IMPACT OF COLUMNS AND BEAMS ON THE THERMAL RESISTANCE OF THE BUILDING ENVELOPE

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ABSTRACT

This paper addresses the effect of thermal bridging due to columns and beams on energy consumption and peak load requirements of typical private residential villas in Kuwait. Although it is common practice to apply thermal insulation to walls and roofs, columns and beams are often not considered. The local climate pattern coupled with uninsulated skeleton structure of reinforced concrete that forms 27% of the external total wall area can have a significant effect on the thermal resistance of the buildings envelope. Multi-dimensional heat transfer method was implemented to assess the magnitude of this effect and then to incorporate this in a whole building energy simulation program to assess the impact on the overall thermal performance of the buildings considered. It was found that the thermal resistance of constructions can be reduced by 48% due to uninsulated columns and beams. In addition, the average effect on the overall annual energy consumption and peak load demand for Kuwaiti type villas was found to be 1.8% and 2.3% respectively.

INTRODUCTION

Thermal bridging due to the presence of columns and beams can significantly affect the thermal performance of buildings envelope. A number of investigations [1, 2, 3, 4] have shown that the effect of thermal bridging can increase envelope heat loss (or gain) by as much as 50%. In cold climates, there is also a concern that condensation problems within the building envelope can also be attributed to thermal bridging which can cause mould growth and degrade the durability of insulation materials. Minimizing the thermal bridging effect depends on many factors such as the type of building construction, the practice adopted in the application of thermal insulation to the building's envelope and also depends on the climate pattern. For instance, masonry type buildings in which reinforced concrete is used for the columns and beams, the thermal insulation is usually placed on the external side of the envelope if the building was constructed in a hot climate. With some wall configurations, it may be possible to thermally insulate columns and beams, with other wall types such as the sandwich type in which the thermal insulation is placed between identical layers of cement blocks, it may not be practical. In this study, thermal bridging was investigated in masonry type buildings typically constructed in Kuwait. The main objective of the study was to quantify the effect of thermal bridging in terms of its impact on the annual energy consumption and peak load of typical residential villas.

The common construction practice used in Kuwait involves a skeleton structure which consists of reinforced columns and beams. Within this frame, masonry blocks are used to construct the walls. The slabs for the floor and roof are also made of reinforced concrete structure. There are three types of wall construction that are commonly used as shown in Figure 1. These include the classical type,

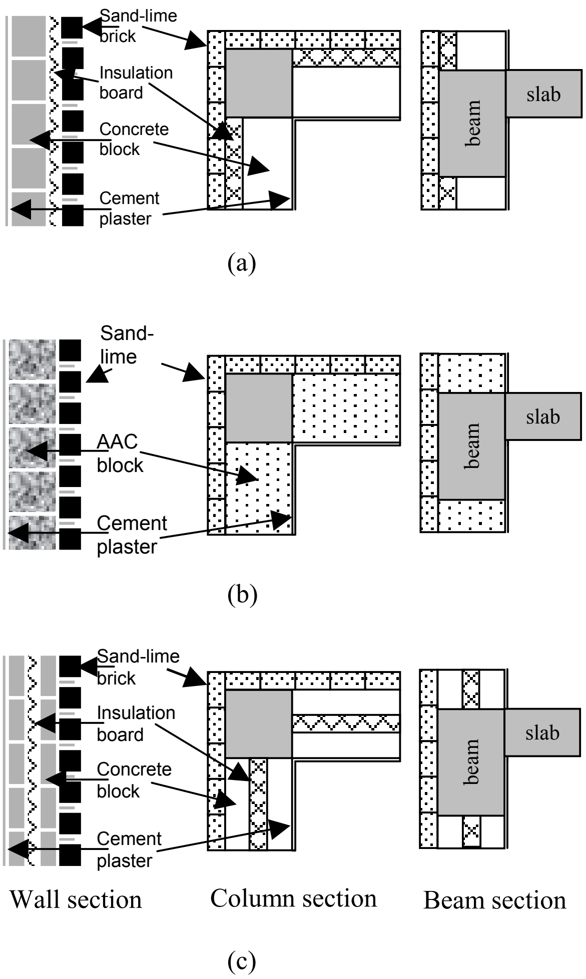


Figure 1. Typical construction types used in Kuwait; (a) Classical type. (b) AAC type. (c) Sandwich type.

the Autoclaved Aerated Concrete type (AAC) and the sandwich type. The figure illustrates the arrangement for each type in terms of a wall section, a corner and beam section. It can be seen from the figure that columns as well as beams are rarely insulated. A field survey to a number of building sites revealed that for private residential villas, area ratio for the columns and beams to total external wall was found to be 27.51% [5]. In addition, the surfaces for the columns and beams were found to be not insulated.

Another important factor to consider that can influence the severity of thermal bridging is the climate. The climate in Kuwait is characterised by a long summer extending over a period of seven months with air-conditioning required over 24 hours basis. The average dry bulb temperature for the month of August is 37.8°C (100°F) with the maximum dry bulb temperature reaching as high as 51°C (124°F) [6]. Such temperature differential coupled with a relatively large uninsulated area of highly conductive reinforced concrete can significantly degrade the thermal resistance of the building envelope.

METHODOLOGY

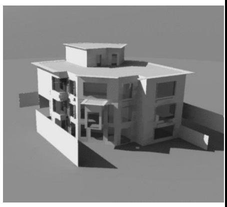
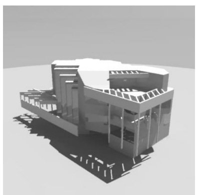
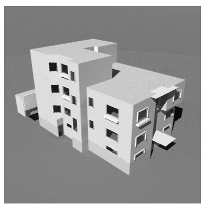
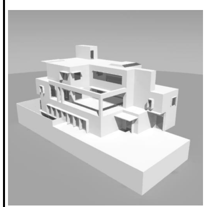
The technique adopted to conduct the analysis was computer based simulation. A three dimensional steady-state heat transfer analysis tool [7] was used to determine the effective U-value for walls and roof. Accordingly, a computer model of a two floor building was developed. The two floor representation was considered to be adequate since it will cover all possible wall/ground floor, wall/floor and wall/roof scenarios. Since it was assumed that the columns and beams in the case of the sandwich type can not be insulated, then only the classical and AAC wall types were considered for the heat transfer analysis. However, in the following sections only the former wall type will be elaborated. The three-dimensional representation was necessary to account for the complex thermal bridging that takes place between the walls, the corner section and the roof or floor section. For each wall type, a computer building model representing real Kuwaiti type building was developed. The model consisted of a ground level room and an upper level room. The two levels were separated by a 25 cm thick floor. The materials used for the columns, beams and the building foundations were identical to those used in practice (i.e. reinforced concrete). The building foundations were also included in the computer model. The foundations consisted of a 155 x 155 x 35 cm square bed section on top of which a 40 cm wide, 25 cm deep and 85 cm high vertical column section sits. Since the heat flow through the floor slab is dominated by the heat transmission at the ground surface in the region immediately surrounding the building (yard), the portion of the model for the ground was accordingly extended to cover the soil region extending some 6.0 m beyond the wall's exterior surface and to a ground depth of 1.9 m. The 6.0 m distance for the yard was arrived at from a number of incremental runs to find the distance at which the change in heat gain in the ground level room was negligible. The boundary conditions for the building were defined in terms of air temperature and heat transfer coefficient and were set at 47.2°C and 20.4 W/m^{2}K for the outside and at 25°C and 8.2 W/m^{2}K for the inside. Because of the geometrical and construction symmetry of the building, only a vertical quarter portion of the building was considered. The ground soil temperature was assumed to be constant at a depth of 1.9 meters and was fixed at 35.74°C. On top of the building's roof perimeter, a wall of 1 meter height was also included because it is commonly used in most Kuwaiti type buildings and consisted of cement blocks. The construction materials used and their thermo-physical properties are listed in Table 1. It should be noted that the building model developed for the heat transfer analysis does not include any windows since only the heat gain through external opaque walls was of interest in this study. The building model for the finite difference analysis was represented by a total number of 5912 nodes. The procedure for such representation involved setting up a two dimensional grid by specifying row and column widths, and then to complete the three dimensional grid by specifying the depth of the layers linking the previously defined two dimensional planes.

The steady-state analysis will approximate the equivalent U-value accounting for the heat gain from the columns and beams. The next step involved using a comprehensive building energy simulation program, such as the ESP-r [8], to allow the estimation of the annual energy consumption and the peak load demand. A computer model for the base case was developed assuming perfectly insulated walls and roof. The computer models represented four typical private villas; one with a large indoor swimming pool, one with a large sun space, one with a large hall and one with 16 bedrooms as indicated by Table 2. For each villa, a second case will be developed to account for the effect of thermal bridging. This was achieved by altering the thermal conductivity of the insulation material so that a U-value similar to that obtained from the heat transfer analysis is used. Hence for each villa, it would be possible to compare the two cases to assess the impact of thermal bridging on the overall thermal performance of the building. In order to perform the annual and hourly simulations, a set of input data are needed to define the boundary conditions. This is explained in more details in the following sections.

Table 1. Physical properties of the materials used in walls and roof.

Construction	Layer	Conductivity W/m K	Density kg/m^3	Specific heat J/kg K	Thickness m
Roof	Mosaic tile	1.1040	2284.0	795.0	0.0200
	Cement mortar	1.0000	2085.0	837.0	0.0200
	Sand	0.3400	2600.0	800.0	0.0200
	Insulation	0.0290	46.0	1214.0	0.0700
	Water proofing	0.1400	934.0	1507.0	0.0030
	Sand screed	1.0000	2080.0	840.0	0.0200
	Foam concrete	0.2100	351.0	879.0	0.1000
	Concrete slab	1.7700	2297.0	921.0	0.1800
Classical wall	Sand lime block	1.3100	1918.0	795.3	0.0900
	Air gap	-	-	-	0.02
(gap resistance	Insulation	0.0320	30.0	1214.0	0.0500
0.17 m^{2}K/W)	Cement block	1.6400	2011.0	921.0	0.1500
	Cement plaster	1.0000	2085.0	837.0	0.0200
AAC wall	Sand lime block	1.3100	1918.0	795.3	0.0900
	Air gap	-	-	-	0.02
(gap resistance	AACB	0.145	480	880.0	0.2000
0.17 m^{2}K/W)	Cement plaster	1.0000	2085.0	837.0	0.0200
Floor	Soil	1.2800	1460.0	879.0	1.900
	Concrete slab	0.8590	2160.0	920.0	0.1000
	Sand	0.3370	1800.0	920.0	0.0600
	Sand cement	1.0000	2080.0	840.0	0.0200
	Mozaic tiles	1.1040	2284.0	795.0	0.0200
Ceiling	Mozaic tiles	1.1040	2284.0	795.0	0.0200
	Sand cement	1.0000	2080.0	840.0	0.0200
	Sand cement	1.0000	2080.0	840.0	0.0200
	Concrete slab	0.8590	2160.0	920.0	0.1500

Table 2. Private residential villas considered in the annual building energy simulations.

	Villa A	Villa B	Villa C	Villa D
				
Land area (m^2)	587	800	587	750
Total constructional floor area (m^2)	990.7	1126.9	1101.7	1351.1
Total living area (m^2)	946.8	1035.8	1031.1	1338.0
Total roof area (m^2)	375.2	391.4	373.9	850.4
External opaque wall area (m^2)	717.7	889.6	955.4	1162.2
Total window area (m^2)	214.3	249.4	146.3	190.2
Main feature	Large Hall	Sun space	16 bedrooms	Swimming pool

Important Simulation Input Parameters

Information that affected the calculation of the annual energy consumption and the final load of the buildings is discussed in the following sections. The parameters considered include the climate, the internal loads and the strategy adopted to control the interior room temperatures.

Climate data.

Figure 2 shows the severity of the climate in Kuwait in terms of degree days. The results were based on a heating base-temperature of 18°C and a cooling base-temperature of 21°C. The dry-bulb temperature was extracted from a typical meteorological year (TMY) of climate data in a coastal region [6]. The data consisted of the dry-bulb temperature, diffuse radiation, direct normal radiation, wind speed, wind direction and relative humidity. The ESP-r uses this set of hourly data, and for sub-hourly simulation, it interpolates the data assuming linear correlations. The TMY was established from hourly weather files, which were collected continuously using the current setup for the Kuwait Institute for Scientific Research's (KISR's) weather station. The geographical location of the weather station was assumed to be similar to that of the private villas. The longitudinal difference and latitude for this location were 3°E and 29.3°N respectively. The figure clearly shows that the cooling season is predominant in eight months of the year and has the highest annual peak. In addition, during the cooling season, the sky is clear most of the time, which implies that the effect of solar radiation on the building's cooling load could be significant.

Casual gains (internal loads).

Casual heat gain in a building is the heat gained from electrical equipment, lighting, and/or occupants. The casual gains for lighting and equipment are usually in the form of sensible heat gains, however, for the occupants, it consists of both sensible and latent heat for which ASHRAE [9] recommends values of 67.4 and 55.7 W/person respectively for moderately active work. The lighting sensible load used for the villas was based on 15 W/m^2 and the equipment load was assumed to be 469 W/m^2. The three types of casual gains mentioned affect a zone's air temperature directly by convection and indirectly by radiation. The latter process accounts for the radiation exchange between a radiative casual gain type and the surfaces within a zone, and therefore, influences the resulting temperature of those surfaces, which in turn, affects the amount of heat transferred to the zone. For this reason, additional data were included to define the convective and radiative split for each casual gain type.

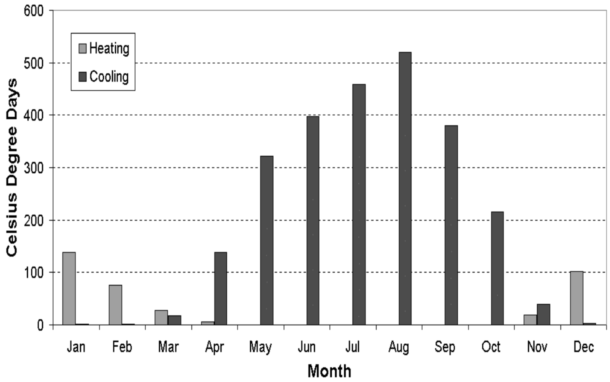


Figure 2. Climate severity in terms of degree days for Kuwait's coastal zone [6].

Control.

The purpose of a control function is to maintain the zone temperature and relative humidity at the specified set point. It does this by making the HVAC system inject the required heating and/or cooling sensible and/or latent load into the conditioned space to satisfy the control function. In the ESP-r, control was achieved using a basic control function that continuously monitors the conditions inside a space so that the right amount of cooling can be prescribed. In the analysis, the cooling set point chosen was 24°C with a relative humidity of 50% and the heating set point chosen was 22°C with a relative humidity of 50%.

HEAT TRANSFER ANALYSIS

The steady-state analysis was conducted on two different building models using TRISCO software package [7]. One with the columns and beams insulated (CASE 1) and one without insulating the columns and the beams (CASE 2). The steady-state heat flows, for the boundary conditions stated above, in the upper level and lower level sections are listed in Table 3. These values were arrived at by multiplying the results from the steady-state analysis by 4 since only a quarter section of the building was considered for the finite-difference analysis. The results clearly show that a significant increase in the heat gain results when the beams and columns are left uninsulated. The percentage increases in the heat gain from the floor of the upper level and from the ceiling of the ground level are the highest. However their contribution to the total heat gain is small. The increase in the heat gain through the upper level walls is higher than that of the ground level. The reason for this is because the heat gain through the beams of the upper level is influenced not only by conduction through the wall but also by conduction through the cement blocks of the 1 m high wall on the roof. It was explained earlier that the cement blocks of this wall is in direct contact with the

Table 3. Steady-state heat flow distribution through building models (Watt)

Construction	CASE 1, insulated columns and beams	CASE 2, uninsulated columns and beams	Percentage Increase
Upper level:			
roof	354.8	430.4	21.31
walls	974.8	1538	57.78
floor	37.84	88.56	134.0381
total:	1367.44	2056.96	50.4242
Ground level:			
ceiling	46.48	141.04	203.44
walls	1055.9	1537.96	45.65
floor	446.72	467.2	4.58
total:	1549.1	2146.16	43.98

beam and is exposed to the same boundary conditions as the roof which enhances the thermal bridging effect through this structure. The difference between heat gains of CASE 1 and CASE 2 is clearly shown in Figures 5 and 6. These figures show the heat gain intensity through all the building components. The bar at the right of the figure gives the range of heat flux intensity in W/m^2 corresponding to each shade. It can be observed that the regions along the columns and beams of CASE 2 have higher heat fluxes than those of CASE 1. This is expected since those regions are not insulated. It can also be seen that thermal bridging effect through the beam on the ground level and supporting the whole wall structure of the building, is also significant. It is clearly obvious from these figures that insulating the columns and beams has resulted in reducing the heat flow through these regions however some thermal bridging effect still takes place through the ground level beam and through the inside surface of the roof perimeter. The thermal bridging through the roof occurs because of the heat flowing from the outside and through the high conductivity cement block material (conductivity 1.307 W/m K) in contact with the roof slab. The investigation was extended to study the effect of using a lower conductivity material such as the Aerated Autoclaved Concrete (AAC, conductivity 0.145 W/m K) instead of the cement block material on the roof beam support. The results indicated that the upper level heat flow was reduced by 5.4 % for CASE 2 and a reduction of 16.4 % for CASE 1. Figure 6 also shows that although the column was also insulated, some disturbance to the heat flow through the walls of the ground level and along the vertical corner edge of the column still takes place mainly due to the heat conduction from the ground soil to the building foundation and then through the columns. A similar effect takes place through the upper level column; however, heat conduction down the column length is due to the thermal bridging effect caused by the sand-lime block on the roof beam support.

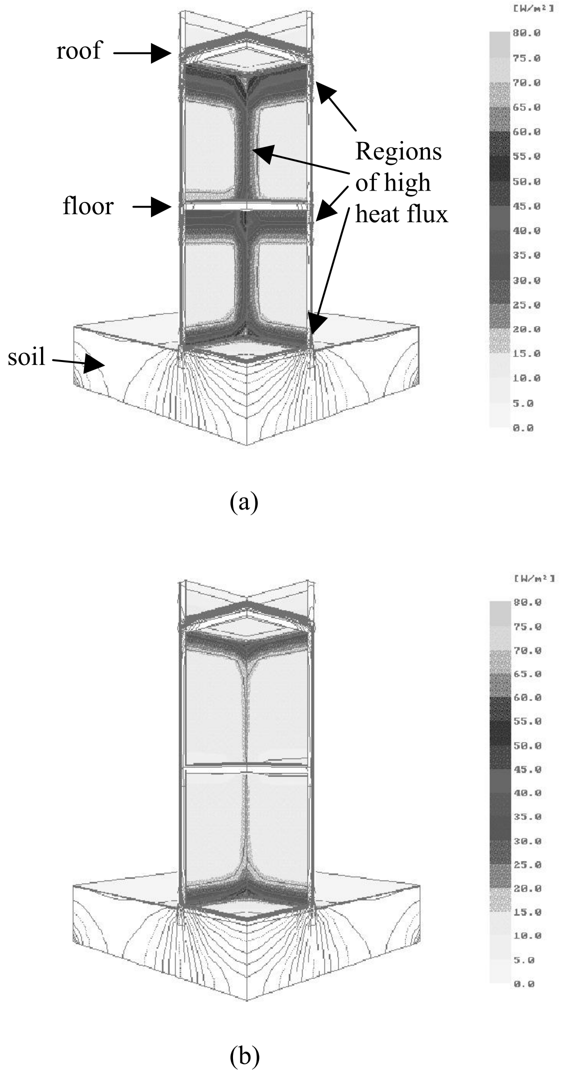


Figure 3. Distribution of heat flux intensity for the case where beams and columns are not insulated (a) and for the case where they are insulated (b).

Table 4 show the effect of columns and beams on the overall R value for the walls and roof. The R value specified for a particular structure does not usually include the presence of beams and columns. Although this assumption might be adequate in the case where insulation is applied to the columns and beams, it is not valid in the case where the beams and columns are not insulated as indicated by the Table. The effective R value was calculated from the steady-state results as follows:

$$R = \frac{A\,\Delta T}{Q} \times 5.67446 \qquad h.f^2.^{\circ}F / Btu$$

where A is the surface area (m^2), ΔT is the temperature difference (°C) and Q is the calculated steady-state heat gain for the surface considered (W).

It can be observed from Table 4 that by comparing against the minimum insulation measures stipulated in the code, a significant reduction in the R value results in the case where the beams and columns are not insulated. This reduction ranges from 41% for the walls to 48% for the roof. In the case where the beams and columns are insulated, the reduction in the R value for the walls was 7% whereas for the roof the reduction was 36.5%. The reduction in the R value for the roof is higher because of the cement blocks of the roof wall which are in direct contact with the roof slab and act as good heat conductors and thus increase the heat gain through the reinforced concrete of the roof. Considerable reduction in the heat gain through the roof may be achieved if the AAC was used instead of using the cement blocks for the roof wall. With this simple measure, the reduction in the R value was reduced by only 7.8%. The negative percentage reduction for the wall indicates that the R value used in the building walls was actually higher than R10.

Table 4. Resulting R values for building model with classical wall.

Construction	R value (code) h.f^2.°F/ Btu	Effective R value h.f^2.°F/ Btu	Percentage Decrease %
Beams and columns not insulated			
wall	10	5.9	41
roof	14	7.32	48
Beams and columns insulated			
wall	10	9.3	7
roof	14	8.9	36.5
beams and columns insulated and using AAC for roof wall			
wall	10	10.6	-6
roof	14	12.9	7.8

BUILDING ENERGY SIMULATION ANALYSIS

The private villas were first simulated using the default R-values for walls and roof which meet the minimum requirement as stipulated in the code of practice for energy conservation. Hourly simulations were carried out for the whole year in order to estimate the annual energy consumption and the peak load occurring at the peak day. The thermal conductivity value for the thermal insulation in walls and roofs for each villa were then modified to yield the same percentage decrease in the R-value as indicated in Table 4. Consequently another set of simulations were conducted and the results were then compared. Both the electric energy consumption and the electric load for air-conditioning are normalized in terms of living floor area for comparison purposes and are listed in Table 5.

Table 5. Simulation results for electric annual energy consumption and peak load requirement.

Villa	Insulated case		Not insulated case		Percentage increase	
	kWh /m^2	W/ m^2	kWh /m^2	W/ m^2	Cons.	Peak load
A	279	66	286	68	2.4	2.9
B	274	62	280	63	2.1	1.6
C	256	66	263	68	2.7	2.9
D	258	61	260	62	0.8	1.6
Avg.	267	64	272	65	1.8	2.3

It can be seen that the approximated overall effect of thermal bridging on annual energy consumption is small and does not exceed 2.7% in the worst case. Similarly, for the peak cooling demand the percentage increase does not exceed 2.9%. The average for the four villas is 1.8% and 2.3% for the annual energy consumption and peak load demand respectively. The reason for this small increase is the fact that the heat gain through the opaque walls and roofs of the buildings is relatively small compared to the sum of the heat gain from other sources such as infiltration, ventilation and transparent surfaces. Higher percentage increases would result if the comparison made was based on the heat gain through opaque surfaces only.

CONCLUSIONS

In this study the effect of thermal bridging due to uninsulated columns and beams in typical Kuwaiti type masonry buildings was investigated. The steady state three dimensional heat transfer analysis indicated that as much as 41% reduction in the thermal resistance of walls is possible if the columns and beams were not considered for insulation. For the roof it was reduced by 48% mainly due to the presence of a larger reinforced concrete slab area. However, the simulations conducted on the private villas and accounting for the decrease in the thermal resistance of walls and roofs, have shown negligible increases in the annual electric energy consumption and peak load demand. The reason for this negligible increase was mainly attributed to a lower magnitude of heat gain through opaque surfaces compared to the summation of other heat gain contribution from internal load, infiltration and ventilation and through transparent surfaces.

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