in Tel Aviv. This work also highlighted the importance of the effect of thermal transmittance on the thermal mass performance. A comparison between a historical building built of stone with a modern one built with bricks was carried out by Yousef [37] in the hot climate of Egypt. This study indicated that the use of a historical building helps to lower the indoor air temperature by 1.4 °C. Furthermore, there many publications which are conducted based on a case study of heritage buildings such as [38,39].

Thermal mass is strongly connected to thermal comfort. According to Kumar [30], 40% to 98% of thermal discomfort can be avoided when using thermal mass in buildings. In fact, some of the published work argues that the use of TM will not aid in reducing the energy demand but will help to improve the thermal comfort level for users [29]. A new design formula was introduced by Li [40] to be used by architects and engineers; it includes three parameters, namely the time constant of the system, the dimensionless convective heat transfer number, and the Fourier time constant.

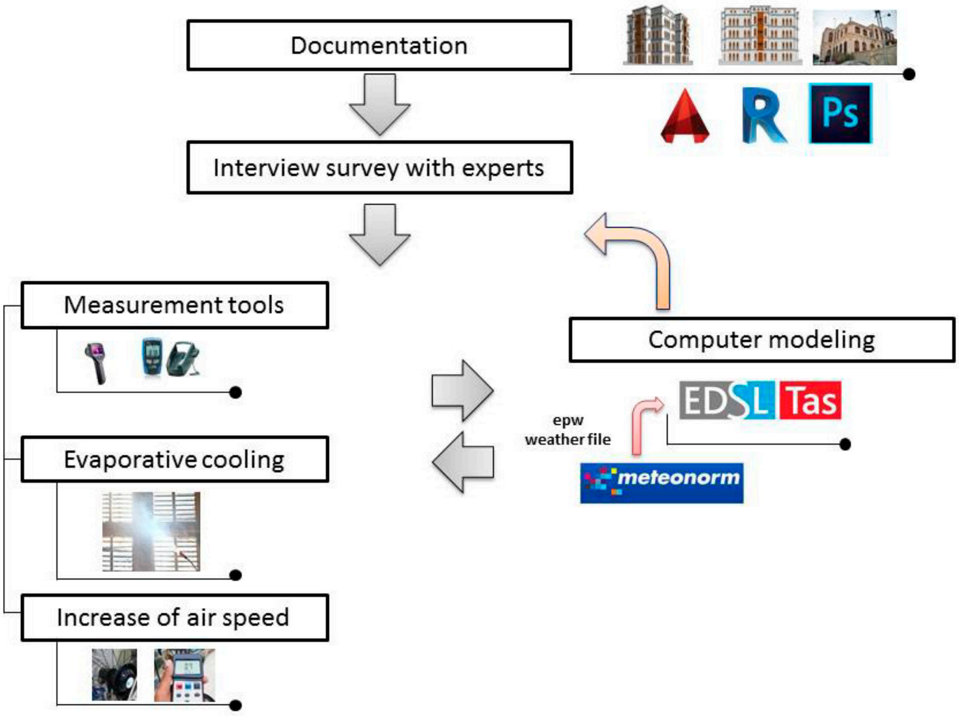


Figure 3. Flow chart of the methodology.

1.4. Evaporative Cooling in Buildings

Evaporative cooling is a widely used method for cooling especially in hot regions [41,42]. In a study conducted by [43] in a hot region, it was found that the use of ventilated wall cavity using spray evaporative cooling system can reduce temperature of outdoor from 45 °C to 25 °C. In addition to that, the work of Alaa [44] indicated that the same system can reduce the amount of cooling load by 23%. In a study carried out by Bagasi [45] where authors used different techniques for indoor evaporative cooling systems in a hot and humid climate. They found that evaporative cooling system using wet cloth can reduced indoor air temperature by 26.3%. However, high relative humidity was observed during the study due to the climate which is hot and humid. There are several some other methods for evaporative cooling such as spray passive Downdraft evaporative cooling (PDEC) which has been intensively investigated such as the work of Kang [46]. In a study conducted by Ana [47] highlighted that use of evaporative cooling systems can achieve thermal comfort level with a free running operation system in the climate of Spain. This study used wide range of tools to conduct the study, Table 2 indicates equipment used.

Table 2. Specifications of the tools used in the study.

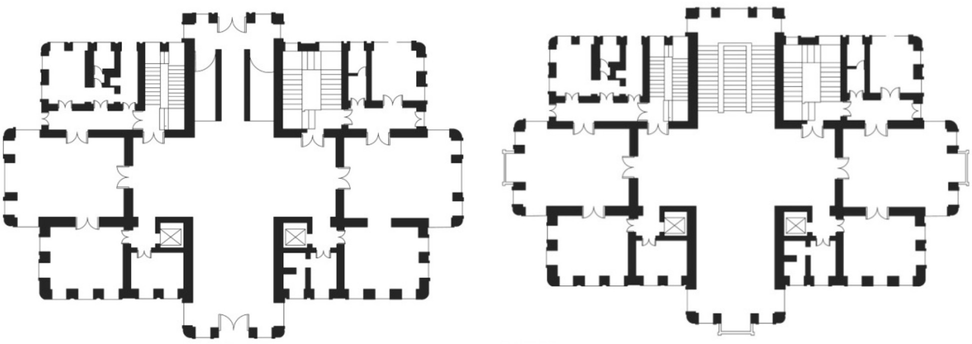
Sensor/Tool	Output		Accuracy/Sensitivity
Thermal imaging photographs	Temperature range from −20 to 250 °C (−4 to 482 °F)		<0.15 °C
Temperature and humidity data logger	- Records 32,000 data points - Built-in sensor to measure temperature and humidity		Temperature: ±1.0° Humidity: ±3.0%
TAS; energy building performance tool	Energy analysis, daylight, thermal comfort, etc.	EDSL Tas	-
Watering Sprayer	To moisturize the air		-
Air fan	To increase indoor air speed		-

1.5. Case Study and Shubra Palace Documentation Contribution

Shubra Palace is considered the most important historical building in the city of Taif and is one of the most important old buildings in Saudi Arabia (Figures 4 and 5).

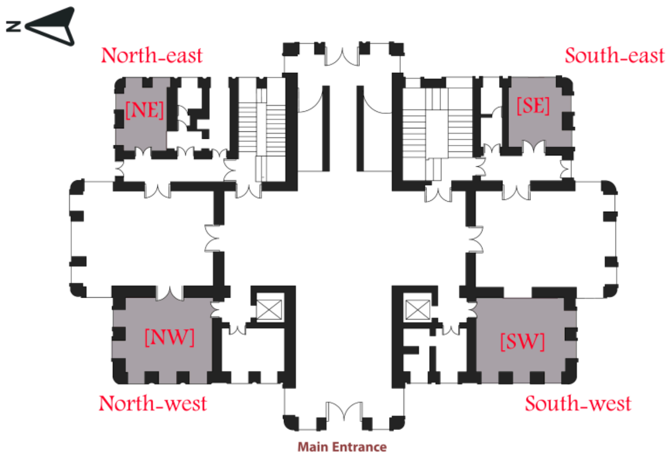
(**A**) (**B**)

Figure 4. Photograph of Shubra Palace (**A**) and (**B**) Boqari Palace (entrance hall), (Source: authors).



(**A**) (**B**)

Figure 5. *Cont.*



(**C**)

Figure 5. Plans of the palace produced by the research team of the current study: (**A**) ground and first floor levels (office and work), (**B**) typical design for second and third levels (family residence design levels), and (**C**) location of each of the rooms examined.

2. Method and Material of Study

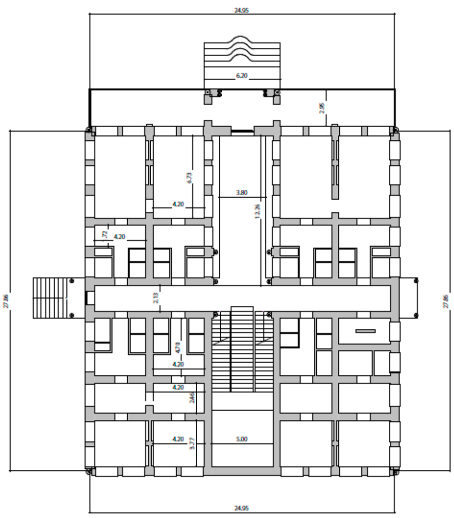
According to Arab news [48], the palace was built in 1907, and it is the first historical building in the city of Taif. It has a museum section attached to it, which represents three major periods of before Islam, Stone Age to Jahiliya period; Islamic heritage; and the unification of the Kingdom. It also contains a large number of valuable artefacts. The palace used to be the residence for King Faisal and his office. This made the building quite important with a valuable historical background. Unfortunately, as the building is quite old, no architectural drawings of this building exist. As a result, the first mission to the research group was to provide all the architectural drawings of the palace (Figures 5–7). These documents are considerably important to be conserved in the palace, displayed in the museum, and used in future research. In addition to that, Boqari Palace also is considered one of the most important historical buildings in Taif city which was built about 100 years ago. The palace is located in the heart of the city and it was made of stone. The Palaces were monitored using number of tools listed in Table 2. The study investigated the case studies presented in Figures 6 and 7 along with conducting a survey designed for experts is that both methods were aiming to highlight historical buildings. This will provide a comprehensive investigation to link the two methods all together.

(**A**) (**B**)

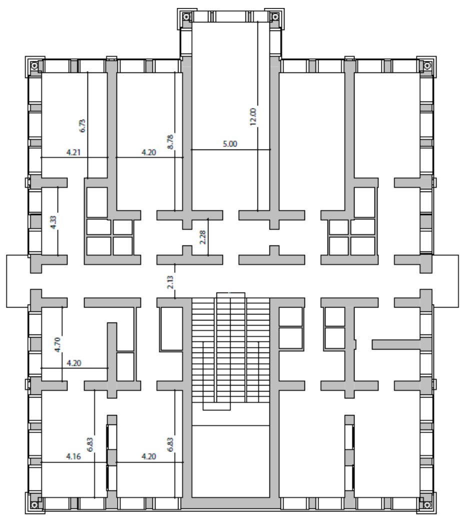
Figure 6. *Cont.*

(**C**)

Figure 6. Views of the palace produced by the research team using AutoCAD and Revit: (**A**) main entrance (west), (**B**) side entrance leading to the house (east), and (**C**) 3D view of the palace.



(**A**)



(**B**)

(**C**)

Figure 7. Elevation and plans of Boqari Palace (**A**–**C**).

2.1. Questionnaire Design and Sample Size

This study aimed to collect the opinions of experts in architecture and of those who were interested in historical buildings and to compare these data with the results of computer modelling as well as the used equipment such as thermal imaging cameras and data loggers. The sample size of the survey was 171 with a vast majority of architecture experts. Approximately 87.3% of the sample lived in the high altitude city of Taif. Table 3 shows the design and content of the questionnaire, which aimed to observe the achievement of thermal comfort in the high-altitude mountain regions of Saudi Arabia, such as the cities of Taif, Abha, and Baha (Figure 1). Most of the people living there were influenced by the local behaviour of relying on air conditioning systems even though it might not be necessary. The participated people were interviewed during November and December of 2019. Most of them were visited in their places of work to set up the interview. However, some other who based in the city of Abha which is very far away from Taif city conducted an online interview.

Table 3. Items of the questionnaire sheet designed particularly for architecture experts.

Item/Statement		Content
1.	Personal information	Age, subject, years of experience, education level
2.	I believe that old and historical buildings in Saudi Arabia are better than modern buildings with respect to providing thermal comfort to the users.	Strongly agree, slightly agree, neutral, slightly disagree, strongly disagree
3.	Can old and historical buildings provide thermal comfort to the users without the use of ACs?	In winter, some seasons in the year, from time to time, in higher altitude areas only, it is not possible at all
4.	What is the most important aspect that helps to improve the thermal comfort in old and historical buildings?	Thermal mass, building orientation, WWR, other, it does not provide thermal comfort
5.	Do you think that modern buildings in the higher altitude areas in Saudi Arabia can provide thermal comfort without the use of ACs?	In winter, some seasons in the year, from time to time, in higher altitude areas only, it is not possible at all
6.	Do you think that old and historical buildings in the higher altitude areas in Saudi Arabia can provide thermal comfort without the use of ACs?	In winter, some seasons in the year, from time to time, in higher altitude areas only, it is not possible at all

Various tools were used in this study, including computer modelling software and monitoring equipment. The study used TAS EDSL 9.4.1, which is considered to be one of the most widely used energy software packages to predict the thermal performance of buildings. This is a globally used software package used for energy analysis studies across the world, including Saudi Arabia [8], Singapore [49], Austria [50], Italy [51,52], Chile [53], Poland [54], the UK [46,55,56], and Turkey [57].

Some of the thermal elements were calculated on the basis of the building material of the Palace (Table 4), such as the solar heat gain, which was affected by the WWR and the type of glazing. It is very important to address the size and type of glazing in buildings in such a region [11]. In addition to this is the building heat transfer, which is affected by the type and the width of the building envelope. All of these variables resulted in the actual indoor air temperature. Haider [26] reported that the insulated glazing system, internal shading devices, natural ventilation, and the use of thermal mass lead to a total reduction of 22% in the energy demand. He also calculated the predicted mean vote using the macros tool EDSL and compared it to the monitored data and the survey data in the form of quantitative and qualitative data.

Table 4. Building envelope characteristics of Shubra Palace.

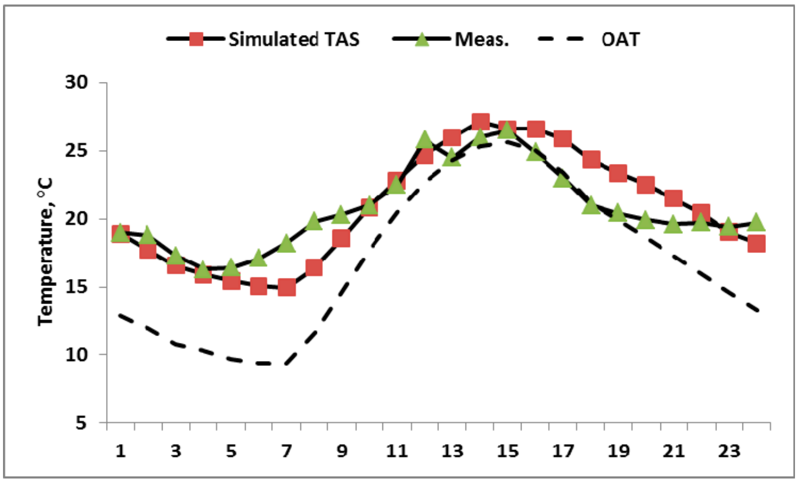
	Material	Thickness (mm)	Conductivity (W/m°K)	Total U-Value (W/m²K)
	Base case model (Palace as it is)			
External wall	Stones	450.00	1.31	1.4
Roof	Wood bars	88.00	0.11	0.44
	Mud	200.00	0.87	
Ground	Stones	450.00	1.31	1.4
	Proposed model (Simulated, modern style building construction)			
External wall	Concrete block	200.00	1.31	3.1
Roof	Thermal insulation	125	0.04	0.22
	Concrete slap	200	1.31	
Ground	Concrete foundation	300	0.87	0.35
	Crashed Aggregate	75	0.55	
	Clay soil	1000	0.70	

2.2. Field Experiments (Evaporative Cooling and Increasing Indoor Air Speed to Improve Thermal Comfort Sensation)

Since Shubra palace windows were sealed to protect the palace and to switch the mechanical system to fully air conditioned, another extended field experiment were conducted in Boqari palace which is still a free running operation system. Both buildings were built with same building materials. The field experiment aimed to investigate the influence of evaporative cooling on indoor environment of the palace as well as increasing indoor air speed in summer. The experiment conducted on 29 August in 2020.

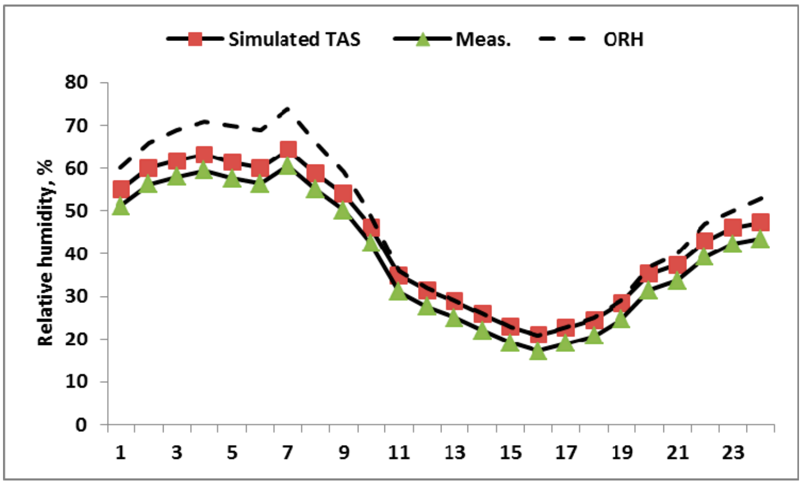
2.3. Calibration of the Energy Model and Validation

Since 1970s, building simulation is becoming an aid to emulate reality [58]. There are so many input data associated with energy building simulation [59]. The study used graphical calibration to justify the accuracy of software. Figure 8 indicated a presentation between measured and simulated figures of temperature and humidity using data-loggers. Actual monitored outdoor temperatures also recorded and applied in the software for proper comparison. Acceptable results found out which are within the tolerances. As a result, TAS EDSL energy model can be used as well-calibrated software. Moreover, the TAS EDSL software has been validated previously by the author in another study converged on the use of sustainable application of an asphalt mixes (RAP) [60]. A real prototype model has been compared to a simulated one in the software (Figure 9).



(**A**)

Figure 8. *Cont.*



(B)

Figure 8. Calibration: Indoor temperatures (**A**) and relative humidity (**B**).

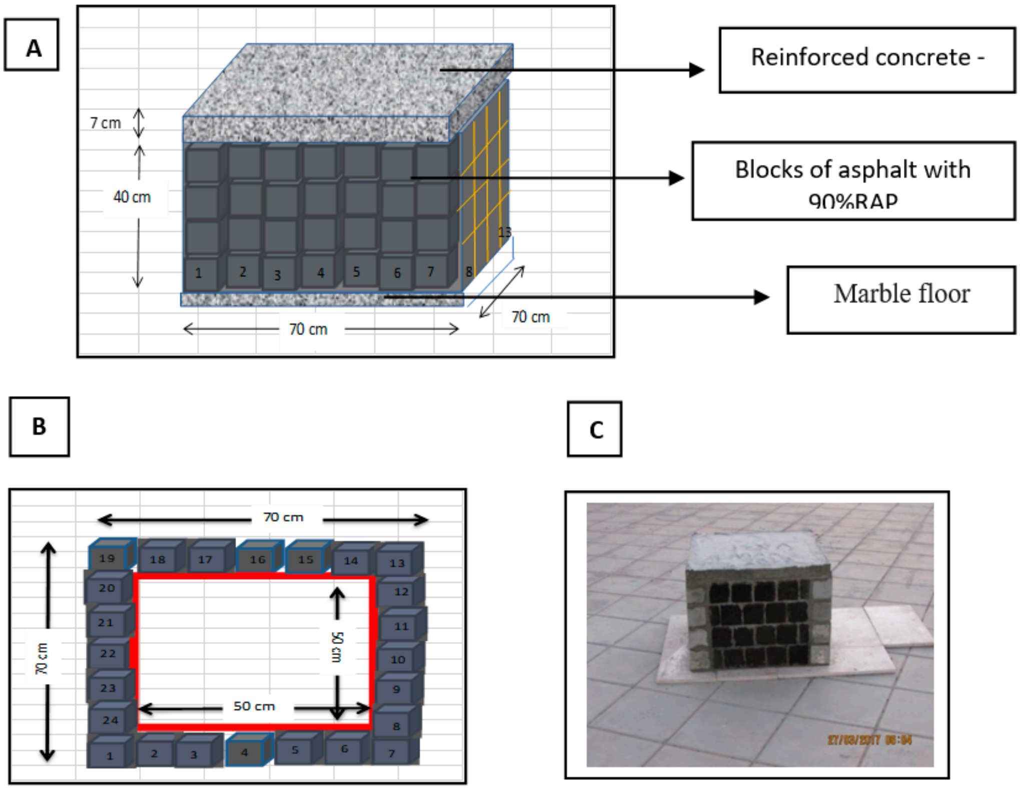


Figure 9. Validated model for TAS EDSL; where: (**A**) is the 3D model, (**B**) is the plan side and (**C**) is a view of the actual model [61].

3. Results and Discussion

One of the major contributions and findings of this research was to explore the feedback of specialists in the field of architecture as the qualitative data to be compared with the quantitative ones, which were in the form of the monitoring and the calculated data. The research aimed to question as many of architects as possible who were living in the city of Taif or a similar climatic zone in Saudi Arabia (Figures 1 and 2), which was considered to be a hot region at a relatively high altitude. This made the climate pleasant in summer as compared to the hot areas in the Middle East. In addition, the questionnaire aimed to identify several parameters, such as age, years of experience, and level of education, that might affect the feedback of the specialists. These data helped to analyse the other data more precisely. Table 3 shows the design of the questionnaire including the items and contents.

Figure 10 indicates the age of the participating experts in the survey. The sample size was 171, and a vast majority of the participants were architects, 87.3%, living in the high altitude city of Taif or a similar region in the Kingdom, such as Abha and Baha, which are located along the mountain line in the western part of Saudi Arabia (Figure 2). Most (more than 70) of the participating experts were recent graduates in the age group of 20–30 years. As far as the thermal comfort derived from the interview survey on the possibility to achieve thermal comfort in the higher altitude areas of Saudi Arabia was concerned, 20% of the participants believed that it was possible to achieve thermal comfort (TC) in modern buildings only in winter, while this number doubled for historical buildings in the same season. More than 100 experts argued that TC could be achieved even in some other seasons in modern n buildings and not just winter. Surprisingly, about half of this number suggested that TC could be achieved in historical buildings in some other seasons. It was observed that the feedback of the specialists varied. As a result, it might be beneficial to consider some other aspects such as years of experience and educational level. For instance, all the participants who mentioned that it was not possible to achieve TC in historical buildings at all had either 6–10 years or less than 5 years of experience. This showed that the years of experience in the field were quite crucial to obtain more accurate feedback. Similarly, most of the participants who voted that historical buildings could achieve TC in some seasons had more than 20 years of experience in the field (Figure 11). These findings will be analyzed and linked to investigation of experity impact of type of buildings in terms of historical and modern as well as years of experience on thermal comfort (Figures 12 and 13).

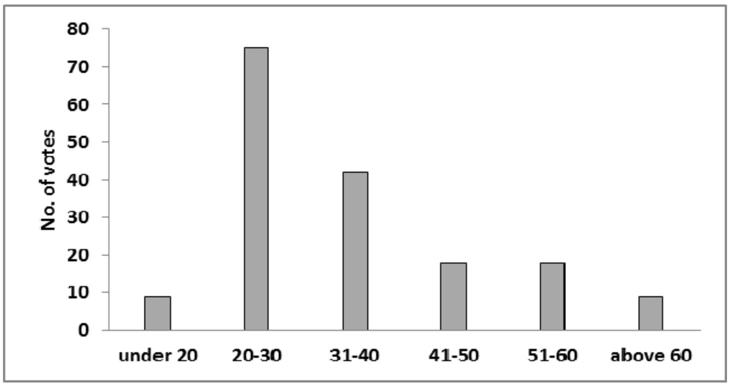
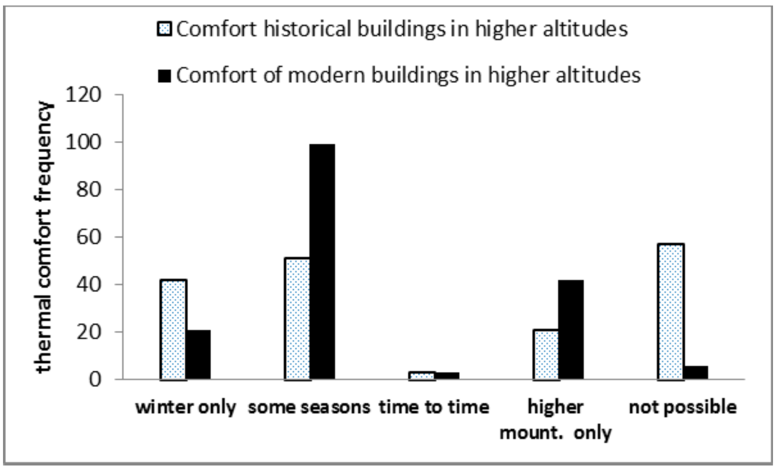
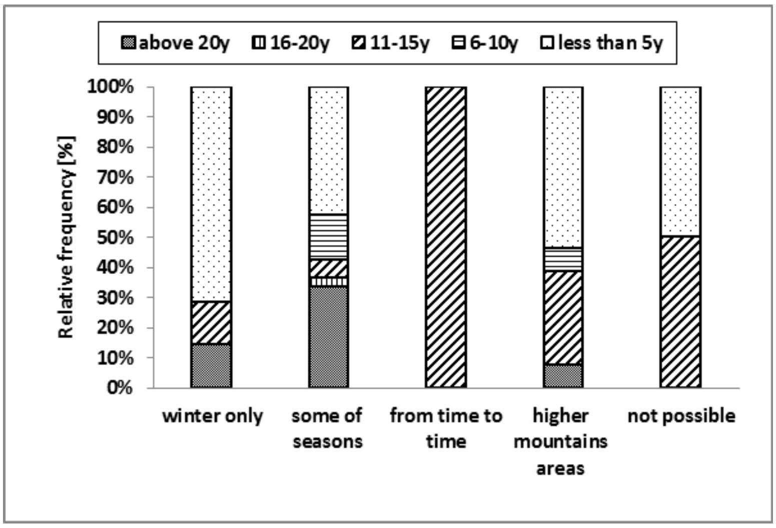


Figure 10. Age distribution of survey participants, i.e., architecture experts.



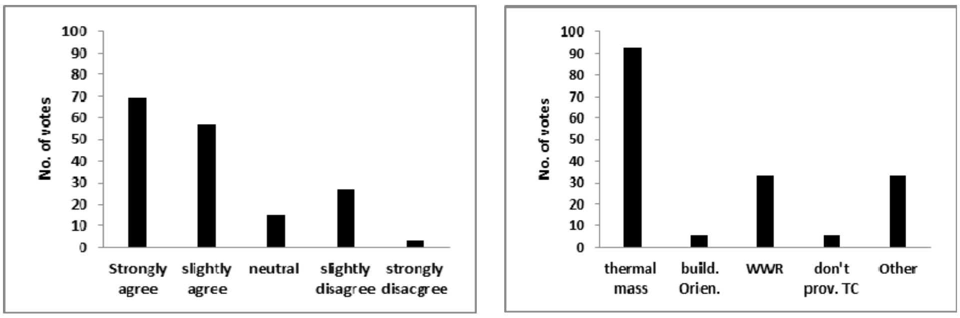
(**A**)

Figure 11. *Cont.*



(**B**)

Figure 11. (**A**) Thermal comfort derived from interview survey on the possibility to achieve thermal comfort in the higher altitudes areas of Saudi Arabia. (**B**) Impact of years of experience on responses to questions asked regarding the thermal comfort at higher altitudes.



(**A**) (**B**)

Figure 12. Responses of experts during the interview survey: (**A**) responses to the statement that historical and old buildings are better at providing thermal comfort than modern buildings in Saudi Arabia, and if agreed, (**B**) the most important elements identified.

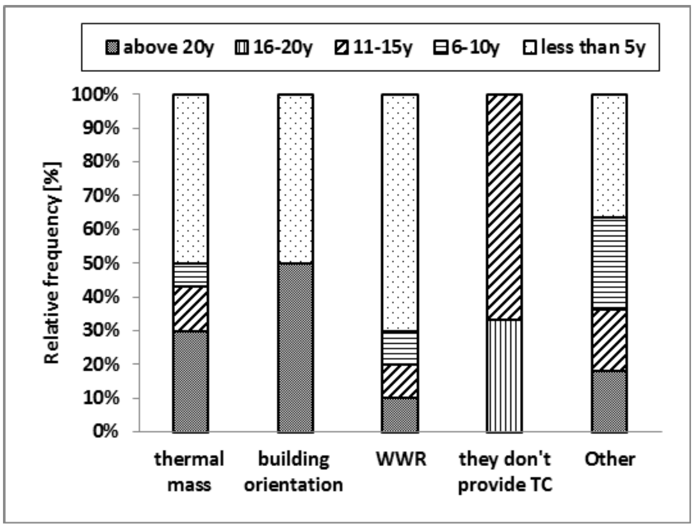


Figure 13. Impact of years of experience on responses to questions asked regarding the most important elements for providing comfort in historical buildings.

Figure 12 shows the number of participants who stated that historical and old buildings were better at providing thermal comfort than modern buildings in Saudi Arabia, these findings also reflected clearly in Figure 16. This finding agreed with the findings reported in the previous sections. It implied that the age of the participants affected the accuracy of the feedback. Further, as shown in Figure 13, most of the participants stated that historical and old buildings are better at providing TC to the users because of the construction materials used as well as the design strategy. Figure 12B shows that thermal mass was by far the most important aspect with respect to the strategies affecting the building performance. The WWR came in second with approximately 30 votes, while the building orientation had a minor impact according to the survey. Figure 13 shows the effect of the number of years of experience on the feedback shown in Figure 12B. Surprisingly, most of the participants who believed that thermal mass were the most important element for providing TC had less than 5 years of experience, while most of the experts who had more than 20 years of experience chose the building orientation as the major element. However, these findings can be compared with latest publication on this subject in terms of parameters such as thermal mass, WWR, and orientation. As far as the thermal mass is concerned, there is abundant research published on it, considering its advantages, particularly in hot regions or where there are clear fluctuations in the outdoor air temperatures. In the hot climate of Hong Kong, Shan [27] investigated the influence of thermal mass on the cooling load and reported that it can reduce the energy consumption by up to 7.23%. Furthermore, Albayyaa [26] investigated the impact of thermal mass in the cold climate of Australia and revealed that a total reduction of 58% can be achieved. Many publications have focused on the fact that thermal mass is more likely to be effective in hot regions, as the drawbacks of a high thermal mass may outweigh its advantages, which will lead to a high energy consumption [31]. Even in the cold and Mediterranean climate, thermal mass is usually used to reduce the amount of cooling load in summer [28] (Figure 14). WWR is also one of the major aspects in hot regions because of the high amount of solar energy, particularly considering the south and the west orientations [11]. Figure 15 shows the amount of solar radiation for the south-west, south-east, north-west, and the north-east orientations. It can be seen that the north and the south-west orientations were the ones that received a high amount of solar radiation of up to 5000 W. This amount of solar radiation was consistent with the distribution of the heat transfer (Figure 15B). The heat loss was the maximum at 5 pm with approximately −1500 W at the outdoor temperature peak, which was at the same time at about 35 °C. In a study conducted by Alshuhail [13] in a similar climate of the UAE, the researcher showed that the south orientation contributes a 9.4% increase in the indoor air temperature. Figure 16 shows the pattern of the south and north orientations. Although both had a relatively similar peak, the fluctuation rate was different.

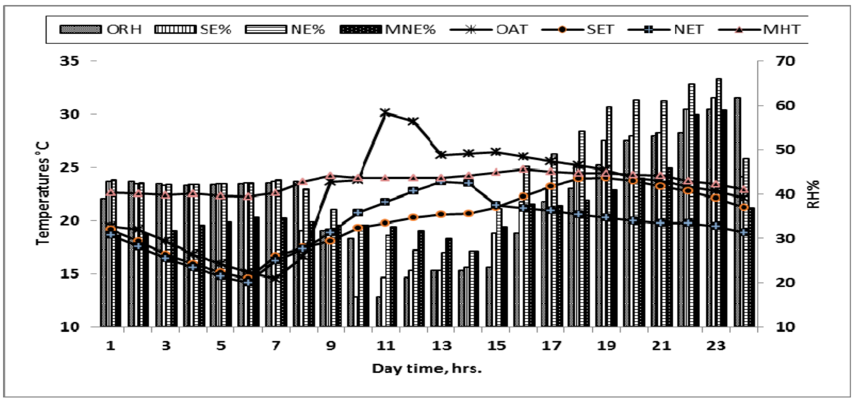
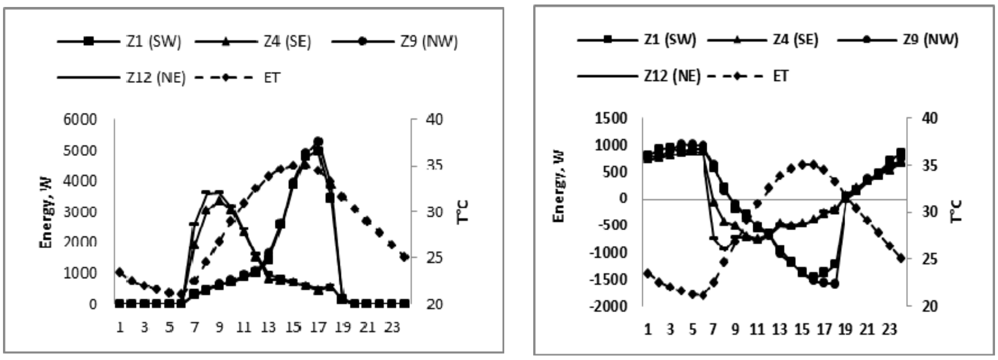
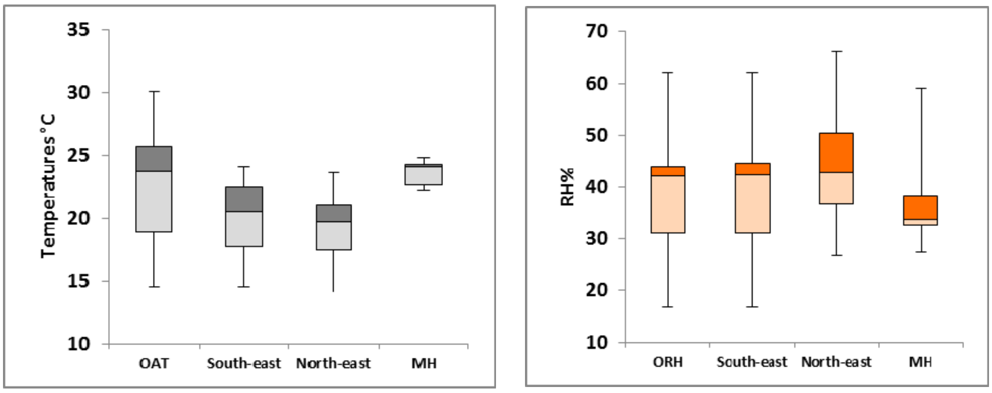


Figure 14. Indoor thermal monitoring of temperatures and relative humidity using data loggers installed in the palace during the field visit: MNE denotes the relative humidity in a modern house, ORH indicates the outdoor relative humidity, SE refers to the south-east humidity, NE represents the north-east humidity, OAT denotes the outdoor temperature, SET indicates the south-east temperatures, NET refers to the north-east temperatures, and MHT represents the recorded temperatures in a modern house.



(**A**) (**B**)

Figure 15. (**A**) Solar heat gain and (**B**) building heat transfer in some selected rooms in the palace, simulated using TAS EDSL in the south-west, south-east, and north-west zones.



(**A**) (**B**)

Figure 16. Box plots of (**A**) indoor air temperatures and (**B**) relative humidity of some selected rooms in the palace compared with a modern house and the outdoor air temperature on the experimental day.

With respect to the monitored indoor air temperature inside the palace and the modern house (Figure 14), it was observed that the orientation did not have a considerable impact on the indoor temperature; however, it influenced the thermal comfort sensation (Table 4 shows characteristics of used materials in both palace and modern building). It has to be mentioned that findings of Figure 16 is comparable with the findings of Deng [29] who found that the use of thermal mass has no effect on the energy load, but it affects thermal comfort. The current study showed that the use of thermal mass had a slight effect on the indoor air temperature, but it helped to provide thermal comfort to the users.

In a hot region with a high altitude, it was possible to achieve thermal comfort throughout most of the year, particularly when using a thermal mass construction building as in the case of Shubra Palace. The use of thermal mass helped to keep the external envelops cool in most of the seasons and in most of the orientations in summer. This helped to utilise the advantage of natural ventilation through the large windows in the palace. A thermal imaging camera was used to explore the influence of orientation on temperature in both traditional and modern building designs (Table 5). In the north-west orientation, the inner surface temperature gap was only 1 °C, while in the south-east orientation, the gap increased to 6 °C. This implied the influence of the orientation and the use of Mashrabiya which acted as the external shading devices. The study revealed that the influence of orientation was important in hot regions, and the south and the west were considered the worse orientations; however, precise consideration has to be implemented. Moreover, it was recommended to minimise the size of the windows in the south and the west orientations and to use external shading devices as in the case of the traditional buildings in the region. It was possible to achieve thermal comfort in such a region in modern buildings when learning from traditional buildings applying thermal mass, external shading devices, and building orientation were applied. Thermal comfort could be achieved throughout the year except in summer, when air conditioning might be required as the outdoor temperatures increase to above 35 °C. This would help to achieve nZEB in such a region, which relies heavily on mechanical means. In the experimental work conducted in Boqari palace, using evaporative cooling aid to bring indoor temperature to about 27 °C with free running operation in summer (Table 6 and Figures 17 and 18). Figure 19 shows 24 h. of indoor temperature monitoring.

Table 5. Comparison between a modern building (University Campus of Taif) and a historical building (Shubra Palace) in terms of inner surface temperatures recorded using thermal imaging cameras at 10am and 2 pm, in spring 2020, °C.

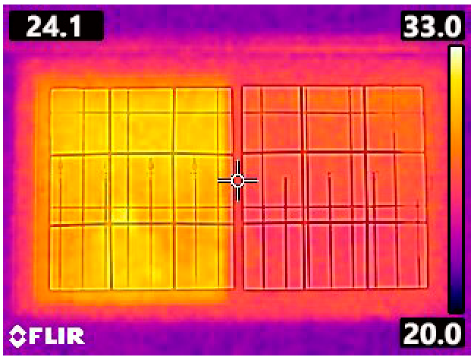
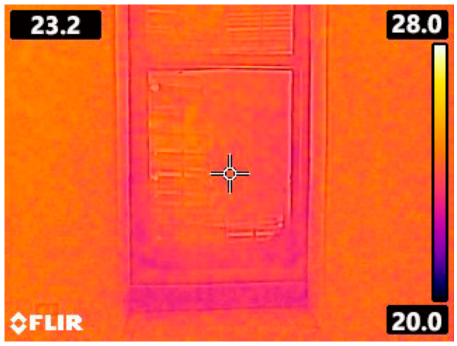
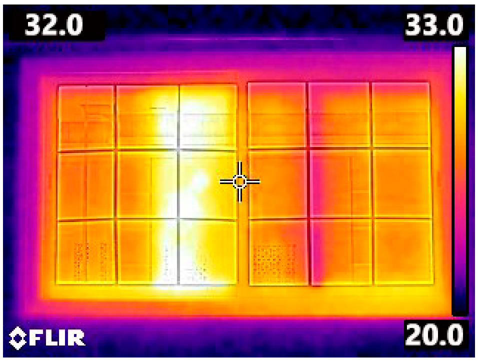
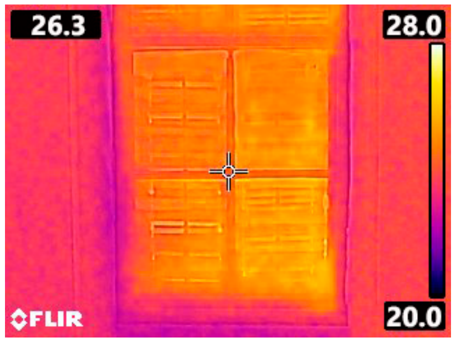
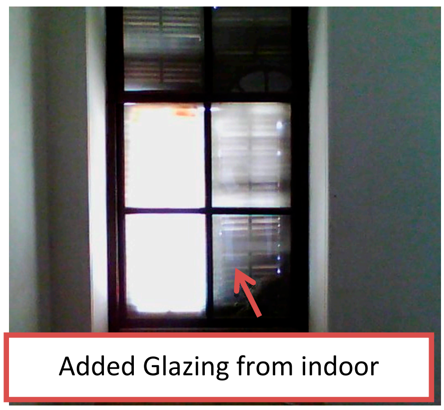
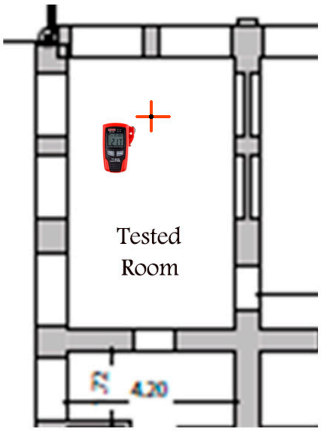
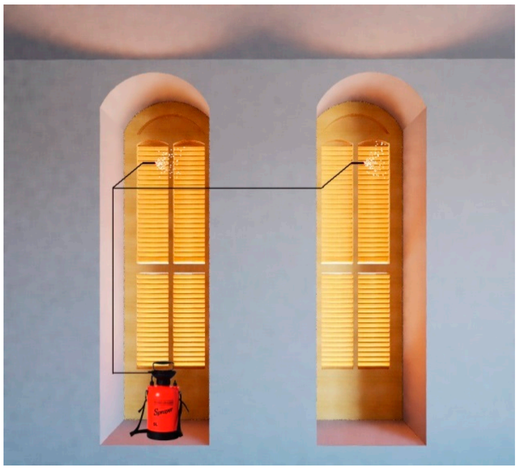
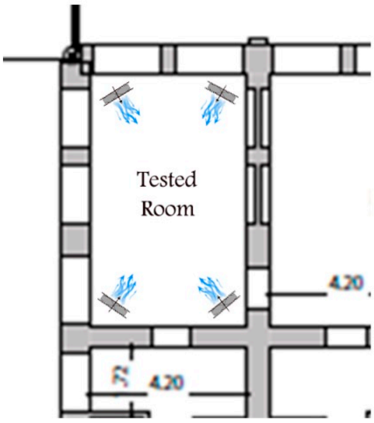
	University Campus (Modern Building)	Shubra Palace—(Historical Building)
North-west		
South-east		
Normal photographs		

Table 6. Design and strategy of evaporative cooling and increasing air speed inside Boqari Palace.

Location of data-logger in tested room		
Evaporative cooling		
Increasing air speed sing fan		

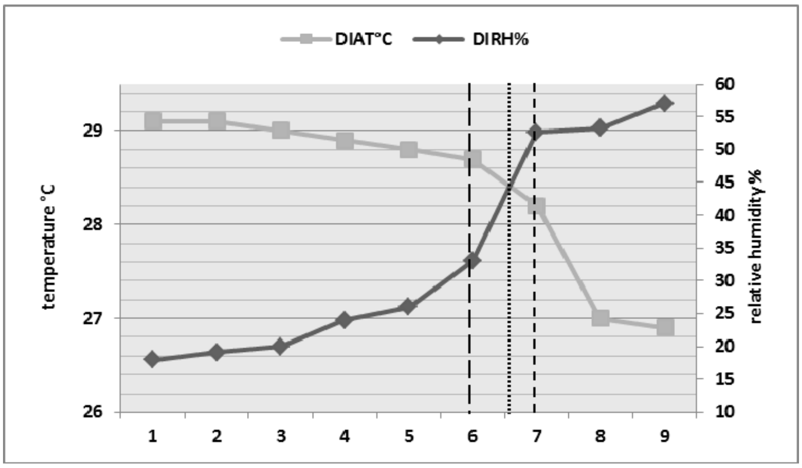


Figure 17. Distribution change in temperature and relative humidity while using water spray in a 5 min slots.

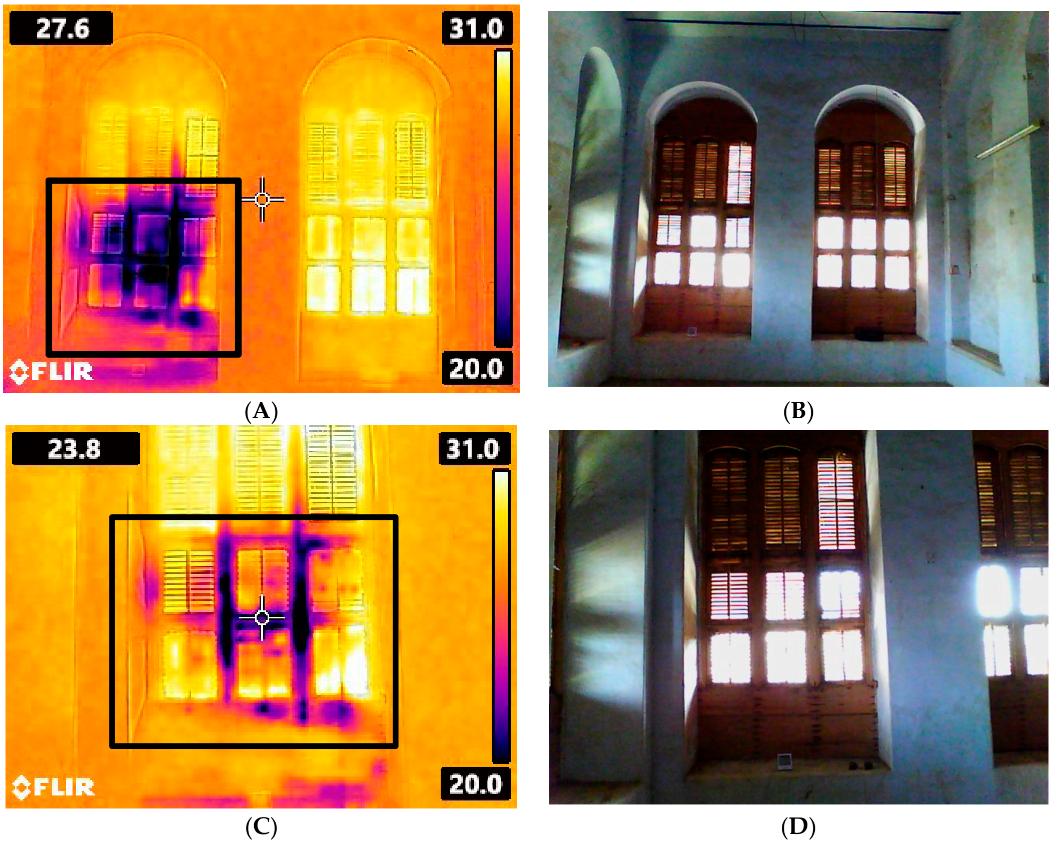
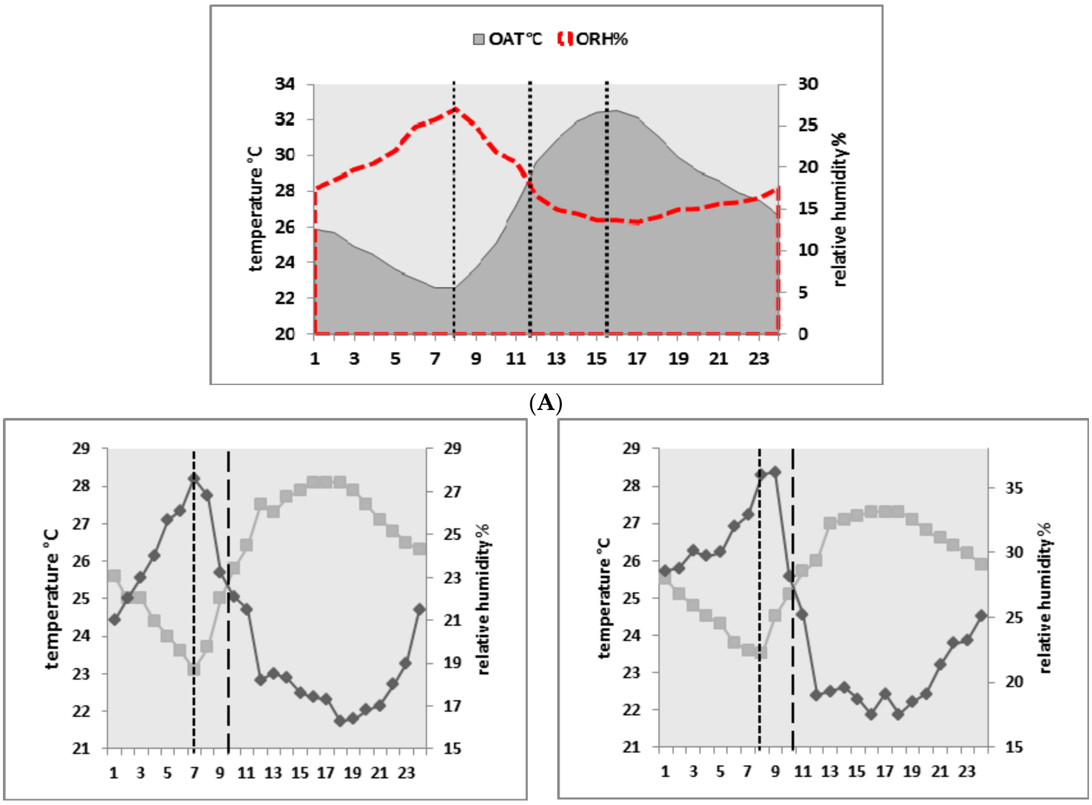


Figure 18. Impact of evaporative cooling on internal Mashrabiya using a thermal imaging camera, °C. (**A**–**D**).



(**A**)

(**B**) (**C**)

Figure 19. Free running indoor air temperatures and relative humidity inside Boqari Palace using data-loggers, where (**A**) is the actual external temperature, (**B**) is the south indoor temperature and relative humidity facing room and (**C**) is the north facing room.

The study of evaporative cooling shows a clear influence on indoor air temperature as well as relative humidity (Figure 17). The distribution of five minute monitoring results which for 9 slots shows a drop in air temperature of about 2 °C (from 29 °C to 27 °C) and a considerable increase of relative humidity from only 19% to 55%. The system aid significantly to improve the dryness in the indoor environment which has resulted in a major contribution to thermal comfort sensation. The use of thermal imaging camera also supported this outcome as it can be seen in Figure 18. Since the selected room is facing south, wood material attached to window system dropped temperature by 4 °C. It can be reported that the use of evaporative cooling in hot region can contribute mostly on improving relative humidity and less impact is reported to indoor air temperature. However, the system can generally improve the thermal comfort preference indoors in free running buildings. In comparison between south and north facing rooms, the later has its temperature peaked at 27 °C which is a one degree lower than south. This is 5 °C lower than outdoor temperature reported in the same day. Considering international standards of comfort level, the suggested operative temperature of comfort introduced by ASHRAE-55 [61] 27 °C is considered as within the comfort zone level. Similarly with ISO 7730 [62], it is worth mentioning that the 27 °C is actually in upper limit of comfort suggested by international standards; however, it is still within acceptable level. As summertime, this is quite acceptable especially with range of relative humidity.

As far as increasing indoor air speed is concerned (ventilation), it can be noted that the experiment shows some improvement in the indoor thermal comfort by the mean of convection heat transfer with obviously no change in either indoor air temperature or relative humidity. It is recommended to use both techniques in hot and dry regions especially in higher altitude mountains where outdoor temperature in summer is not as high as other hot locations in the region. The system can contribute significantly to improve free running operation system which will have a clear impact on energy efficiency and thermal comfort in buildings.

4. Conclusions

This study investigated the advantages of historical buildings, taking into consideration the case study of Shubra Palace in the city of Taif (Saudi Arabia). The work explored the advantages of thermal mass and large windows with external shading devices designed and constructed on the basis of the local climate of the higher altitude mountains in the hot region. The elevation of this city makes the climate warm in summer and moderate in winter as compared to the other parts of the Arabian desert of Saudi Arabia. Various methods were used in this research. First of all, as the palace had no architectural drawings from since it was built, the research group aimed to provide the drawings as a contribution of this work (Figures 6 and 7). Along with the site observation, the indoor air temperature of the palace was monitored using data loggers. Furthermore, thermal imaging cameras were used to evaluate the physical patterns of the external walls. The building was compared with a modern house while monitoring the indoor air temperatures and relative humidity and compared with a modern university building while monitoring with external and internal thermal imaging cameras. The work also included a questionnaire interview with architecture experts. As the study involved analyzing a historical building which has never been examined before, it was beneficial to ask experts who know such buildings very well. The study led to the following results and recommendations:

- Duration of experience in a field is quite important to obtain more accurate feedback. The study found that as the years of experience increased, the feedback became more accurate.
- The study highlighted that the use of thermal mass had a slight effect on the indoor air temperature and energy consumption, but it helped to provide thermal comfort to the users.
- In a hot region with high altitude locations, it was possible to achieve thermal comfort during most of the year (autumn, winter, and spring), particularly when using a thermal mass construction building as in the case of Shubra Palace. However, air-conditioning systems might be necessary in summer because of the rise in the outdoor temperature to above 35 °C.
- The study showed that the influence of orientation was major in hot regions; the south and the west were considered the worse orientations because of the exposure of high solar radiation even at a high altitude.
- Glazing windows had a more significant effect on the indoor building environment than the thermal mass. As a result, the window system had to be taken into account precisely in hot regions, even at higher altitude locations.
- The use of external shading devices is recommended in larger windows to reduce the amount of solar radiation, particularly in the south- and the west-facing zones.
- The use of evaporative cooling can improve indoor thermal comfort significantly; it can lower indoor air temperature by 2 °C and relative humidity from 19% to 55% in about 45 min during the field experiment.

Author Contributions: M.A.: Conceptualization, Data curation, Writing—original draft. A.B.: investigation A.A.: review and editing, U.I. and I.S.: analysis, A.S. and M.A.-S.: research method, M.A.-H. and M.G. supervision. All authors have read and agreed to the published version of the manuscript.

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