Fifth International Conference on Sustainable Construction Materials and Technologies. http://www.claisse.info/Proceedings.htm

LONG-TERM MONITORING OF AN EARTH MASONRY SHELL HOUSE IN JOHANNESBURG, SOUTH AFRICA: THERMAL PERFORMANCE

Ryan Bradley[1], Mitchell Gohnert[1] & Anne Fitchett[1]

[1]School of Civil and Environmental Engineering, University of the Witwatersrand, Private Bag 3, PO Wits, 2050, South Africa. ryan.bradley@wits.ac.za; mitchell.gohnert@wits.ac.za; anne.fitchett@wits.ac.za.

ABSTRACT

Earth has been used as a building material for millennia, and several structures built in antiquity still exist today. Recently, there has been renewed interest in earth-block masonry as it offers several benefits over more traditional materials, including sustainability, low embodied carbon and energy, good thermal and climatic performance, and affordability. Additional benefits may be achieved by utilising pure-compression shells for roof or structure, thus eliminating the need for expensive and/or energy intensive components and materials. Such structures have been built and inhabited in several regions across the world. Of particular focus in this paper is a prototype shell house built in Johannesburg, South Africa. It is a double storey house, comprising of interlocking masonry (dry-stack) walls, mortared earth block vaults, reinforced concrete foundations, and a rib and block slab. The roof of the structure is comprised of two unreinforced steep catenary vaults, which removed the necessity for conventional roofing materials. This paper presents some observations and in-situ experimental results from a long-term thermal evaluation of the prototype shell house. The effectiveness of several passive design strategies was also examined. Natural ventilation and painting external surfaces white were especially effective at reducing late afternoon (and evening) temperatures during summer. Another important finding was that the shading of the shell's surface resulted in a significant reduction of indoor temperatures during the winter months. Specifically, the temperature within the north vault was regularly 3°C - 5°C warmer than in the partially shaded south vault between 5 PM – 9 PM in mid-winter (during June and July, 2018). Subsequently, several performance recommendations are presented for unreinforced earth-masonry shells.

Keywords: Earthen masonry; vaults; thermal performance; low-cost housing

INTRODUCTION

South Africa, like many developing countries, faces significant challenges in meeting the demand for affordable housing. The post-Apartheid government has worked towards improving the situation by providing over 2.8 million opportunities through housing subsidies for poor households (National Department of Human Settlements, 2017). However, the proportion of informal housing, which typically lacks basic services and satisfactory quality of construction, remains troublingly high. The 2016 General Household Survey revealed that 13.9% of households lived in informal dwellings (Stats SA, 2016); only 2% lower than that reported in 2005 (Department of Human Settlements, 2017). The magnitude of the problem is emphasized further when recognizing that the eradication of informal settlements was originally predicted by 2014 (Department of Human Settlements, 2017). The problem is especially severe in Gauteng Province, the economic centre of South Africa, where informal structures account for about 20% of all dwellings.

Although the proportion of state-subsidized formal houses has increased over the past few years, there are issues with the quality and resiliency of these structures. Some inhabitants have reported dissatisfaction with the quality of their state subsidized housing, citing issues with the walls and roofs (Stats SA, 2016). Structural issues aside, poor thermal performance is another deficiency with these houses; especially those that lack ceilings and roof insulation (Naicker *et al.*, 2017). This is not uncommon. This problem is particularly acute in houses built with zinc or corrugated iron roofs, where temperatures get very hot during the day in summer and cold in the night during winter (Bolton and Burroughs, 2001). There is certainly a need to improve the performance and resilience of these structures but also to develop inexpensive alternatives to make housing more affordable. In order to reduce costs, innovative systems should be investigated instead of searching for marginal savings with conventional systems, which may result in reduced performance and/or strength. Several cost-effective systems have entered the housing market in recent times, such as prefabricated light-weight wall and roof panels. However, several other aspects, apart from initial cost, should be considered such as resilience, energy usage, material consumption, sustainability and the comfort and health of inhabitants.

These considerations have resulted in renewed interest in sustainable building materials, such as earthen masonry. Although an ancient building material, earthen masonry possesses several positive attributes appropriate to the modern housing industry, such as: low cost; low embodied energy and carbon; sustainability; and good thermal performance (Morton *et al.*, 2005; Zami and Lee, 2010). The excellent thermal performance associated with vernacular earthen buildings is attributed to the material properties, specifically its heat capacity and thermal conductivity, as well as the considerable thickness of earthen walling (sometimes greater than 400 mm). The benefits of earthen masonry have also promoted its adoption for roofing in the form of singly- and doubly-curved shells (Habitat, 1992; Norton, 1997; Adam and Agib, 2001; Auroville Earth Institute, 2016). Some studies have reported significant cost reductions by replacing a standard roof with an earthen masonry shell (e.g. Adam and Agib, 2001). This is accomplished by eliminating expensive and/or energy intensive materials as well as transportation costs if the soil is sourced from, or near, the building site. It has been reported in some studies that greater economic efficiency is possible by replacing the walls and roof with a shell, such as a dome (Gohnert and Magaia, 2004; Gohnert and Talocchino, 2011) or vault (Gohnert *et al*., 2018).

It must be recognized that a heavy earthen shell is fundamentally different from a conventional housing structure, which incorporates several components to meet structural, performance and thermal insulation requirements. Like other heavy building materials, e.g. concrete and standard brickwork, earthen masonry possesses high thermal mass, and numerous sources advocate their adoption throughout much of South Africa (e.g. NBRI, 1987; Conradie, 2012). In particular, heavy materials absorb heat during the day, keeping the indoor temperature relatively low, and then release it at night by convection when the temperature of the adjacent air drops below that of the masonry. Domed and vaulted masonry roofs have been widely used for centuries, particularly in the Middle East (Dabaeih *et al*., 2015; Hadavand *et al*., 2008). The thermal performance of curved roofs in these hot arid regions has been examined in several studies, and some authors report that vaulted roofs are superior to flat roofs in terms of thermal performance (Dabaeih *et al*., 2015; Hadavand *et al*., 2008). Although masonry shells provide additional thermal mass, several such structures situated in South Africa are somewhat thinner than walling implemented in conventional housing. In many cases, these exposed shells comprise of only a single-leaf brick, roughly 100 mm thick. This reduced thickness, as well as the solar exposure of the envelopes, raises questions about the thermal performance of such thin uninsulated masonry structures.

Although several studies report on the structural and economic benefits associated with such structures, there is little information on their liveability – specifically in South African climates. To elucidate the salient performance considerations, a long-term in-situ assessment was undertaken for a compressed stabilized earth block (CSEB) shell house built in Johannesburg, South Africa. This paper presents some results from the study, as well as several recommendations for the design of these structures.

EXPERIMENTAL ARRANGEMENT

Prototype house

The prototype affordable house evaluated in this paper was built in an open area on the main campus of the University of the Witwatersrand, Johannesburg, South Africa (situated at an elevation of ~1700 m above sea level, with coordinates of 26°11'09"S 28°01'30"E). The house is somewhat unique, incorporating several materials and components to achieve improved cost and structural efficiency. The roof of the structure comprises of two steep catenary vaults, which eliminate the need for conventional roofing materials and doubles the living space. These vaults are uninsulated and utilise thermal mass to improve indoor comfort. Figure 1a shows the completed structure. The important load considerations and design details are presented by Bradley *et al.* (2017) and Gohnert *et al*. (2018), respectively. Walls at ground and first-floor levels were built with dry-stack interlocking blocks, manufactured from recycled building rubble; whereas the vaults were constructed from CSEBs in a cement:sand mortar (Figure 1b). The CSEB and dry-stack blocks are 150 mm and 220 mm thick, respectively. Internal surfaces of the vaults are plastered (cement-sand), whereas the external surfaces are coated with a cement-wash, and a dark acrylic roof paint. The total thickness of the shell is roughly 170 mm, and the load and non-load bearing walls are 220 mm thick. A 170 mm deep rib and block slab was included above the dry-stack ground-floor walls.

(a) Prototype from the north-west

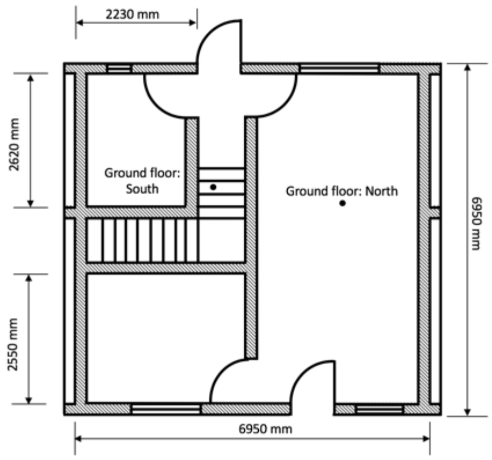
(b) Catenary vault construction

Figure 1. Construction of the prototype house at the University of the Witwatersrand

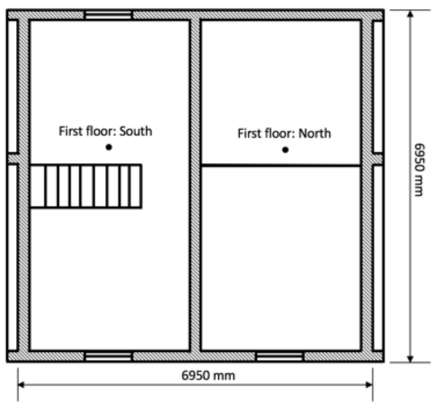
Openings were incorporated in the east and west-facing dry-stack walls, which is ideal for ventilation during the summer in Johannesburg. Hourly wind direction data for a typical year, acquired from Meteonorm (Meteotest AG, Bern, Switzerland), shows that the prevailing wind comes from the east during the summer months. The windows integrate aluminium framing and McCoys's McLam® clear low-E glass (6.38 mm nominal thickness; R-value = 0.28 m^2.K/W). This single-glazed glass transmits 83% of visible light and 70% solar energy (McCoy's Glass, 2018), which still facilitates passive gain through the east and west facing windows in the morning and afternoon, respectively. In the summer, vertical or lateral shades could prevent unwanted solar gain, particularly though west-facing windows in the late afternoon, but these mechanisms were not considered in the present study. However, the windows were shielded on a few days to facilitate several assessments. Heavy curtains or blinds were not implemented to reduce night-time winter heat loss.

Instrumentation

The operative temperature (T_{op}) was measured in several spaces within the building, away from any direct solar radiation. Operative temperature represents the combined effect of air temperature, mean radiant temperature as well as air movement, as a single quantity. CIBSE Guide A (CIBSE, 2006) notes that operative temperature can be measured using a ~40 mm diameter black globe thermometer, and that these may be constructed with standard table tennis balls, which are appropriate for indoor spaces. Subsequently, several black globe thermometers were produced by mounting J-type thermocouples inside table tennis balls, which were sprayed with black paint. The exposed end of the wire was positioned at the centre of the globe. The location of the globes, relevant to the discussion presented in this paper, are illustrated in Figures 2a and 2b. Temperatures were measured 1.1 m above the floor, per the recommendations of ASHRAE Standard 55 (2010). Data was recorded every 15 minutes with an Agilent data-acquisition unit (Agilent Technologies Inc., Santa Clara, California). The outdoor air temperature was measured hourly, in a continually shaded region of the southerly side of the building.



(a) Ground-floor

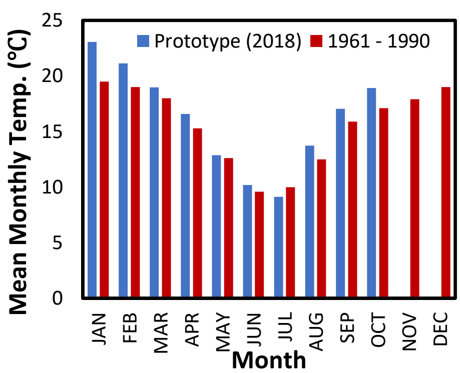


(b) First-floor

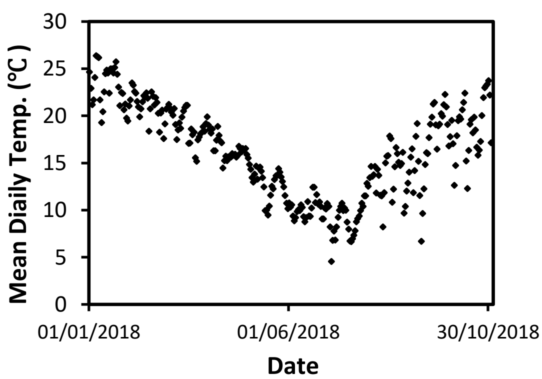
Figure 2. Black-globe thermometer positions

Monitoring Period

The building was monitored from January to October 2018, to record characteristic data from peak summer through to late winter/spring. Summer in Johannesburg is from October through to March (Dyson, 2009). The mean monthly outdoor temperature corresponding to the measurement period is shown in Figure 3a. Additionally, the mean monthly temperature for the period 1961 – 1990 (Johannesburg) was also included for reference (National Oceanic and Atmospheric Administration, n.d.). Daily mean temperatures measured at the location of the house are shown in Figure 3b. It is worth noting that January and February were hot, with many days having mean temperatures above statistical historical records (Figures 3a and 3b). Two heat wave warnings were issued in January by the South African Weather Service (SAWS). SAWS declare a heat wave if the maximum temperature is expected to meet or exceed the average maximum temperature of the hottest month by 5°C, for that particular location, as well as persisting in that mode for 3 or more days (SAWS, 2018). Presently the threshold is 32°C for Johannesburg (SAWS, 2018), and temperatures in excess of this were measured on the 6th, 7th and 8th of January at the prototype house. A minimum temperature of -0.2°C was recorded on 3rd July, following the arrival of a cold front.



(a) Mean monthly temperature



(b) Mean daily temperature

Figure 3. Outdoor temperatures during the monitoring period

PERFORMANCE CRITERIA

Thermal comfort of occupants in smaller residential buildings, such as free-standing houses, is dominated by the design of the building envelope (i.e. walls, fenestration, roofing, etc.). The South African building standard SANS 10400-XA: Energy Usage in Buildings: 2011 offers a deemed-to-satisfy route, in which all external walls (of habitable parts of the building), roofs, floors with under-floor heating and fenestration must adhere to minimum thermal requirements. For practical reasons, these deemed-to-satisfy regulations address established building types and components. When the design falls outside these criteria it must be shown, using thermal calculation software certified by the Board of Agrément South Africa, that the building has a theoretical energy usage performance less than or equal to that of a reference building in accordance with SANS 10400-XA. Agrément South Africa is a technical assessment agency that certifies innovative and non-standard construction products, and is recognized in the National Building Regulations. For the certification of novel buildings types, Agrément South Africa make such comparisons against a standard masonry building, referred to as the Standard Agrément South Africa Comparative House (see SANS 10400-K:2015). However, no specification on the maxima or minima allowable internal temperatures is given in the building regulations.

The expected extreme indoor temperatures within the aforementioned building, for a design summer and winter day in Johannesburg, without heating or cooling are 5℃ and 34℃. This information was attained through the lead author's position on the technical committee of Agrément South Africa. Peak temperatures may be significantly higher than 34℃ in low to moderate mass structures, without artificial cooling, even though the energy demand may be lower than the Comparative House. Though, it must be recognized that the occupants of low-cost housing in South Africa are unlikely to be able to afford much heating or any mechanical cooling due to socio-economic conditions (NBRI, 1987). This is also a problem in developed countries. The Building Research Establishment (BRE) in the United Kingdom noted that air conditioning may not be an option for those on a low income due to increased housing running costs (BRE, n.d.). Centralized heating, ventilation, and air conditioning (HVAC) systems are very rare in residential buildings in South Africa. The penetration rate of air conditioning (AC) is just 4% of households (Covary *et al*., 2015). Due to tremendous economic constraints it is apparent why the chief mechanisms to improve personal comfort are passive: opening or closing windows and by occupants adapting their clothing to the thermal conditions.

Several standards (e.g., ASHRAE Standard 55-2010 (ASHRAE, 2010); BS EN 15251 (BSI, 2007)) provide information on the acceptable range of temperatures in naturally ventilated buildings. Adaptive comfort models used in these standards express the comfort temperature through its relationship with the outdoor temperature. Several codes are applicable for the assessment and design of naturally ventilated structures. BS EN 15251 (BSI, 2007) is adopted in the present study, and this standard stipulates the following equation to estimate the comfortable temperature (T_{comf}) in naturally ventilated buildings:

$$T_{comf} = 0.33\ T_{rm} + 18.8 \text{ (where } T_{rm} > 10\ °C), \quad (1)$$

where T_{rm} is the exponentially weighted running mean temperature (°C) for the day under consideration. This calculation puts higher importance on the most recent days. The equation for the determination of the running mean temperature is given below:

$$T_{rm} = [1-\alpha]\{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots\} \qquad (2)$$

where α is a constant and T_{od-1}, T_{od-2}, T_{od-3}, etc. are the daily mean temperatures for yesterday, the day before, and so on. A value of 0.8 for the parameter 'α' is recommended by Tuohy *et al*. (2009). CIBSE suggest that designers should aim to remain within Category II (Normal expectation) limits prescribed in BS EN 15251 (BSI, 2007), which sets an acceptable temperature range of ±3°C about the comfort temperature (T_{comf}) for naturally ventilated buildings. Although the building was not inhabited during testing, these evaluations are still valuable in identifying potential performance issues and/or design improvements. It should be noted that the building was occupied, by several people, on a few occasions and conservative heat gain from electrical sources was also considered. Internal heat gain was examined to estimate its influence on indoor operative temperature whilst the space was naturally ventilated.

RESULTS AND DISCUSSION

Thermal performance: Summer

Figure 4a shows both the indoor operative temperature in the south rooms and the outdoor air temperature for a hot day in 2018. The peak outside temperature exceeded the applicable monthly average maximum by several degrees Celsius, per the 1960 – 1991 historical data. The benefit of high thermal mass is evident, especially for the ground-floor room, illustrated by the slower rate of indoor temperature development compared with that of the outdoors (Figure 4a). High thermal mass is most effective in regions which experience large daily temperature variations, such as Johannesburg. The lower indoor temperatures measured in the ground-floor space can be attributed to a combination of factors, namely:

1. Greater thermal mass, e.g. 220 mm thick walls versus 175 mm thick shell;
2. Better insulation associated with a greater wall thickness, i.e. thicker masonry envelopes having higher thermal resistance (lower U-value/ higher R-value);
3. Less exposure to direct solar radiation (intensity and duration). During the summer monitoring period, the edge beams and piers acted as vertical and horizontal shades for the walls for much of the day (Sunrise and sunset occur south of east and west in Johannesburg in the summer months). In contrast, due to the orientation of the structure and the summer sun trajectory, both shells were directly exposed to solar radiation for the majority of the day.
4. Lower surface albedo. Surface albedo has a significant impact on the extent of heat gain through the shell envelope, as well as indoor temperatures, due to the extent of surface area exposed to direct solar radiation – see the Design Considerations section.

Figure 4a reveals that the operative temperature in the first-floor vault exceeded the maximum acceptable temperature (T_{max}) in the late afternoon. Although high indoor temperatures are less concerning in the afternoon, when inhabitants are likely to be out of doors or away from home (Agrément Board of South Africa, 1986), they should not persist into the evening. Assuming that the vaults were to be used as bedrooms (i.e.

night-time spaces) then the building would pass all overheating criteria as per CIBSE TM52 (2013). It should be noted that realistic internal heat gain, from several occupants and lighting, only marginally affected indoor temperature when the first-floor vault was ventilated. It is apparent in Figure 4a that the elevated temperatures recorded in the late afternoon were not sustained into the evening and night because the outdoor temperatures dropped sufficiently to induce cooling of the space.

It should also be said that the operative temperature in the first-floor vaults only occasionally exceeded T_{max}, which is partly attributed to the summer climate on the Highveld in South Africa. In the summer months, there is significantly more cloud cover than in the winter, which assists in reducing the amount of direct solar heat gain through exposed parts of the building envelope (Figure 4b). Furthermore, there are about 100 days with rain per annum in Johannesburg (Kruger, 2004), most of which occur in the summer months (Dyson, 2009). According to Kruger (2004) the maximum rainfall over Johannesburg occurs during December and January. These summer conditions are coupled with cyclical temperature patterns, where prolonged periods of summer heat do not persist, apart from infrequent heat-waves. This is demonstrated in Figure 4c, which shows the variability in operative temperature for the ground and first-floor levels for 50 days in the late summer (after the heat-waves of early January).

Thermal improvements can be achieved through air circulation to cool the living space, by removing solar heat gain and heat generated indoors. Furthermore, air movement strips away the warm air from the surface of the body and is therefore important for convective heat loss (CIBSE TM52, 2013). In a similar way, air movement promotes evaporation of perspiration from the skin (NBRI, 1987). Bhikhoo *et al*. (2017) report that several studies have shown that air movement of up to 1 m/s can reduce operative indoor temperatures by as much as 3.5°C in hot climates. However, the effectiveness of natural ventilation is dependent on the climate, as well as several design factors, e.g. internal layout of the building and the distribution, size and number of openings. It is also reliant on occupants opening and closing windows at appropriate times, and several factors may limit the potential benefits associated with opening windows, such as noise and security concerns (BRE, n.d.).

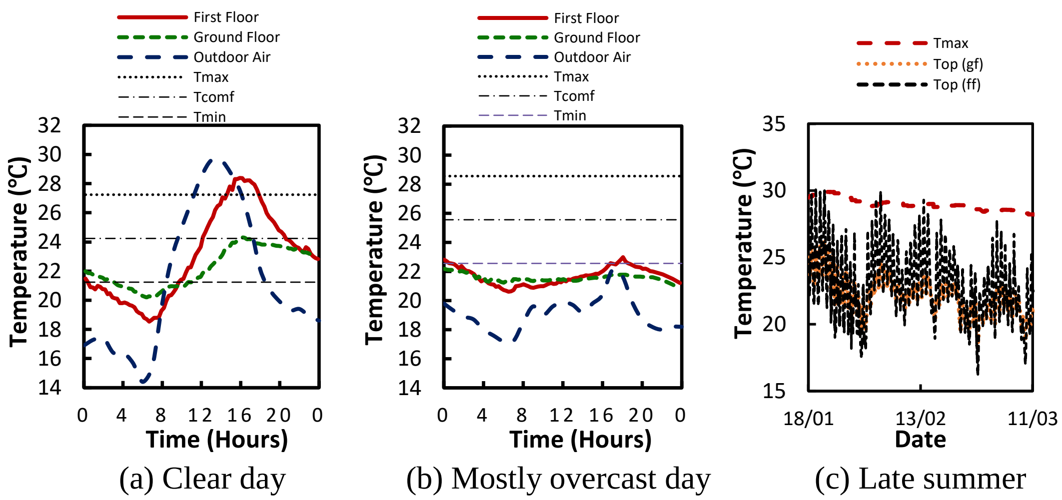
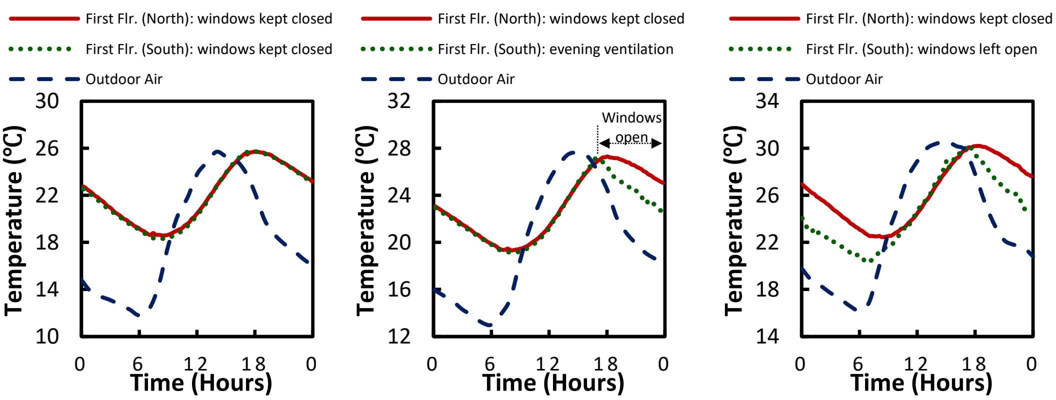


Figure 4. External and indoor temperatures during summer, 2018

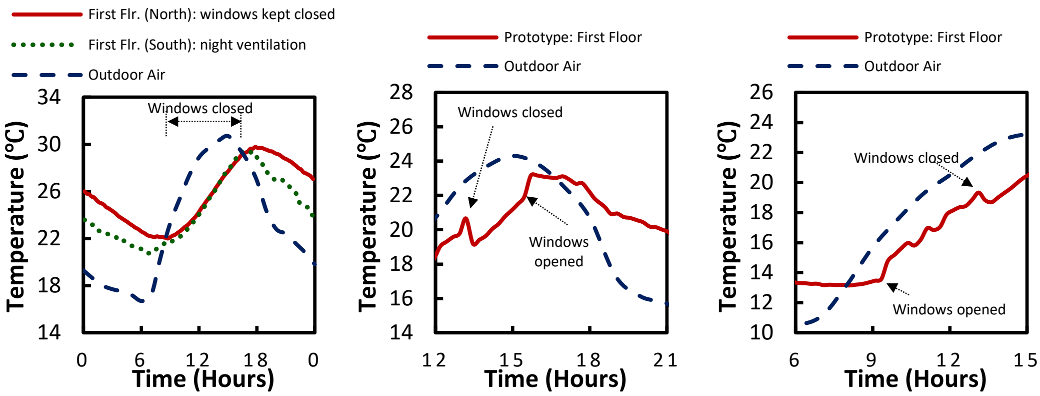
When windows were kept closed in early summer there was negligible temperature disparity between the vaults (e.g. Figure 5a). This similarity enabled a direct assessment of ventilation, and several window opening/closing scenarios were considered. For reasons of brevity only a few are presented here (Figures 5b through 5d). The opening of windows in the late afternoon or evening, when the outside air temperature fell below that indoors, was very effective at reducing operative temperatures. Figure 5c shows temperatures corresponding to a set-up where windows were continuously open, which was similarly effective to night ventilation (Figure 5d). Figures 5b through 5d reveal that a 2ºC - 3ºC reduction in the indoor operative temperature was induced in the first-floor vault if the windows remained open at night. However, opening windows when the outside temperature was greater than that indoors offered no benefit in reducing indoor temperatures, but may be necessary for indoor air quality. In some cases, a rapid increase in temperature was observed (Figures 5e and 5f). When windows were closed, whilst outdoor temperatures exceeded those indoors, the operative temperature typically fell sharply before gradually increasing again.

Thermal performance: Winter

Figures 6a and 6b show the indoor operative temperature plotted against outdoor running mean temperature, between 15 May 2018 (early winter) and 15 August 2018 (late winter), for the northern ground and first-floor rooms. Additionally, the indoor operative temperature and outside air temperature distributions for two typical winter days are shown Figures 6c (windows kept closed) and 6d (windows kept open during the day). It is relevant to mention that the majority of winter days in Johannesburg are sunny and clear. It is apparent that the first-floor spaces experienced greater diurnal temperature variations than those at ground-floor. For the peak winter monitoring period (15 May – 15 August), indoor diurnal temperature ranges were largest for the northern vault (Mean = 6.2ºC; Stdev = 1.2ºC), followed by the southern vault (Mean = 4.9ºC; Stdev = 1.0ºC), then the northern ground-floor (Mean = 3.2ºC; Stdev = 0.8ºC), and finally the southern ground-floor (Mean = 1.8ºC; Stdev = 0.5ºC). The larger diurnal range for the first-floor spaces can be attributed to greater heat gain during the day and heat loss at night.



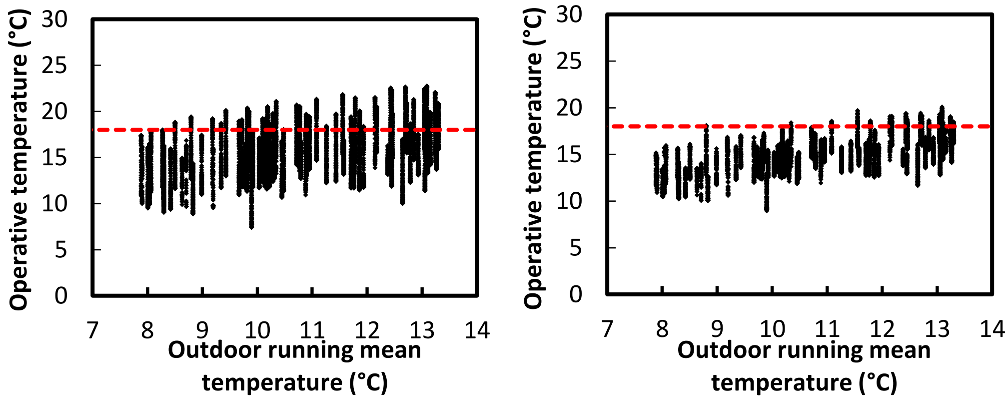
(a) 18th October (b) 19th October (c) 28th October



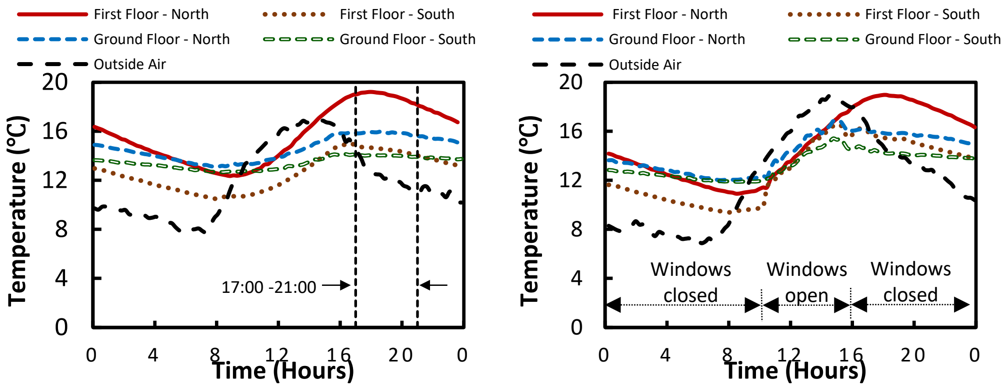
(d) 27th October (e) 14th September (f) 15th October

Figure 5. Exterior and interior temperatures on several summer and spring days

Temperatures measured in the northern side of the building were mostly greater than those in the southern rooms (Figures 6c and 6d). In fact, the mean operative temperate for a typical winter's day in the northern vault and ground-floor room were roughly 3ºC and 1.5ºC greater than their southern equivalents, respectively. The source of the temperature disparity between rooms on the north and south sides of a building was anticipated, and associated with the quantity of direct solar radiation (i.e., the extent of solar exposure of the building envelope). Incident solar radiation is absorbed at the surface, which generates heat that is transferred by thermal conduction through the masonry. The rate of heat transfer through sunlit elements is governed largely by the surface temperatures rather than the air-air temperature difference across the element (NBRI, 1987). Figure 1a shows the sunlit and shaded parts of the prototype's envelope at midday on the 6th June 2018. The majority of the south facing portions of both vaults, apart from a small region near the apex, were shaded throughout the day (i.e. auto-shading). At midday, when the sun is at its zenith, about 45% of the north vault's surface was shaded. The south vault was partly shielded by the north vault (Figure 1a), which resulted in ~70% of its surface being shaded at midday. The majority of the south shell surface was shaded in the early morning and late afternoon.



(a) First-floor (North) (b) Ground-floor (North)

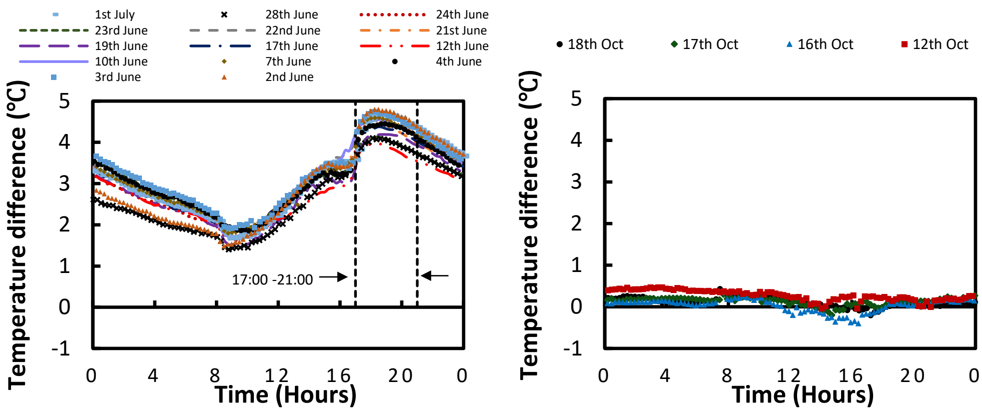


(c) 10th June 2018: Windows closed (d) 15th June 2018: Daytime ventilation

Figure 6. Exterior and interior temperatures during winter

Of particular importance are the indoor temperatures in the house during the evenings, between 17:00 and 21:00, when inhabitants are most likely to be at home, and energy demand is the greatest (Guedes, 2015; Sigauke, 2014). It should be noted that space heating is one of the largest sources of electricity consumption in the home during winter in some regions of South Africa (Eskom, n.d.). Figures 6c and 6d illustrate that the operative temperature measured within in the northern vault was significantly higher than those in other internal spaces between 17:00 and 21:00. Figure 7a emphasizes this point further, where it is shown that the temperature in the north vault, during the abovementioned period, was frequently between 4ºC and 5ºC warmer than the south vault on a typical winter's day (i.e., sunny and clear). The difference between ground-floor spaces was somewhat less, normally between 1.5 ºC and 2ºC in magnitude. For comparison, the temperature differences corresponding to a period in early summer when windows were kept closed, is shown Figure 7b. Because the sun rises and sets very close to east and west in early October, as well as having much higher altitude angle than in the winter, neither vault shades the other for most of the day. During this period, the peak temperature difference between vaults was regularly less than 0.5 ºC (Figure 7b).

It is apparent that shading of the shell surface is extremely detrimental to thermal performance during winter. Moreover, the exposed north vault had the most winter hours above 18 ºC; a temperature below which most people would prefer to turn on a heater (Agrément, 1986). The minimum temperatures measured in this space were also only marginally lower than that at the ground-floor (Mean = - 0.7ºC; Stdev = 0.3ºC). It is apparent that the spaces on the north side of the building, and especially the vault, were most suitable for living rooms due to greater indoor temperature and expected lower energy demand associated with space heating.



(a) Mid-winter (max surface shading) (b) Early-summer (minimal surface shading)

Figure 7. Temperature difference between the vaults (windows closed)

DESIGN CONSIDERATIONS

The maximum and minimum temperatures measured in the prototype house occurred during a heat-wave and a cold-front, respectively. These extreme temperatures were lower and higher than those expected on a design summer and winter day in the Standard Agrément South Africa Comparative House. Nevertheless, the indoor temperatures in the vaults occasionally exceeded the maximum acceptable temperature (T_{max}), following BS EN 15251 (BSI, 2007), during the summer months. A thicker shell could have reduced the occasionally high indoor temperatures in the summer, as well as night-time heat loss through the envelope in the winter. It is important to mention that the section thickness of the shells was selected based on structural considerations alone (see Gohnert *et al.*, 2018). Summer temperatures could also be reduced by adding insulation such as EIFS (Exterior Insulation and Finish System) cladding. Such systems incorporate urethane, extruded polystyrene, or moulded or extruded expanded polystyrene (EPS) applied to the exterior of the shell (Wilson, 2005). However, the implementation of an EIFS system would add significant additional costs, and may not be affordable for low-income households.

High albedo lime-wash has traditionally been used to limit solar gain through earthen masonry in hot and dry climates (Adam and Agib, 2001) but such finishes are unsuitable in Johannesburg's climate (Bradley and Gohnert, 2018). Using light coloured paints, or those incorporating infrared reflecting pigments, is a durable alternative for moderating heat gain through CSEB masonry (Bradley *et al.*, 2018). Figure 8 shows the influence of surface albedo, under hot and clear weather conditions, on the indoor air temperature in two conventional housing types situated in the neighbouring city of Pretoria, South Africa (NBRI, 1987). The temperature inside the high-mass house was reduced by 3°C when exterior surfaces were painted white. The effect of surface albedo on the light-weight structure was negligible, which was attributed to the well-insulated building envelope. The extent to which the indoor temperature was reduced within the prototype house by means of painting external surfaces white, is also illustrated in Figure 8. It is apparent that a significant reduction, ~5°C, in peak temperature was induced by increasing surface albedo. High albedo paints would, however, also reduce heat gain through the shell during the winter, resulting in lower indoor temperatures. For this reason, it is unlikely that adopting white coatings over uninsulated masonry shells is advantageous in Johannesburg.

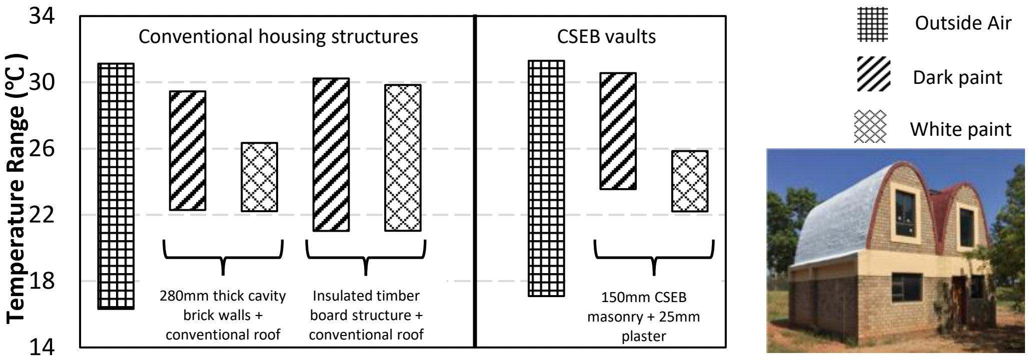


Figure 8. Temperature range in traditional houses and the CSEB vaults

CONCLUSIONS

During summer, the first-floor vaults occasionally exceeded the maximum acceptable temperature due to the high transmittal of heat through the envelope. More specifically, these high temperatures are attributed to the large surface area exposed to direct solar radiation and low surface albedo. Reducing solar gains through shading or coating with white paint each resulted in a roughly 5°C drop in peak operative temperature within the vaults. These observations highlight the significance of surface albedo and shading on the thermal performance of CSEB shells built in the South African interior. The aforementioned techniques may be an effective means of improving thermal comfort in the warmer parts of South Africa; however, solar exposure was tremendously beneficial during winter in Johannesburg. Of specific significance to energy consumption, and the associated costs of space heating, was that operative temperatures, between 5pm and 9pm during the winter period, were typically 3°C - 5°C warmer in the north vault. On many occasions in the winter, the operative temperature within the north vault was sufficiently high during the evening that artificial heating may not be necessary. Nevertheless, there is a juxtaposition between unfavourable and beneficial solar heat gain in summer and winter respectively, highlighting the necessity for further investigation based on energy demand using building simulation modelling. Other passive design measures should also be examined, e.g. improving the thermal resistance of the shell by using a thicker section and/or adding insulation. Finally, the results reported in this paper highlight the need to consider the thermal characteristics of the masonry envelope/shell and the orientation of the building during design.

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