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LIMITATIONS OF BUILDING PERFORMANCE SIMULATION: MODELLING A BUILDING WITH GABION WALLS

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ABSTRACT

Simulations were conducted to optimize the design of a small building with walls constructed of limestone-filled gabion baskets. Different methods of insulating and weatherproofing the gabion walls were compared, with the indoor operative temperatures in the summer design week providing the critical comparison. The performance of the gabion building was compared with that of more conventional construction types to demonstrate the superior thermal performance of gabions in a temperate climate (Australia). This paper also addresses an issue with simulating gabion walls. Due to the inconsistent nature of gabion walls, the simulation requires the thermal properties of the gabion walls to be approximated as the simulation program cannot accurately model the voids and variations in a gabion wall. The material simplifications are discussed and the buildings thermal performance with these assumptions are analysed.

INTRODUCTION

This research project was based on the Solar Decathlon brief, an international competition held in the U.S. that challenges teams to design and engineer a fully sustainable house to respond to the 10 contests of the Solar Decathlon. These included sustainability, architecture design, engineering/construction, thermal comfort, energy requirements, solar power, embodied energy, water/waste, life-cycle cost and innovation (*US Department of Energy, 2014*). The small-scale building's footprint was to be no more than 70m^2, and the building had to be a positive response to these challenges. The site chosen for this project is in Stokes Bay, Kangaroo Island, South Australia (S 35° 37', E 137°12') on the edge of a cliff with strong wind conditions.

Due to its remote location, the building must be self-sufficient, and the design must provide a comfortable living space while minimizing environmental impact. One important strategy to reduce the impact on the environment is to use materials with low embodied energy. For this project, gabions have been selected as the structural walls as this type of construction offers a sustainable alternative to traditional construction. Locally found limestone in its naturally occurring state can be utilised to build gabion walls as they are inherently low in embodied energy due to their unprocessed state and locality to the site. Due to the density and thermal capacity, natural stone within the gabion baskets is an ideal material for thermal mass within buildings. Another important aspect is that unlike other rock walls, gabion walls do not require the skilful placing of stones, binding agents or high-embodied energy concrete footings (*Dernie, 2003*).

Although gabion walls are common, they are predominantly used as retaining walls due to their strength and permeability. There is little information on the use of gabions as load bearing walls for buildings. Factors such as settlement of rocks within the baskets could affect the load bearing capacity of the wall and therefore will require further investigation to decide if this is a viable wall construction option in terms of engineering. Furthermore, gabions characteristically have voids between the stones, making weatherproofing and climate control potential issues. As a result, investigation should be conducted into innovative implementation of gabions to form a climate-controlled envelope, further to the theoretical performance presented in this paper.

This paper focuses on the potential thermal performance of the house using limestone-filled gabion walls and addresses three main objectives of the research. First, the building design will be presented followed by a discussion about a number of ways to improve the thermal performance of the gabion house, supported by the use of building simulations and theoretical research. Next, the performance of the gabion walled house will be compared with a house with the same design but using more conventional construction types. The challenges of simulating gabion walls will be also discussed.

ABOUT GABIONS

History of gabions

Gabions are wire mesh baskets filled with rock to form larger modules. Gabions are primarily used in engineering and landscape design due to their capability of resisting large lateral loads while being self-supporting structures. Applications include retaining structures, protection against corrosion of coastal shores/river-banks and ventilation of landfill sites (*Gabion Supply, 2014*). Recently, architects have recognized the potential of gabions as either cladding or non-structural facades due to their cost effectiveness compared to traditional concrete or reinforced walls, as well as their aesthetic value. Gabions provide the potential to use small pieces of local stone recycled from buildings or quarries that would otherwise be used as waste or fill. The construction process is simple and specialist foundations or installation is not a requirement for small-scale gabions, allowing local labour to be employed (*Dernie, 2003*).

Architectural application of gabions

The most common use for gabion walls in architecture is currently as a cladding system. This natural aesthetic is obviously appealing to architects. An example of this is the Barnsley Digital Media Centre in South Yorkshire, constructed in 2007 using lightweight stone blocks, stone gabion with stainless steel mesh, concrete and glass. Stone is the predominant material used in the construction with gabion stone in cages grounded at the base to reflect the rough stone of an existing retaining wall (*Meyhöfer, 2009*).

There are few examples where gabion walls have been used in building design as structural walls. One example is the Boat House, Tunbridge Wells (shown in Figure 1) – a small structure with free standing trapezoidal gabion walls (Type B in Figure 2) supporting a timber-framed roof. Due to the strong wind on site, vertical anchorage embedded within the gabion was installed to resist possible uplift forces when the doors are open (*HY-TEN Gabion Solutions, n.d.*). However, as this structure was not residential there was no requirement to provide impermeability or weatherproofing.

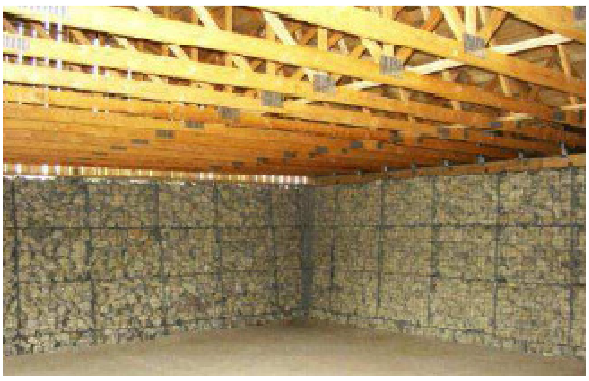

Figure 1 Walls of the Boat House (HY-TEN Gabion Solutions, n.d.)

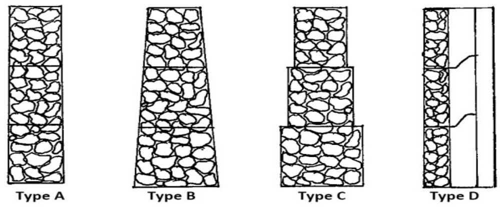

Figure 2 Example Cross Sections of Gabion Walls (Milosevic et al., 2014)

Another example using trapezoidal gabions (Type B in Figure 2) is the Classroom of the Future, London, where the main wall was covered in a sandwich of geotextile and membrane prior to facing the structure in a 300mm thick gabion cladding. (*HY-TEN Gabion Solutions, n.d.*). This gives an example of a weatherproofing system implemented to resist moisture entering the interior. There is no mention of consideration to comfortable temperature levels in documents associated with this building.

PROJECT INFORMATION

Project site

The climatic conditions of the site influence the passive design principles applied to the building. Stokes Bay is within a temperate climate zone with winter temperatures ranging from 1 to 22°C in winter and 8 to 41°C in summer, and relative humidity ranging from 45% to 94% (*BOM, 2013*). The average daily solar radiation in winter is 8.4 MJ/m2 and 26 MJ/m2 in summer. Wind speed varies from 30 to 46 km/h (*BOM, 2013*).

Building design

The house consists of a living space, study, kitchen, bedroom and a bathroom, which also doubles as a laundry space. Three key factors were considered when designing the layout of the building. The primary factor was utilisation of natural light and passive solar design principles. For this building located in the Southern Hemisphere the main aperture should face northwards to allow for the greatest solar heat gain in winter, and for direct sunlight to radiate onto the internal thermal mass of the gabion (*Morrissey et al., 2011*).

The secondary factor is the site location and the potential for observing the scenic views from the house. Although the whole locale is serene with the ocean to the north, it was decided that the ideal view was to the north east looking across the bay and beach.

The third and final factor considered for the orientation and layout of the building was the strong wind conditions on site, which would necessarily make outdoor or exposed areas unpleasant to use when inundated with extreme wind. This affects the outdoor deck area and operable windows. The maximum wind speeds that occurred each day were obtained from the local weather station and are

Table 1 Predominant Wind Direction on Site (BOM, 2013)

Wind Speed and Direction (km/h): Kingscote												
9am Highest	41	46	30	30	26	33	37	39	39	48	33	46
	NW	ESE	SE	SE	SE	ENE	N	N	E	W	S	SSW
3pm Highest	39	44	39	39	30	41	37	44	44	46	39	37
	SW	SE	WNW	WNW	SW	S	NNW	WNW	WNW	WSW	SSE	S

shown on Table 1. With all these three factors considered, and with the passive solar design aspect taking priority, it was decided that the building should be oriented towards the North, offset slightly to the East by an angle of 10 degrees.

The final floor plan and section of the house are presented in Figures 3 and 4 below.

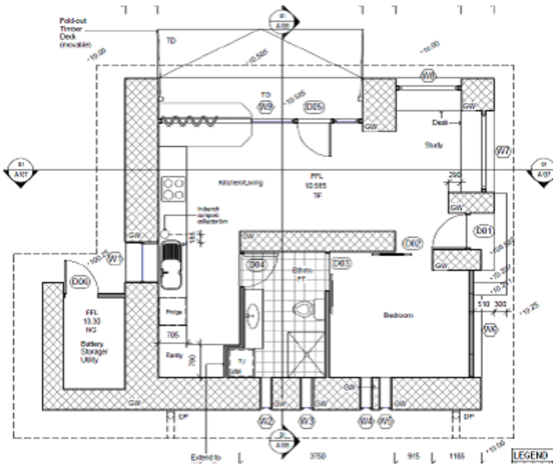

Figure 3 Floor Plan (Milosevic et al., 2014)

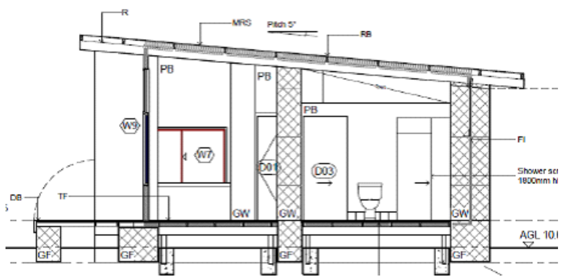

Figure 4 Cross Section of the Building (Milosevic et al., 2014)

METHODS

Model assumptions

The research was primarily conducted through simulation given the expense of other research avenues and the availability. Simulations were carried out using DesignBuilder (*DesignBuilder, 2013*). Figure 5 shows how the building was modelled within the parameters of DesignBuilder. 'Component blocks' were used to represent eave extensions as well as the shading that would be provided for the western window by the inset into the gabion wall. Shading devices were included on the northern and eastern windows, with the southern windows being rows of glass blocks. The preliminary design was modelled directly north facing for simplicity and preliminary testing or results, while the final design was modelled more accurately at 10° east of north.

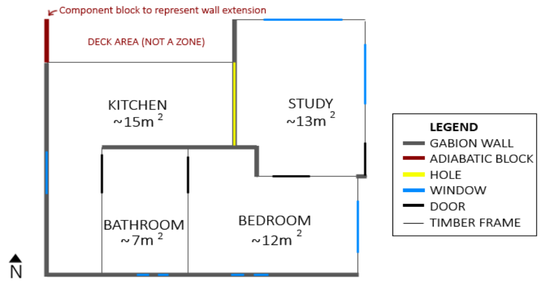

Figure 5 Preliminary Representation of the Building (Milosevic et al, 2014)

It was realised that an intricate model would have been required to achieve accurate simulation of the thermal performance of gabion walls. The highly variable and random nature of rock placements within the basket, as well as natural variation within the limestone, makes any model theoretical. Each section would be different varying slightly in terms of rock density and properties, void locations and dimensions to a physical model. Due to all the assumptions that would be required for the theoretical model, any modelled results would need to be verified through physical testing. This is simply out of the scope of this research; hence, a simplified model is the logistic way of drawing conclusions of the thermal performance of gabion wall construction. While a simplified model (such as presented in this paper) would not be entirely accurate to simulate actual performance, the simulations would allow for an informed opinion on the anticipated thermal performance with different insulation compositions.

To represent the nature of gabions, several different compositions of limestone and air gaps were considered in the early preliminary design stages. As these slight differences in the configuration of the construction had very little impact on the simulated performance of the preliminary building, the gabion constructions were approximated, as shown in Figure 6.

Table 2 Thermal Properties of Materials

Material	Modelled Thermal Properties		
	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)
Sheep Wool Insulation	**0.039**	**1000**	**22**
Limestone	**1.4**	**1000**	**2000**
	U-Value (W/m2K)	Visible Light Transmittance	Solar Heat Gain Coefficient
Double Glazing	**1.635**	**0.682**	**0.417**
Glass Blocks	**3.0**	**0.55**	**0.68**

Source: Black Mountain Insulation Ltd, n.d., Adelaide Glass Blocks, n.d., DesignBuilder, 2013

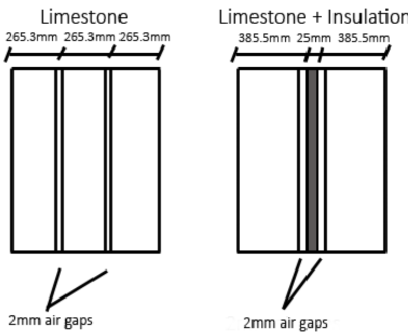

Figure 6 Approximation of Gabion Wall in the Simulation (Milosevic et al, 2014)

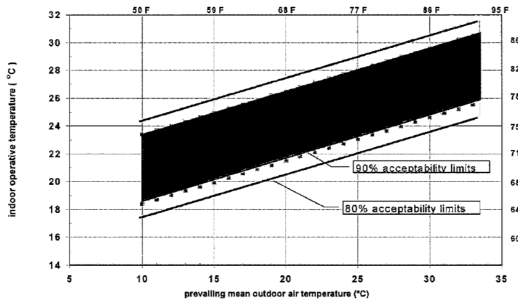

Figure 7 Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces (ASHRAE, 2013)

The thermal properties of the limestone to used for the gabion wall and thermal insulation simulation are presented in Table 2 This table also shows the thermal properties of the glazing and glass blocks as modelled in *DesignBuilder.*

Properties of materials more commonly utilised and less customisable than glass, such as hardwood, metal roof cladding and plasterboard were chosen from DesignBuilder's default material library as their thermal properties are unlikely to change.

DesignBuilder takes weather data files from EnergyPlus (*EnergyPlus, 2013*) to simulate the site conditions. As data for Stokes Bay was not available, the Cape Borda weather data was selected for use as being the closest geographical location to Stokes Bay, as well as being fairly consistent with the site's expected climate.

To model the ability for air to penetrate the subfloor gabion baskets as Gabions are not airtight without additional weatherproofing treatment (such as render or non-porus insulation) small vents were added to the below floor zone to simulate this effect. Small slatted grille vents operating on a 24/7 schedule allowed for the effect of below floor ventilation to be considered in the building's final temperature analysis.

One particular limitation of modelling a building with such thick walls (500 to 800mm) with DesignBuilder is how the walls were drawn. DesignBuilder does not allow partitions to be modelled at multiple thicknesses within the same model. Zones were modelled as being separated by thin partitions where in reality some of these internal 'partitions' are thick Gabion walls (500mm to 800mm) and some are thin stud walls (90mm). While the actual construction and thickness of the internal walls can be specified in the input file, the difference between the actual wall and modelled partition in the drawing can have impact on the computation of the room's floor area and volume.

Another assumption was made in modelling the internal partitions. As the internal timber framed partitions in this design do not meet flush with the ceiling, the partitions were modelled as floor-to-ceiling walls with small holes inserted to represent this effect along the tops of the affected partitions.

Analysis

The thermal performance of the initial and subsequent designs of the house was analysed by examining the indoor operative temperatures of the main spaces. As the house is intended to be self-sufficient, it was assumed that no heating and cooling would be in operation. Thus the adaptive thermal comfort model (*ASHRAE, 2013*) was used to analyse the results. A building that remains within the 80% acceptability limit, as per Figure 7, without the aid of mechanical cooling, appropriately meets this adaptive thermal comfort standard and would generally be considered comfortable to the occupants.

While ASHRAE presents a widely accepted range for thermal comfort, Daniel et al. (*2014*) presents research within Australia of the thermal comfort occupants of houses of atypical construction (earth and naturally ventilated houses) that indicates people often consider temperature ranges to be comfortable even outside of the adaptive thermal comfort range. As such, the simulation results were analysed against both ASHRAE and Daniels et al. comfort ranges.

RESULTS

Simulations were conducted to investigate a number of design solutions. First, the indoor operative temperatures of the house without insulation inserted in the gabion walls was compared to that with various insulation types. Second, the placement of the insulation within the gabion wall construction was studied and its impact analysed. Third, the performance of the house using insulated gabion walls was compared to that with more conventional wall constructions used in other houses in the area, such as double brick, brick veneer, timber framed and AAC blocks.

Uninsulated and insulated gabion walls

Without the use of heating, adding 25mm insulation to the gabion wall would improve (increase) the indoor operative temperature in winter by 2°C. The addition of insulation allows the building to reach a more comfortable temperature in winter, by slowing the rate of heat loss through the thermal mass of the gabion walls.

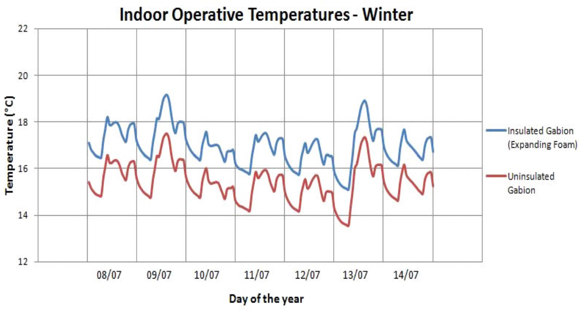

Figure 8 Comparison of Winter Operative Temperatures Between Insulated and Uninsulated Gabions

Placement of the insulation

Anani and Jibril (*1988*) recommend that the external side of a thermal mass wall be insulated to prevent external heat from being absorbed and the heat within the mass wall being lost to the outside. Different positioning of expanding foam insulation within the gabion wall was therefore considered as shown in Figure 9. It was found that although there was some improvement from placing insulation closer to the external edge of the wall, as shown in Figure 10, using different thickness rock leaves makes the construction process (and engineering details) more complicated and a simpler design is therefore recommended and was thus continued in analysis.

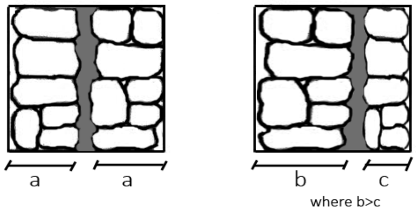

Figure 9 Positioning of Insulation within the Gabion Wall (Milosevic et al, 2014)

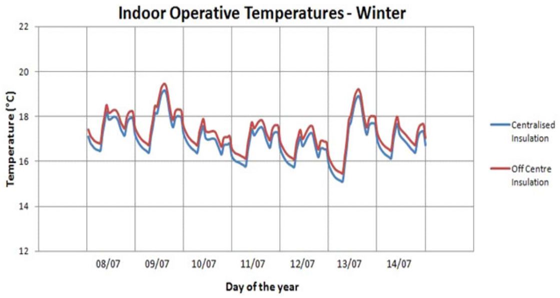

Figure 10 Comparison of Winter Operative Temperatures With Different Placements of Insulation

Figure 11 Trial Gabion Wall Construction

The closed cell soy-based foam insulation (Heatlok Soy 200 Plus) is able to adequately insulate the gabion baskets, creating a protective weatherproof/air tight barrier, add structural integrity to the wall and only requires a depth of 25mm to achieve good thermal performance (*Demilec, 2014*). It was therefore suggested that similar insulation be used in the construction of a climate controlled gabion wall. However, it is recommended that further testing of the foam insulation in combination with the gabion baskets be conducted before construction. In particular, the practicality of constructing gabion baskets with two internal diaphragms to create a uniform 25mm gap in the rocks should be considered in further research, as only the ease of constructing an uninsulated gabion basket was trialled (shown in Figure 11) due to the costly nature of physical testing.

Table 3 Chosen Construction Types for Comparison

Elements	Type A Gabion House	Type B Double Brick House	Type C Brick Veneer House	Type D Lightweight Timber House	Type E AAC Block House
External Walls	Gabion	Double Brick	Brick Veneer	Timber Frame	AAC Block
Internal Wall	Gabion	Brick	Brick	Timber Frame	Timber Frame
Partitions	Timber Frame	Timber Frame	Timber Frame	Timber Frame	Timber Frame
Roofing	Timber Frame	Timber Frame	Timber Frame	Timber Frame	Timber Frame
Flooring	Suspended Timber	Concrete Slab	Concrete Slab	Concrete Slab	Concrete Slab

Final Design

Based on the preliminary design iterations the final design was settled upon, based primarily on thermal comfort results. The final design model was analysed for full comfort consideration. As can be seen in Figure 12, without cooling in the summer design week the building maintains a relatively stable indoor operative temperature as the outdoor temperature fluctuates, with peaks of over 30°C degrees reached outside on most days. The indoor operative temperature remains within ASHRAE's 80% acceptability limits, thereby maintaining a comfortable temperature throughout the summer months.

In the winter design week, without heating the building maintains indoor operative temperature between 14 and 19°C. A large difference between the indoor and outdoor temperatures is observed in the design week, as well as throughout the winter months. Note As the mean monthly outdoor temperatures on the site in winter were below 10°C the ASHRAE's acceptability limits for indoor operative temperatures at outdoor temperatures below 10°C were considered the same as those at 10°C. While the indoor operative temperatures in the building do not stay within ASHRAE's 80% acceptability limits, it is still considered relatively comfortable as they are within the findings by Daniel et al. (2014) presented earlier, as shown in Figure 13.

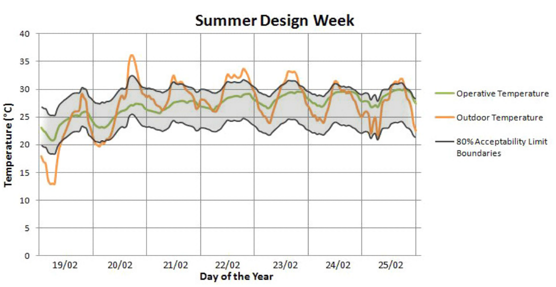

Figure 12 Indoor Operative Temperature During Summer Design Week

Comparisons to conventional construction

To further understand how the gabion house performs, four conventional house construction types were chosen for comparison - the key materials of which are summarised in Table 3. A comparison of the thermal performance of the house with these different construction types was performed with one of the building models. No heating or cooling was used in the building in these comparisons, and only the material constructions were changed from the final gabion model.

As can be seen in Figure 14 the gabion building performs substantially better in summer than the other construction types considered, with temperature differences of 2 to 4°C being achieved across the summer design week between the gabion building and the other construction types modelled. Similarly the building with gabion wall construction outperforms other wall construction types in the winter design week, producing temperatures which average 2 to 4°C warmer than other construction types, as shown in Figure 15. These results demonstrate the ability of the gabion walls to provide a more thermally comfortable environment year round compared to other wall construction types.

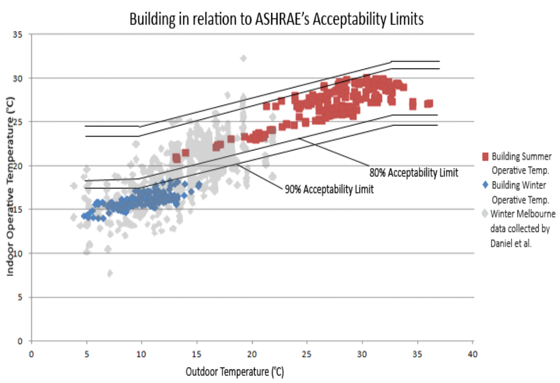

Figure 13 Comparison of the indoor operative temperatures in the building during winter design week compared to Daniels et al. (2014) and ASHRAE's acceptability limits

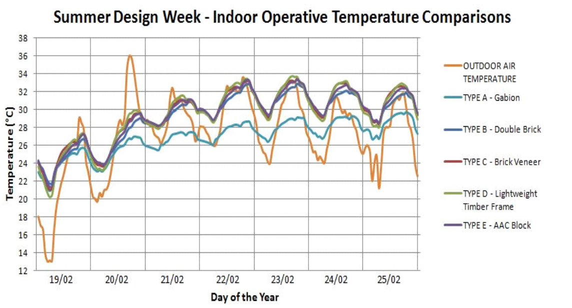

Figure 14 Indoor operative temperature comparisons during summer design week

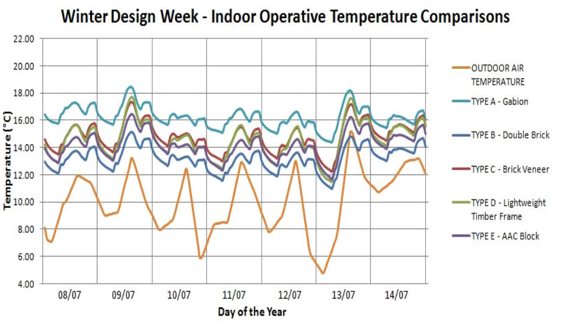

Figure 15 Indoor operative temperature comparisons during winter design week

CONCLUSION

This paper has confirmed the feasibility of gabion walls for residential construction. A method for insulating and weatherproofing gabions (expanding foam insulation) has been theoretically verified as both feasible and well performing thermally. Further design and testing of the weatherproofing solution presented in this paper would be required to further understand the applicability of this theoretical solution to construction. Ideally this would be tested with the construction of full scale gabion walls. Further testing (both simulation and real world) is suggested to support the initial conclusions presented in this paper. While DesignBuilder provides a sound platform for simplified testing of a very complex construction type, the computer power and simulation time for a more complex model of the heat transfer/conductance of a gabion wall model with expanding insulation, surface and void variation is suggested to further the understanding of gabion performance and potential in a climate control envelope.

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