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Analysis of thermal bridging in Arabian houses:
Investigation of residential buildings in the Riyadh area

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The electrical energy demand in Saudi Arabia has been increasing over the last decade. The building sector (residential, governmental and commercial) consumes about 80% of the total electricity produced. Residential buildings consume about 50% of the total electricity consumption in Saudi Arabia. Up to 70% of the electric energy consumed in buildings id for air conditioning of internal space. This study investigates the relative impact of thermal bridging through the building envelope as a cause of this scenario. The analysis focuses on typical detached villa housing, which represent 29% of all residential accommodation. The results of this paper show that insulated clay blocks by themselves do not ensure compliance with the minimum requirements of the Saudi Code. Bridging caused by mortar joints and structural elements can increase the U-value of the building envelope by 141% above the hypothetical unbridged base case. Through simulation study the impact of thermal bridging on the building is calculated at 68% increase of the total energy consumption. A 55 mm additional external insulation layers can improve the performance considerably and achieve compliance with new building codes.
KEYWORDS: Thermal bridging, Thermal performance, Finite element analysis, Whole building energy modelling, Thermal simulation

1. INTRODUCTION

Saudi Arabia has experienced a rapid population and economic growth over the last decades. This growth led to marked increase in the demand for electricity at an annual rate of 6% [1] and it is expected to increase by 50% by 2020 [2]. The increase in electrical energy demand in Saudi Arabia in the period 2005 to 2018 is shown in Figure 1. Moreover, according to the International Energy Agency (IEA) Saudi Arabia ranked 15th worldwide in energy consumption per capita in 2017 [3]. Also, the electrical energy consumption per capita in Saudi Arabia increased from 6.11 MWh in 2004 to 9.60 MWh in 2017 [3]. The Saudi Arabian Monetary Authority annual statistics [4] documented that residential buildings consume about 50% of the total electricity consumption in Saudi Arabia as presented in Figure 2. Also, several studies have indicated that, the building sector (residential, governmental and commercial) consumes about 80% of the total electricity produced [5],[6]. Moreover, the electricity demand will increase even more to cover the Saudi plan to build 2.32 million new homes by 2020 to service the ongoing rapid population growth of 2.5% per year [1].

According to Felimban et al. [5] up until January 2019, the old building codes (from 2007) were still being used for about 33% of the new homes. Moreover, the Saudi Energy Efficiency Center (SEEC) documented that more than 70% of the existing residential buildings are energy inefficient and lack thermal insulation [7]. Also, there is a massive national cooling demand caused by the 5.47 million existing residential building [5]. As presented in several studies, up to 70% of the electrical energy used in building in Riyadh is consumed for air conditioning as presented in Figure 3 [8], [9].

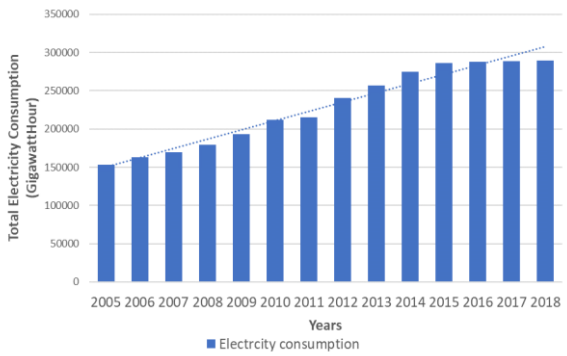

Figure 1: Electricity consumption in Saudi Arabia from 2005 to 2018 (Data abstracted from [4])

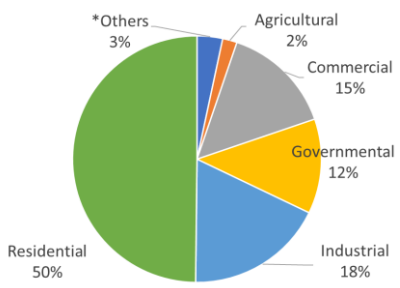

Figure 2: Average energy consumption per sector in Saudi Arabia from 2005 to 2018. (Data abstracted from [4])

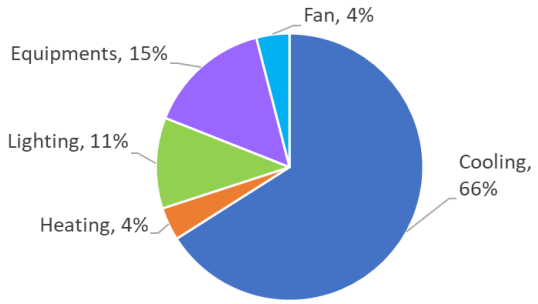

Figure 3: Annual energy end-use distribution in Riyadh [8], [9]

Saudi Arabia experiences extreme weather conditions, with a maximum summer temperatures of 46°C and an annual average temperature of 27°C [10]. It is clear from these high temperatures that the building envelope in Saudi Arabia is hence facing extreme conditions and extreme heat stress. As a result, transfer heat is highly expected.

A primary and essential function of the building envelope is to enable thermal comfort for the building's inhabitants and protect the building's interior from the outdoor climatic conditions. A well-designed envelope should enable a reduction of energy consumption from air-conditioning and heating. A weakness of a poorly designed building envelope is thermal bridging, which is caused by materials of high thermal conductivity creating a bridge between the tempered indoor environment and the varying, and often extreme conditions, on the building exterior. Thermal bridges can result in high energy consumption, when heat is conducted across the envelope. The present study focuses research attention on this matter and investigates ways to improve building energy conservation by improving the design of the building's envelope. It aims to investigate compliance with the requirements of the Saudi Code 2018 (SC2018).

Firstly, the study identifies thermal bridges in common residential Arabian building typologies. Subsequently it quantifies the energy impact of these thermal bridges; this is achieved using Finite Element Models. The study investigates bridging due to cast concrete structural elements in external walls but also due to small-scale bridging in insulated clay blocks used to infill between the concrete frame elements. Finally, we present the effect of the thermal bridge on building energy consumption using building simulation modelling software. Proportions and quantifications of thermal bridges are incorporated into simulation models of examples of a typical villa design. The villa in Saudi Arabia is a detached residential building surrounding ground with various sizes. 29% of the total housing units in Saudi Arabia are recognized as villa. In Riyadh the capital city of Saudi Arabia, villa is the most commonly built housing by about 45% of the housing units [11] as presented in Figure 4.

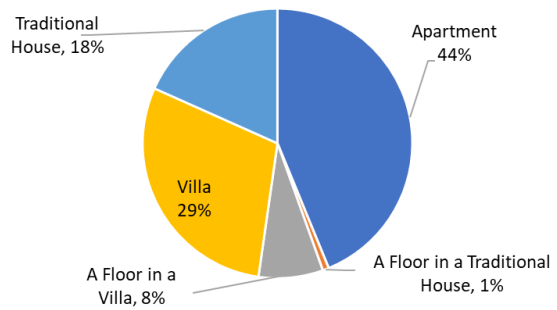

Figure 4: Saudi Arabian total housing unit types [11]

Thermal bridging due to the cast concrete frame structure is clearly shown by thermal image presented in Figure 5. The image shows the surface temperature of the structural concrete to be 42.6 °C on the interior 36.7 °C higher than the surface temperature of the adjacent in-fill block wall.

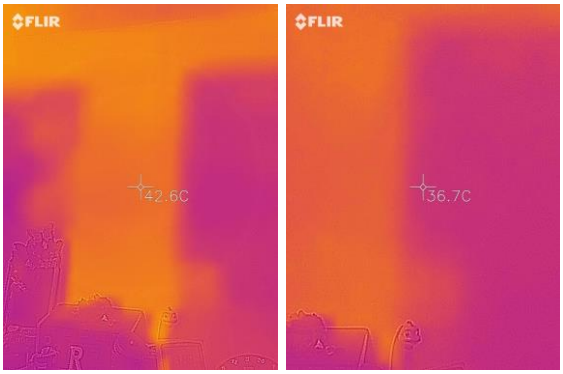

Figure 5: Thermal image of a thermal bridging due to structural elements in the envelope of a Saudi house.

This paper presents experimental and simulation analysis of thermal bridging through the building envelope, and quantifies the energy impact of this. This is part of an ongoing study to evaluate reasons for inefficiency in Saudi Arabian dwellings and propose means by which their performance can be enhanced.

2. METHODOLOGY

This paper analyses thermal bridging endemic in Saudi Arabian building designs. Particularly it looks at bridging in the main wall fabric, which encompasses insulated clay blocks. Subsequently it investigates the heat flow through the mortar joints and cast concrete structural elements. Finally, evaluate the energy performance of the whole building and the impact of thermal bridging in the building envelope.

The results outlined in this paper will be compared to results presented in a journal paper submitted and due shortly for publication [12]. To study the effects of mortar joints on thermal bridging two methods are used in this larger analysis using simplified calculation methods including; parallel path, zone and combined methods, outlined by organisations CIBSE and ASHRAE [13], [14] or by using

Finite Element Method (FEM). For brevity, in this short paper the FEM is used.

2.1. Block types analysis

Investigating the energy performance of the clay block types used in Saudi Arabia shown in Figure 6, is an essential step to determine the thermal bridging impact on buildings. Eight blocks are analysed – the first four blocks (C1(ins), C2(ins), C3(ins) and C4(ins)) are insulated and the other four (C5, C6, C7 and C8) are not insulated. These blocks are commonly used in Saudi Arabian residential construction to provide for insulation and/or trapped air insulation. Alternative concrete typologies are also used, and these have separately been analysed [12]. Here, the best performing clay block is evaluated and that is utilized for further investigation in this study.

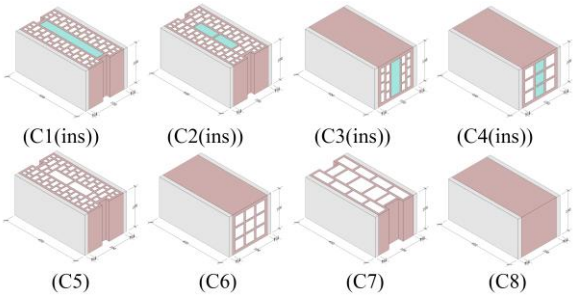

Figure 6: Clay block types used in Saudi Arabia

2.2. Thermal bridging due to mortar joints and structural elements

As well as the localised thermal bridging in the insulated clay blocks models, a major thermal bridging is specified in Saudi Arabian residential construction via bridging due to mortar joints between blocks and an uninsulated structural element.

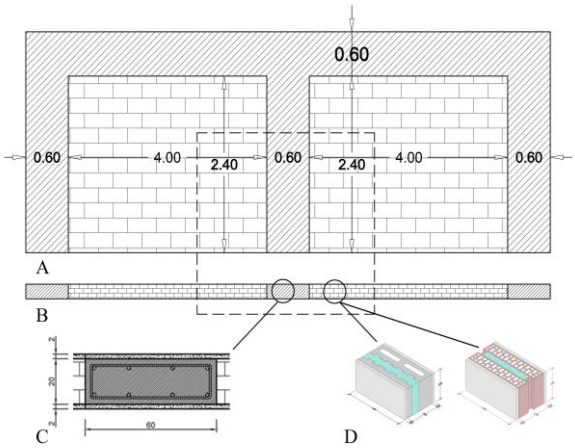

Figure 7: Detailed wall section of common building style used in Saudi Arabia A) elevation, B) horizontal section, C) detailed column and D) 20 cm insulated concrete block (B2(ins)) or 20 cm insulated Clay block (C1(ins)) infill.

Figure 7 shows a section of wall used in Saudi Arabian residential building (typical villa), the constructional style including the reinforced concrete structural frame, and concrete or clay blocks infill. Structural elements such as columns and beams cover about 35% of the façade area and usually are not insulated in Saudi Arabian dwellings (Figure 8). Therefore, their effects of transferring heat from outside to inside the building is greater than for the mortar joints. To determine the thermal impact of this a Finite Element (FEM) analysis is undertaken using ANSYS 19.2.

Figure 8: Residential construction method in Saudi Arabia

2.3. Boundary conditions and material properties

The weather of Riyadh King Salman AB (WMO: 404380) station (latitude 24.710 N, longitude 46.725 E, Elev. 635) is applied in this paper. The FEM boundary conditions set to 47.3 °C for hot side and 25 °C for the cold side. The simulation weather data was imported from ASHRAE handbook- fundamentals (SI) 2017 and Onebuilding.org data [15][16] for a 15 years period (from 2003 to 2017).

All the material properties used are presented in Table 1. Those materials properties chosen in Table 1 were from some reliable resources such as ASHRAE [13], ISO 10456 [17]and CIBSE [14] or the most used in research papers done for Saudi Arabia.

Table 1: Material Properties used

Common Materials	Density ρ kg/m³	Design thermal conductivity k W/ (m.K)	Specific Heat Capacity c J/ (kg. K)
Clay Blocks 200 mm	800	0.65	840
Cement mortar	1800	0.72	1000
Cement plaster	1800	0.72	1000
Reinforced concrete (2 % steel)	2400	2.5	1000
Extruded polystyrene	40	0.035	1450
Air Space (15mm)	1.1	0.16 (k_{eff})	1007
Air Space (20mm)	1.1	0.17(k_{eff})	1007
Air Space (25mm-300mm)	1.1	0.18(k_{eff})	1007

A FEM mesh independent study is undertaken for both 2D and 3D meshes before starting the analysis in

ANSYS. The meshes used that gave stabilised U-value remain stable without increasing the calculation time unnecessarily.

2.4. Whole building energy analysis

2.4.1. Case study building

Figure 8 shows an image of a residential construction method in Saudi Arabia, which include of concrete frame construction with blocks infill. The frame structure is reinforced concrete structural frame and the blocks used are typically either an insulated or cavity and concrete or clay blocks. An example of these villa style residential buildings used in Saudi Arabia are shown in Figure 9 along with a perspective view of the model that used for whole building energy analysis.

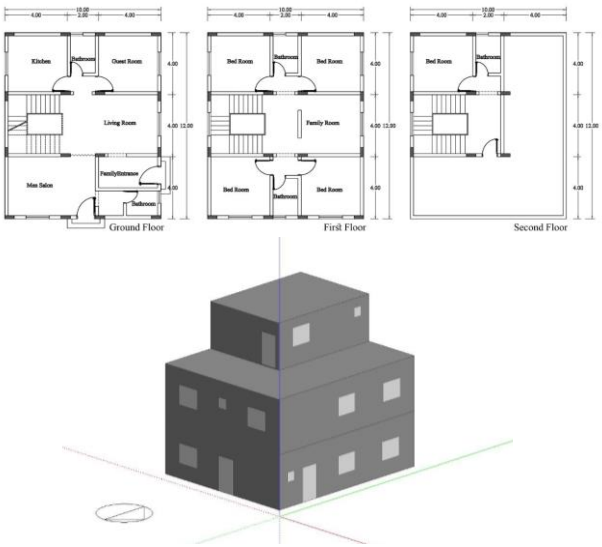

Figure 9: The floor plans and perspective of an example studied villa

DesignBuilder v6.1.2.009 is used to investigate the effects of thermal bridging on the energy consumption of the whole building. Two case studies are simulated, one with standard and identified levels of thermal bridging and the other hypothetical case without thermal bridging. Details of the villa construction are presented in Table 2.

Table 2: The villa construction properties

Latitude position	Riyadh (latitude 24.710 N, longitude 46.725 E, Elevation 635)
Face direction	Front elevation facing East
No. of floors	2.5
height of floors	3.50 m
Total floors area	245.98 m^2
Total walls area	391.99 m^2
Windows to wall ratio	6.43% as common practice (<10%)
Window type	Double layered glazing (6 mm, 12mm, 6mm)
Air conditioning system	Split unit
Heating system	Electrical heater
Thermostat setpoint	25 °C for cooling and 20 °C for heating
External walls	Model-1 bridged walls U-value = 1.57 W/(m^2·K) Model-2 un-bridged walls U-value = 0.65 W/(m^2·K)
Roof construction	20 mm cement plaster, 200 mm reinforced concrete slab, 50 mm EPS extended polystyrene, 4 mm waterproof membrane, 50 mm lightweight cast concrete and 20mm Terrazzo tiles

3. RESULTS

3.1. Investigation of insulated clay block types

The results of the thermal analysis of the clay blocks shown in Figure 6 are presented in Figure 10. As expected, the blocks with insulation show better thermal performance, quantified by its U-value (W/m^2K), than the uninsulated blocks. Also, the more the amount of insulation as in C1(ins), the greater the thermal performance. The solid block C8 shows the worst performance. Using block type C1(ins) could reduce the heat flux gained by up to 80%, 62% and 66% when compared with the uninsulated solid block C8, and cavity blocks C6 and C7 respectively. Furthermore, the insulation when included as one piece (as in C1(ins)) makes for better performance than in the case of C2(ins), C3(ins) and C4(ins) where the insulation is included in multiple pieces.

In general, the result of clay blocks show better thermal performance than the result of concrete blocks [12]. In instance, the solid clay block (C8) shows better thermal performance than the solid concrete block (B8). However, as a consequence of continuous insulation in the concrete blocks B1(ins) and B2(ins), they perform better than insulated clay blocks.

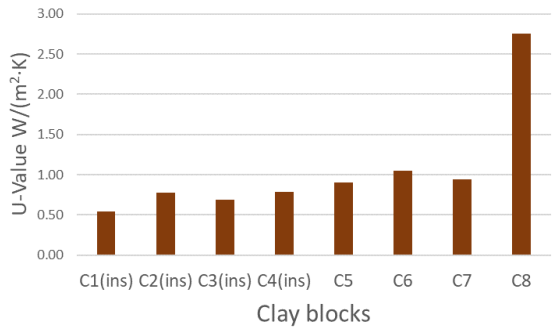

Figure 10: Thermal transmittance of clay block types shown in Figure 6

FEM heat profiles are shown in Figure 11, for the boundary conditions outlined in Section 2.3. Although, the insulation (as in C1(ins), C2(ins), C3(ins) and C4(ins)) reduced the heat movement compared to uninsulated blocks. However, discontinuity of insulation by the clay joints, creates a bridge that allows for transfer of heat to the other side. In C6, the alignment of clay joints between air gaps increases the heat transfers compared to non-alignment alternatives (as in C7) as shown in Figure 11.

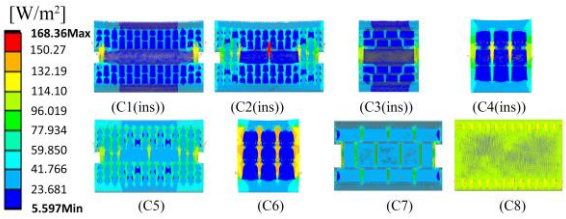

Figure 11: Heat transfer through different clay block types, total heat flux transfer[W/m2]

3.2. Investigation of mortar joints and Structural elements

The effective evaluation of the villa building envelope's thermal performance that investigate all the thermal bridging impacts, not only the ones occurs in the insulation clay clock but also due to mortar joints and structural elements.

The effects of mortar joints and structural elements on the building's performance are presented in Figure 12 and Table 3. Figure 12 presents the total heat flux calculated using the FE method for bridged elements in a wall section with insulated clay block (C1(ins)), mortar joints and structural elements. The heat flux distribution Figure 12 shows that, the majority of the heat flow moves across the structural elements which has the highest thermal conductivity of the wall section. Also, it presents the impact of mortar joints between the clay blocks. It is evident from the heat transfer image shown that heat flow through the structure (~160W/m2) is between 2 and 3 times as high as through the mortar joints (~60W/m2). This is due to the difference in density between the structural (2400kg/m3) and mortar (1800kg/m3) concretes respectively, that results in a thermal conductivity difference, as outlined in Table 1.

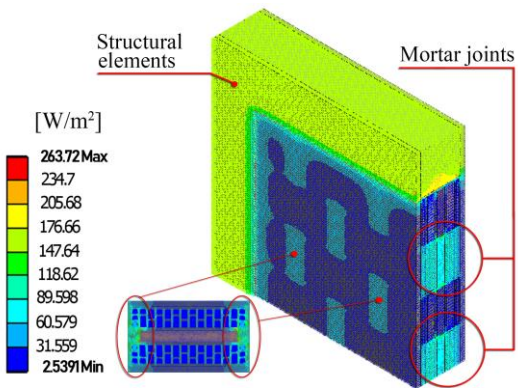

Figure 12: Total heat flux for bridged elements in wall section (clay blocks with mortar and structural elements)

When comparing the insulated clay block with and without the mortar joint, it is observed that the mortar joint can cause up to 50% increase in U-value of the wall. Furthermore, when the structural elements are also included this increases the U-value by 141% above the hypothetical base case wall built purely with insulated clay block. The cast concrete structural elements are responsible for 61% increase in the wall U-value compared to the block wall with mortar joints.

Table 3:The impact of the different bridging sources on the U-value of the building

	U-value (W/m²K)	Difference between unbridged and bridged case (%)
Insulated block wall section	0.65	0%
Insulated block wall section with 10mm mortar Joints	0.98	50%
Insulated block wall section with structural elements & mortar Joints	1.57	141%

3.3. Evaluation of whole building performance

The impact of thermal bridging on the building is calculated as responsible for a 68% increase in the total energy consumption as presented in Figure 13. That is reflected in the summer energy load which shows a difference of 64% due to the air-conditioning load, when compared to the base case house with an insulation layer and no bridging (built solely of insulated clay blocks (C1(ins)). Moreover, the impact of thermal bridging increased the yearly energy consumed per floor area from 92.90 to 136.60 kWh/m^2/year, for the unbridged building and bridged building, respectively.

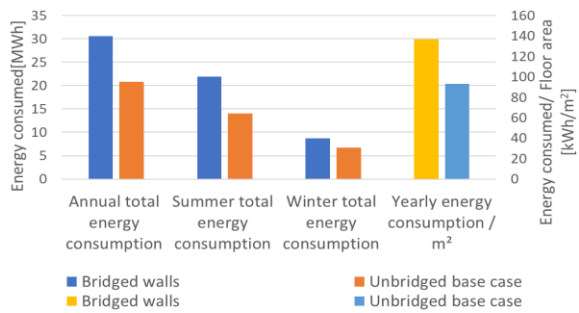

Figure 13| Energy consumption comparison of buildings with bridged and hypothetical unbridged envelopes (simulated for a year for clay blocks building)

4. DISCUSSION AND SOLUTION

It should first be noted that all the clay block types by themselves do not comply with the minimum requirements of the Saudi Code 2018 (SC2018) [18]. Results show that the best performance insulated clay block exceeds the Saudi Code 2018 and 2007 by 60% and 3%, respectively [18], [19].

As a solution, several studies indicated that, the external wall insulation systems (EWIS) could eliminate the effect of thermal bridging by up to 50% and that will lead to a reduction by about 16% of the total annual energy load [20],[21],[22]. In this study, through simulation it has been identified that adding 20 mm external extruded polystyrene reduced the U-

value by 57% and the reduction increased by increasing the insulation thickness as shown in Table 4. Moreover, to reach the Saudi code 2018 climatic zones regulation requirements for Riyadh city, we need to add 55 mm external insulation to reduce the U-value by 79% compared to bridged walls.

Table 4: The effects of applying external insulation of varying thickness to the evaluated wall shown in Figure 7.

External insulation thickness (mm)	0	20	30	40	50	55
U-Value W/(m^2·K)	1.57	0.68	0.49	0.41	0.35	0.33
% reduction	0%	57%	67%	72%	78%	79%

5. CONCLUSION

This paper concludes that insulated clay block designs used in Saudi Arabian houses by themselves do not ensure compliance with the minimum requirements of Saudi Code. Moreover, in general, the clay blocks show better thermal performance however, as a consequence of continuous insulation in the concrete blocks B1(ins) and B2(ins), they perform better than insulated clay blocks.

Thermal bridging caused by the mortar joints between blocks, and the cast concrete structural elements can increase the heat gain by about 141%. The cast concrete structural elements are responsible for the majority of thermal bridging by about 61% increase in the wall U-value compared to the block wall with mortar joints.

Finally, applying 55 mm external insulation will reduce the U-value by 79% to comply the Saudi code 2018 regulation requirements for Riyadh city, whereas the concrete blocks building needs 60 mm.

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