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Sustainable Shells:

New African vaults built with soil-cement tiles

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Abstract

The Mapungubwe National Park Interpretive Centre, South Africa achieves economy of means, social improvement and low environmental impact in a remote World Heritage site. This paper outlines the design methodology and construction process for a series of thin shell domes and vaults in rural South Africa. We use the Valencian tradition of tile vaulting, a 700-year-old construction system, to create lightweight and durable buildings from thin soil-cement bricks. The load-bearing masonry is used to construct roof vaults achieving high structural strength with minimal material. The largest free-form vaults span 14.5m with an unreinforced masonry vault of 300mm thickness. We replaced fired-clay bricks with less energy-intensive stabilized earth tiles, which have a well-established tradition in sustainable practice. At Mapungubwe they are used to create sophisticated engineered forms by adapting a hand-press to locally manufacture tiles of sufficient strength. In addition to being structurally efficient, elegantly simple and environmentally sustainable, tile vaults have advantages for construction in developing areas. When compared to conventional construction, this system offers material and financial savings, waste reduction, and local employment with transferable outputs and skills for future projects. For this project, we introduced the structural masonry of tile vaults to South Africa, and for the first time we combined tile vaulting with locally made stabilized earth tiles that have low embodied energy. No steel reinforcing simplifies construction, lowers cost and reduces embodied energy. The vaults are built with minimal support, saving time, money and resources on formwork. The Centre represents a significant step forward in structure and material for sustainable construction.

Keywords: Tile vault; graphic statics; Guastavino; form finding; structural masonry; limit analysis; natural materials; traditional construction; formwork; masonry shells.

Figure 1: Mapungubwe National Park Interpretive Centre

1. Introduction

In designing the vaults of the Mapungubwe National Park Interpretive Centre (Figure 1) we were faced with typical constraints of budget and construction time, but also unusual constraints of minimizing steel and a mandate from the client to use local materials and to put people to work under a poverty relief program. These limits led to a design incorporating tile vaults made with no reinforcing and needing minimal formwork for construction. Making 200,000 pressed soil-cement tiles locally has put a dozen people to work for a year.

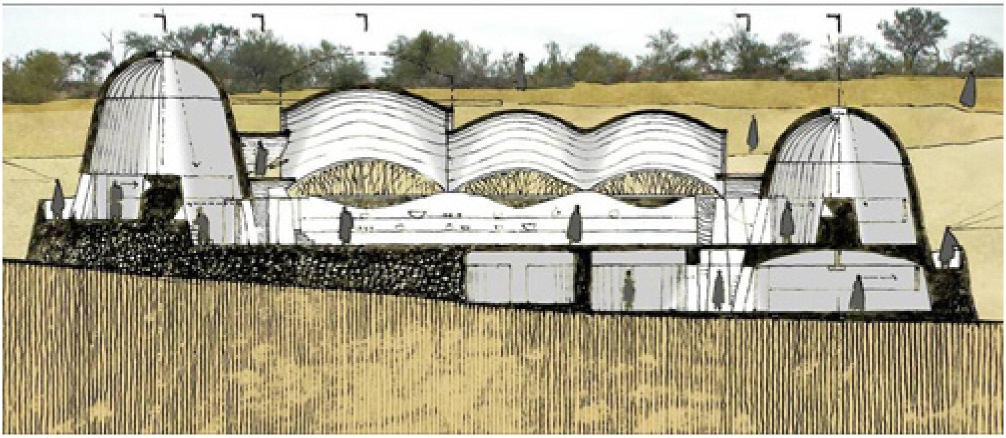

Figure 2: Section thorough main hall of the Mapungubwe National Park Interpretive Centre

2. Mapungubwe National Park

Mapungubwe National Park, on South Africa's northern border with Botswana and Zimbabwe, celebrates a UNESCO World Heritage cultural landscape. South African National Parks assembled the park from private land in the last decade, and held a competition in 2005 to design the Interpretive Centre. The design by Peter Rich Architects, with structural masonry vaults designed by J. Ochsendorf and M. Ramage, has recently been constructed.

The design of the Centre draws from indigenous forms and ordering principles that are adapted to meet contemporary physical needs and aspirations. The vaults establish a rhythm that speaks of the geological formations and of the earliest regional dwellings. These are contrasted with the cairn-like forms, whose interiors provide the beginning and end of the spatial experience (Figure 2). Inside, the cavernous spaces are reminiscent of archaeological sites in southern Africa. Natural light reflects off cooling pools to create dappled patterns on the earthen ceilings.The Centre represents a significant step forward in structure and material for sustainable construction in southern Africa. The improvements offer material and financial savings, waste reduction, and local employment with transferable outputs and skills for future projects. We introduce the structural masonry of tile vaults to South Africa, and for the first time we combine tile vaulting with locally made stabilized earth tiles that have low embodied energy. No steel reinforcing simplifies construction, lowers cost and reduces embodied energy. The vaults are built with minimal support, saving time, money and resources on formwork.

The design grows out of an appreciation of its natural and social context. The volumes respond to the terrain and resonate with the rolling hills. We look to earth construction for inspiration while delivering a public building with stringent demands and excellent environmental performance.

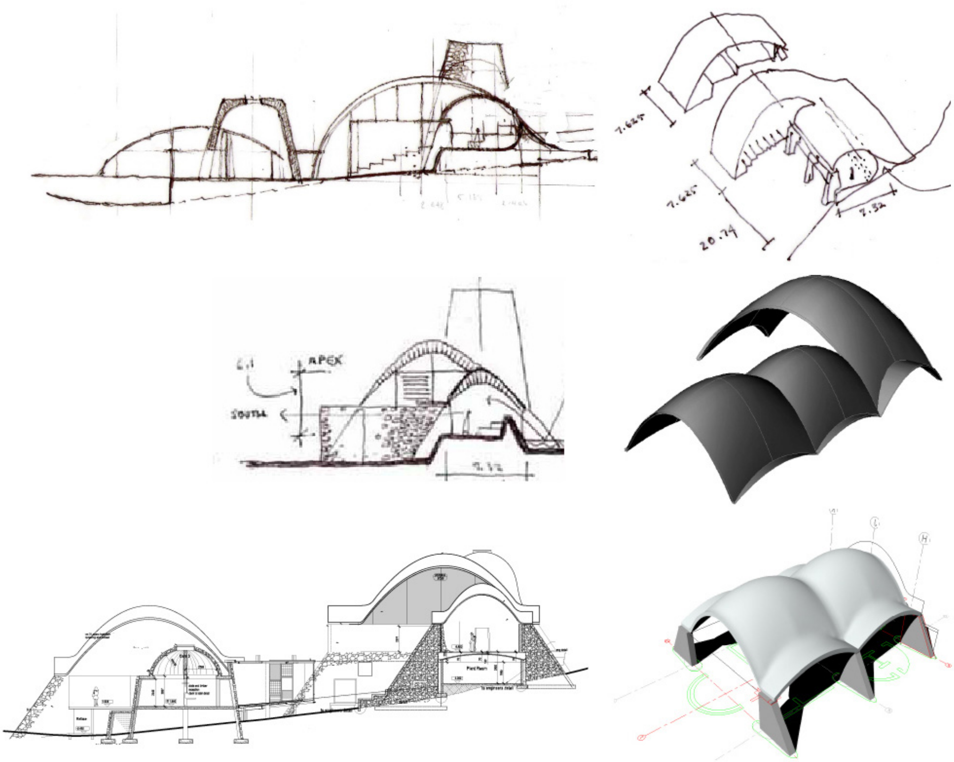

Figure 3: Development of Mapungubwe structural form

3. Structural Design

The tile vaults at Mapungubwe are doubly-curved structural masonry shells that were built with minimal formwork. The museum complex includes ten free-form vaults, the largest of which spans 14.5 meters, and a number of regular barrel vaults and domes used as permanent formwork for floor slabs.

The structural form of the building was designed with equilibrium methods based on graphic statics, allowing us to continually relate the forces in the structure to its form (Allen and Zalewski [1]). During the course of the design development the initial sketches evolved from single curvature barrel vaults to doubly curving parabolic structural forms (Figure 3).

We designed the shells to have low stresses of about 1.5 MPa acting in compression only, and the soil-cement tiles have an average strength of 5 MPa. The three-dimensional thrust surfaces are based on two dimensional thrust lines cut through the high apex (Figure 4) which are then aggregated perpendicularly to span across the lower "eyebrow" vaults. The initial geometry was determined with two dimensional interactive thrust line analysis, as described by Block *et al*. [2]. Finally, Thrust Network Analysis was used to verify the three-dimensional equilibrium (Block and Ochsendorf [3]) (Figure 5).

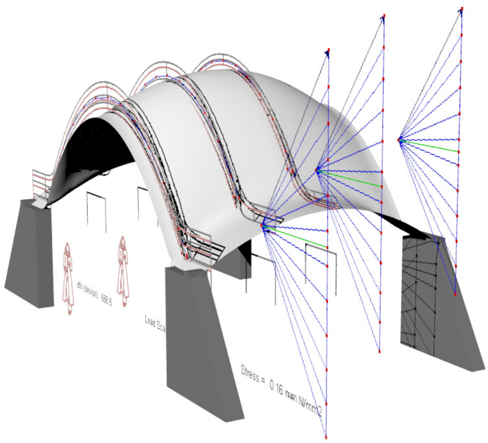

Figure 4: Thrust line analysis

The lateral thrust of the vaults is highest across the "eyebrows" because they aggregate the loads across the long span. In the biggest vaults the horizontal thrust can be as high as 400 kN, although we can define thrust lines within the masonry thickness that have lower force. The thrust is resolved with steel tension ties embedded in reinforced concrete buttresses, whereas the thrust across the longer span is resisted by those buttresses. We also use steel tension ties across the barrel vaults, which have a thrust of 125 kN per meter of vault.

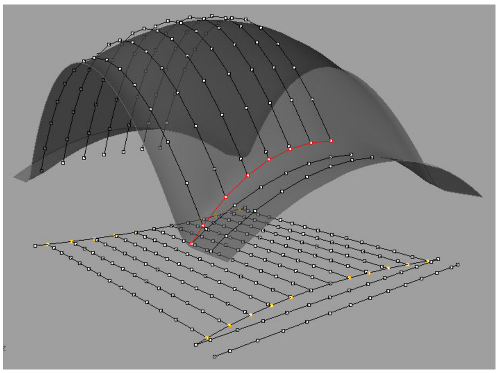

Figure 5: Thrust Network Analysis

Using the dead and live loads to develop the initial structural geometry, we then apply reasonable asymmetric loads to determine the thickness and degree of curvature for the vaults such that we can always find a compressive solution that lies wholly within the masonry (Heyman [6]). As such, these vaults are designed according to Heyman's safe theorem of limit analysis for masonry. The vaults become more stable with greater load on them, so we covered them in local stone for architectural and structural benefit: they fit better into the landscape, and the added weight ensures that gravity loads are dominant over wind loads. Finally, the areas of highest compressive stress are checked against the material strength of the tiles to make sure there is a sufficient margin of safety.

4. Construction

Mapungubwe is a remote site more than ten hours of driving from Johannesburg, so building with local materials and local labor made economic and ecological sense. Three primary tasks comprise the vault building: tile-making, guidework construction, and tile laying. SANParks managed the tile-making in the year prior to construction of the vaults using poverty-relief funding, while the guidework carpentry and vault masonry was managed by the general contractor.


Figure 6: Tile vault construction requires only geometric guides

Tile vaults rely on fast-setting gypsum mortar and thin tiles laid on edge. This Mediterranean vaulting method is not in common use today, but between 1880 and 1960 over 1000 buildings in North America were built this way by the Guastavino Company (Collins [4], Ochsendorf [8]). The tiles are stuck together using limited structural formwork and geometrical guidework to define the shape. The rapid set of the mortar and the structural shape allow the mason to span between guides, relying on structural action to develop while the building is under construction (Figure 6). Recent research at the Massachusetts Institute of Technology and the University of the Witwatersrand has shown that this system could have an important future in southern Africa and other areas of the world where labor costs are relatively low in relation to material costs (Fitchett [5]). The vaulting is usually made from thin fired bricks or tiles, joined together by gypsum mortar and Portland cement. A typical vault is 3-4 layers of tile thick with the first layer bonded by gypsum mortar and subsequent layers with Portland cement.

At Mapungubwe we have replaced fired clay bricks with less energy intensive stabilised earth tiles. While stabilised earth has a well-established tradition with close links to sustainable practice, at Mapungubwe it is used to create sophisticated engineered forms through the adaptation of a hand-press to manufacture tiles of sufficient strength for vaulting. In this way, an established structural system and a well known material are brought together for a novel solution. From an engineering perspective, computational techniques are used to determine the structural geometries for the vaulting. This ensures that adequate safety factors can be achieved for un-reinforced thin shells constructed with low strength tiles. By avoiding the need for reinforcing, the process of construction is simplified, the cost of imported materials is lowered, and the embodied energy of the building is reduced.

We also use tile vaults as permanent shuttering for cast concrete floors. The formwork becomes part of the structure, lessening the overall amount of concrete needed and ensuring minimal material waste during construction.

4.1 Tile manufacture

The tile vaults were made in a Hydraform block-press modified to produce tiles. These presses are normally used to make blocks 140 mm x 290 mm x 200 mm; we packed the form with plywood blanks so that the depth of the pressed tiles was only 20 mm (±3 mm). The plywood blanks were also used to support the fragile, recently-pressed tiles as they were carried to the drying yard (Figure 7). We used a mix of 4 parts soil, 1 part river sand, 1 part cement and a small amount of water.

Figure 7: Block press

4.2 Guidework construction

Each of the three types of vault (parabolic, barrel and dome) needed to be defined in space so the newly trained masons could visualize the shape they were building. In most cases we built only a lightweight framework of wooden guides to generate the shape, because the tile-vaults are self-supporting even during construction. This can be a significant advantage in areas where the supply of wood, typically used for support and formwork, is scarce. In the 1960s the technique was successfully introduced to resource-starved Cuba, where the National Art Schools in Havana were built using unskilled labour trained in tile vaulting (Loomis [7]).

Figure 8: Wooden guides established the geometry

The edge arches of the parabolic sail vaults require full formwork, but the primary central vault spans require only a sparse network of geometric guides to help the masons place the tiles accurately (Figure 8). In order to reduce the amount of material used in constructing the formwork, we built multiples of many of the vault shapes. The barrel vaults had the simplest formwork, but due to their shallow curvature in only one direction they were the most difficult to build. We built the domes using the rotation of a triangulated string following a technique adapted from traditional Spanish practice (Ramage [9]).

4.3 Tile Laying

The first tile vaults built in southern Africa were a series of small test vaults to teach local bricklayers the technique. Although it takes some time to gain expertise and to master the nuances of laying delicate tiles in fast-setting gypsum mortar, the results from the initial vaults, one tile thick and built in two days, were impressive (Figure 9). In a short period of time, the masons gained enough skill to begin laying the soffit of the first vault using tiles set with gypsum, while those who were still learning laid tiles for the subsequent layers in cement-based mortar on the outside of the soffit, which could now be used as formwork for the rest of the vault.

Figure 9: Test Vaults built on site

5. Sustainability

Mapungubwe is intended to be economically, socially, and environmentally sustainable. During the design development of the complex, a cost comparison was made between stabilized tiles and reinforced concrete for the vaulting. Despite the low productivity of the tile manufacture due to ongoing training, the tiled vaults were found to be 30% more cost effective. If the economic and socio-economic factors were included (as is standard practice in employment-intensive work) the tiled vaults would perform even better. Moreover, there is a high ratio of the project cost retained within local communities, an important factor in a country with a dual economy. This is consistent with government initiatives in respect of targeted procurement in under-developed areas.

Mapungubwe is located at considerable distances from the nearest commercial and manufacturing centres. For this reason, the emphasis on local resources has the dual benefit of reducing transport costs of materials and equipment, and lowering the amount of fossil fuel in the construction of the project. Labor-intensive methods have far lower environmental impact than machine intensive: bulk excavation is avoided; air and noise pollution are eliminated; hand tools generate far less damage to the surrounding fauna and flora; there is potentially less material wastage; and the site is easier to reinstate at the end of construction. The reliance on significant labor improves local livelihoods and provides a skilled base for future projects.

A primary reason for the exclusive use of tile vaulting for the enclosed spaces in the hot-dry climate is its high thermal mass, which assists in keeping the spaces cool during the day and radiates the accumulated heat at night. The forms of the vaults aid in naturally ventilating the spaces that do not require highly controlled environments for the display of the more sensitive artefacts. The vaults are vented at the apex to reduce the buildup of hot, stale air.

In the manufacture of the primary building components – stabilised earth tiles and stone overburden – local quarries have been established that will be reclaimed on completion of the project. This minimises the need for transport of materials and components, with economic, environmental and social benefits. The entire construction process is planned to be completed without machinery that uses fossil fuels, relying entirely on labour-intensive methods. This principle is continued in the minimal use of materials and equipment that are removed after construction, namely formwork and shuttering. Here the materials used in construction are integrated in the final buildings with the first layer of each vault becoming permanent shuttering for the subsequent layers while also increasing the thermal mass and stability of the vault.

All of the materials used in the buildings reveal their natural properties – sandstone inlaid in cement screed for the floors; stabilized earth block walling; exposed tiles to the underside of the vaults; stone chip on their exterior; and natural timber and steel for the minor components. In this way, routine maintenance is reduced to a minimum with positive environmental consequences throughout the life of the buildings.

6. Conclusions

This paper has described the design and construction of innovative masonry shells for the South African National Parks Mapungubwe Interpretive Centre in South Africa. For its innovative design, the project was awarded a Holcim Award for Sustainable Construction in 2008 for the region of the Middle East/Africa. The construction is noteworthy for:

- the use of soil-cement tiles with low embodied energy;
- the use of equilibrium methods to determine structural geometries designed to act in pure compression;
- the introduction of traditional Mediterranean tile vaulting to South Africa; and
- labor-intensive construction methods as an effective system of poverty-relief in developing regions.

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References

[1] Allen, E. and Zalewski, W., *Form and Forces: Designing efficient, expressive structures*, New York: John Wiley, 2009.

[2] Block, P., Ciblac, T., and Ochsendorf, J.A., Real-Time Limit Analysis of Vaulted Masonry Buildings. *Comput. and Struct.* 2006; **84**(29-30): 1841-1852.

[3] Block, P. and Ochsendorf, J., Thrust Network Analysis: A new methodology for three-dimensional equilibrium. *Journal of the International Association for Shell and Spatial Structures*, 2007; **48**; 167-173.

[4] Collins, G.R., The Transfer of Thin Masonry Vaulting from Spain to America. *The Journal of the Society of Architectural Historians*, 1968; **27**(3): 176-201.

[5] Fitchett, A., *Skills development and employment creation through small public buildings in South Africa*, 2009. unpublished PhD Thesis, Johannesburg: Univ. of the Witwatersrand.

[6] Heyman, J., *The Stone Skeleton: Structural engineering of masonry architecture.* Cambridge, Cambridge University Press, 1995.

[7] Loomis, J.A., *Revolution of Forms: Cuba's Forgotten Art Schools*. New York: Princeton Architectural Press, 1999.

[8] Ochsendorf, J., *Guastavino Vaulting: The Art of Structural Tile.* New York: Princeton Architectural Press, 2010.

[9] Ramage, M., Guastavino's Vault Construction Revisited. *Construction History*, 2007; **22**: 47-60.