Design and Construction of the Mapungubwe National Park Interpretive Centre, South Africa

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Abstract:

The Mapungubwe Interpretive Centre in South Africa uses novel design and construction techniques to allow local materials and labour to be used in production. The project is developed for labour-intensive construction to enable poverty relief and skills transfer into the surrounding area. Form-finding based on equilibrium thrust line analysis allows the design of thin unreinforced masonry shells that act in pure compression. Digital models let us translate advanced geometry into simple guides for construction. Traditional tile vaulting, using locally-made, pressed soil-cement tiles, allows the complex shapes to be built by newly trained workers without extensive formwork. A hands-on programme of design and construction suggests a new way to jointly manage architecture and development programs. This merging of novel structural geometry with traditional materials and craft has resulted in a new interpretation centre for a trans-frontier national park in South Africa.

Keywords: form-finding, thrust line, masonry vaulting, local production, earth architecture, development

1. Introduction

Mapungubwe National Park, on South Africa's northern border with Botswana and Zimbabwe, celebrates the Mapungubwe Kingdom, an ancient civilisation and trading culture linked to the Great Zimbabwe. It is a UNESCO World Heritage cultural landscape and a game reserve of stunning natural resources. 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 vaults designed by J. Ochsendorf and M. Ramage, has recently been completed. The design and construction of the Mapungubwe Interpretive Centre is collaboration of architecture and development, and of architecture, engineering and construction. Architecture and development meet in a labour-intensive programme to employ local workers with minimal skill to make both the materials for the building and the building itself. The building is constructed of locally-made pressed soil-cement tiles which are then used to form the thin shell structural tile-vaults of the roof. [Figure 1 - Overall Panorama] Architecture, structural engineering and construction meet in the design of the thin shell vaults, using a 700-year old Mediterranean tradition adapted for the southern African context. Each of the disciplines relies on the other, so that the construction methods inform the engineering that in turn allows reciprocity between the structural forces in the vaults and their architectural form.

2. Mapungubwe Interpretive Centre

Mapungubwe National Park

Sited at the confluence of the Limpopo and Shashe Rivers in far northern South Africa, the Mapungubwe National Park celebrates the UNESCO World Heritage site in the context of a natural setting that re-establishes the indigenous fauna and flora of this region. [Figure 2 Park View] The park has been assembled from private land in the past few decades, and there are long-term plans to create an international peace park joining wild-lands

Figure 1 - Overall Panorama

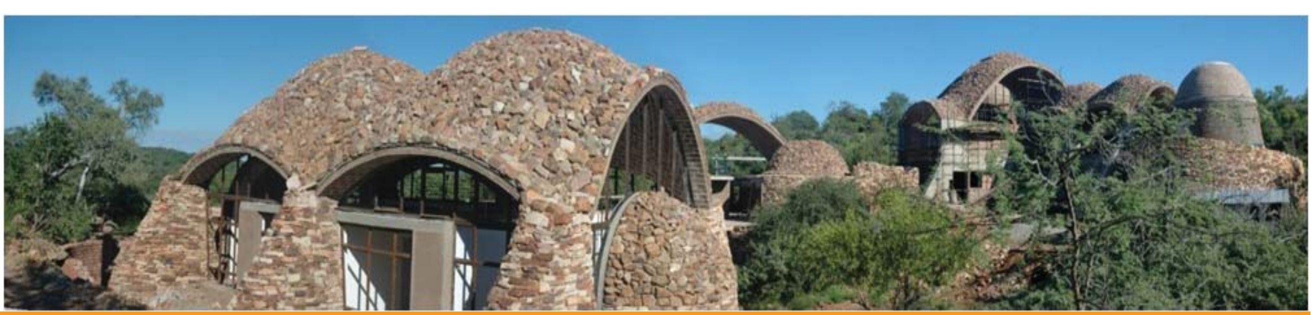

Figure 2 Park View

across the border in Botswana to the northwest and Zimbabwe to the northeast.

The dramatic rocky landscape of the park is a result of violent geological events that resulted in the Limpopo River changing its course from flowing into the Atlantic Ocean to discharging into the Indian Ocean. Sandstone formations, mopane woodlands and unique riverine forest and baobab trees form a scenic backdrop for a rich variety of animal life. The complex landscape was both the inspiration for the design and the source of most of the materials for its construction, resulting in a composition of structures that are authentically rooted to their location.

3. Design Requirements

The Mapungubwe Interpretive Centre is the result of an invited design competition held by South African National Parks (SANParks) in 2005. The proposals needed to provide about 3000 m^2 of exhibition space for the artefacts of the Mapungubwe Kingdom, interpretive areas for the cultural and natural significance of the park, and headquarters for the park staff, and amenities for visiting tourists. Coupled with these architectural requirements were development aspirations to improve the conditions of communities surrounding the parkland. In merging architecture and development SANParks sought to use poverty relief funding to inject money and skills into the local community. The winning proposal by Peter Rich Architects, Michael Ramage and John Ochsendorf responded to these requirements with a labour-intensive design that employed local people for a year making tiles on site from the surrounding earth.

The project's agenda extends beyond the presentation of ancient and more recent history of the area to awaken an understanding of the local ecology. The problem of a remote site, coupled with a high local unemployment rate also had to be taken into account. These are manifested in the choice of technology, the language of the building, the materials and construction process in which unemployed local people were trained in the manufacture of stabilised earth tiles and in building the tile vaults. The resulting knowledge transfer has been adopted in the local culture of the region, with the masons privately continuing the skills they have learned by using the remaining tiles for their houses in nearby villages. Thus, the centre is not only emblematic of the site, Africa and its unique place in the origin of the world, but has also become part of a story that is still unfolding, of culture developing in symbiosis with its natural legacy.

4. Constraints

In designing the building we were faced with typical constraints of budget and construction time, but also unusual constraints of minimising steel, making use of local materials and putting people to work under the poverty relief program. These limits led to a design incorporating tile vaults made with no reinforcing steel and needing minimal formwork for construction. Making 200,000 pressed soil-cement tiles locally put a dozen people to work for a year. Mapungubwe National Park is ten hours' drive from Johannesburg, so all material that is brought to site has an added financial and environmental cost. This suggested a solution of local material, which fit naturally with the programme requirements. South Africa at the time was undergoing a construction boom associated with the

ATDF JOURNAL Volume 7, Issue 1/2 2010

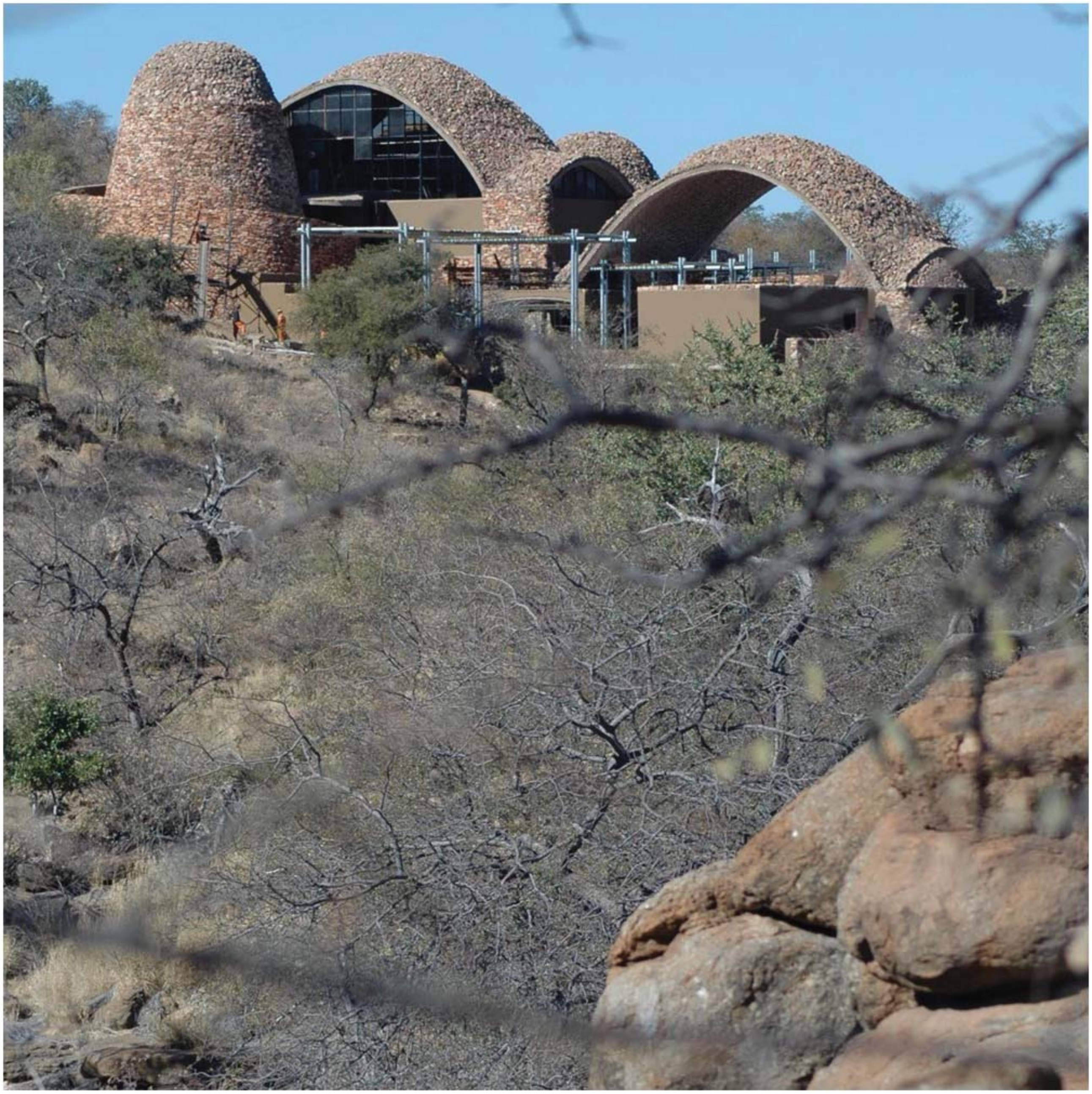

Figure 3 - side view up stream

run-up to the 2010 World Cup, so both materials and skilled labour were in short supply. Our choice of unreinforced tile-vaults minimised the use of steel in the construction, and being able to train the workers ourselves meant that we would not have to rely on a depleted labour pool. In fact, during construction the price of steel rose over 200%, so the fact that we were using very little of it sheltered the overall project budget from what could have been a large external financial impact.

5. Design Architecture

The vaults delicately rest in the undulating landscape and billow upward, exposing the arched edges of their thin shells. Three vaults are explored – a rectangular large span vault (15m x 8m) resting on four corner supports, a domed vault (topping the round cairns), and a shallow barrel vault (built as permanent formwork for floor slabs above). [Figure 3 - side view up stream] These are choreographed to create a series of sacred, cave-like interior spaces and well-defined external spaces containing exhibition and learning areas. [Figure 4 - interior] Africans believe in the veldt being a place of danger and fertility. Here, the buildings envelop external spaces– creating shelter and safety.

The domical language of vaults is contrasted by the delicate walkways that create a zigzagging ramped route through the complex. The visitor's first view, across a seasonal stream, is of the chameleon-like vaulted forms springing directly from the land on robust buttresses.

Figure 4 - interior

The surfacing of all of the masonry in local rubble stone creates a timeless quality, as if they had erupted from the earth in a geological event

Volumes are linked by terraced seating, contrasting the structured horizontality of the contours with the diaphanous domes and arches. The surfacing of all of the masonry in local rubble stone creates a timeless quality, as if they had erupted from the earth in a geological event similar to that which created the mesas of the site and Mapungubwe Hill.

The use of vaulting and other forms inspired by the dramatic landscape, avoids any overt references to any potentially controversial tribal vernacular (the area has many contesting land claims between different tribal groups).

6. Material

At Mapungubwe, we replaced the traditional use of fired-clay bricks with less energy-intensive stabilised earth tiles. The tiles are made of local earth and sand mixed with 5% cement and pressed using a modified Hydraform block press. The modification allows thin tile production from a standard press on reusable plywood blanks. The tiles are weak, but strong enough for the structural application. They must be handled carefully, and are susceptible to damage from transport and water. Although the tiles have some disadvantages, for this project they are the most appropriate solution to building in the local context. The structural forms of the shells were designed to have low stresses of about 1.5 MPa acting in compression only, because the soil-cement tiles can only withstand about 5 MPa. 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, typically used for the very common compressed earth blocks (CEB), to manufacture tiles of sufficient strength for vaulting. [Figure 5 - Hand Press] In this way, an established structural system and a well known material is brought together for a novel solution.

7. Structural Design

Our structural form-finding [1] relies on techniques of graphic statics [2]. To define the geometry of the vaults, the envelope of all possible lines of thrust under dead load and asymmetrical loads is found. A line of thrust is a theoretical line that represents the path of the resultants of the compressive forces through the structure. That envelope of generated geometry is translated into architecture using guides to define the shape in space, by taking section cuts through the digital model. We mainly use a mix of commercially available CAD software (Rhinoceros), the application of graphic statics in coordinate geometry programs (Cabri or Geogebra). Tile vaults rely on fast-setting gypsum mortar and thin tiles laid on edge. This type of vaulting, sometimes called Catalan or Guastavino vaulting, is not in common use today, but is a traditional Mediterranean technique which, between 1880 and 1960, was used to build over 1000 buildings in North America by the Guastavino Company [3,4]. The tiles are stuck together using limited structural formwork and geometrical guides help to define the shape during construction [5]. 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. 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 labour costs are relatively low in relation to material costs. [6] [Figure 6 - HQ under construction] More typical forms of masonry vaults, such as domes, rely on standard masons' tools of taut string (although when thoughtfully applied, the range of forms possible with these is large and exquisite). In particular, the load-bearing masonry is used to construct roof vaults achieving high structural strength with minimal material. We use lower-bound equilibrium analysis based on interactive graphic statics [7] to find the form of the vaults. This is a design method, rather than a design tool, in which the gravitational loads dictate the structure. The role of the architect and engineer is to evaluate and manipulate the forms within the natural constraints of the material, a skill that can be learned. The resulting form is neither geometrically nor mathematically defined, but is instead a direct structural response to the loading. This is crucial to being able to build without steel reinforcing, as the structurally efficient shape leads to a compression-only solution (with no bending), and therefore requires no tensile reinforcing. 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 line of thrust that fits within the masonry [8]. The static equilibrium of these surfaces is then checked with recently developed thrust network analysis [9]. The project incorporates ten masonry vaults, ranging in span from 5 meters to 20 meters, and a similar number of regular barrel vaults and domes.

Figure 5 - Hand Press

8. Building Programme

Three primary tasks comprise the vault building: tile making, guide work construction, and tile laying. The tile-making proceeded for a year before other work on site began. The construction work on site began with laying foundations to support the vaults. The vaults spring from walls and raised buttresses structurally tied to resist the (horizontal) thrust of the vaults. Once those foundations were complete the guide-work construction and tile-laying could commence. Learning the technique is straightforward; good results come quickly. Local communities supplied the construction workforce. The site is an area of high unemployment with depleted skills, a legacy of the apartheid government. The introduction of stabilised earth manufacture using a manual press is suitable for establishing entrepreneurs with start-up costs in the micro-credit bracket, although for this project SANParks managed the tile making. Moreover, constructing the vaults aided in entrenching good building practice. The tile vaults are 30% less expensive than an alternative in reinforced concrete shells. If we include their socio-economic benefits (standard practice in employment creation), the economic performance is even better. [6] A high ratio of project cost is retained locally, an important factor in a country with a dual economy. The reliance on local labour improves liveli-

ATDF JOURNAL Volume 7, Issue 1/2 2010

Figure 6 - Headquarters under construction

hoods and provides a skill base for future projects. We are actively pursuing projects in the region to make use of the skill base.

9. Construction

Building up tacit knowledge among local workers Building the vaults required training the workers in the construction technique. We organised a workshop where we taught the tile-laying in a series of small vaults, so that the workers would gain skills and confidence in the unfamiliar materials and method. Two or three builders working together built a vault of small tiles against an existing wall, and then stood on the result after only a few days of practice. [Figure 7 - workers test vaults] Teaching new skills to unskilled workers turned out to be easier than relying on existing skills in other trades, such as carpentry, where a severe shortage of expertise delayed the project at significant junctures, especially for the substructures and guide-work for the vaults. Skilled carpenters apparently did not want to come and work at the remote Mapungubwe building site. Vault-building skills were most important on the inside layer, where the form and appearance of the vault are fixed. There was a high turn over of staff which did not pose a huge problem for the labour on the outside tile layers of the vault construction, but it did for the inside tile layers. Of the 24 initial labourers trained on the inside technique, only 13 remained on site at the end of construction. Training new people on the vaults meant more breaking down and repairing of low quality work, more building waste, more loss of time and less aesthetic appeal. Over the eight-month course of building the vaults, there were nearly a hundred people trained in the tile-vaulting technique. Constructing the vaults took significant project management where close coordination between the contractor and the design team was required to avoid idle workers and unnecessary delays.

One challenge for the Western construction supervision team was working in a different culture with a different work ethic and ways of looking at the world. From early on, it was clear that creating relationships based on mutual trust and understanding fostered an effective method of operating onsite. Up to six languages were spoken onsite, each used interchangeably. Sign language, demonstrations and interpreters were the most effective methods to communicate an entirely new skill.

The people onsite had a mix of skills in construction, but the most skilled were accustomed to working with cement mortar and fired bricks. The knowledge and experience of using a trowel was the basic skill required, but the range of new materials, especially gypsum (the fast-setting mortar) with a setting time of less than a minute

Figure 7 - workers test vaults

in the temperatures at Mapungubwe, really tested even basic trowel skills.

Construction in a curve or arch, with minimal forms and guidance, means that the worker has to have an eye for the shape, which is entirely different from most of their previous experience of constructing straight walls and square corners. If the workers are unable to see and feel the shape, prior to laying the tiles, the structure will take the wrong shape, and consequently could crack or even collapse. One way we dealt with this was to print a scale model of the structure on a 3D printer, so that the builders could see and feel a physical version of the final form. This let them visualise the structure which they were building at full scale, otherwise quite a difficult task.

The biggest challenge in constructing tile vaults is the attention to detail. Taking time to lay the tiles to ensure they are placed in exactly the correct angle, pitch and direction takes a lot of concentration. Vault construction requires close attention, so idle conversations were distracting. When song broke out among workers, the attention to detail and work output increased.

The endless ingenuity onsite created great surprise. When a problem faced the workers, it would be discussed and different ideas bantered about, often for some time. As a result, a collective resolution formed and often creative and functional solutions were developed given the minimal resources in the remote location. Some of these included ladders made using fellow workers to access difficult parts of the vault [Figure 8 - Human Ladder] and passing tiles around site like a rugby ball. This turned out to be the most efficient and produced the least amount of breakages while moving tiles around the high scaffolding.

From a structural view point, it is not difficult to see when the shape is incorrect, as when the vault loses its curvature and departs from a compression-only form. It is as simple as a right and a wrong shape, which everyone can see and feel, but often this needed pointing out. It means standing back looking at the work, from different angles and deciding if it is acceptable. If it is not right one learns soon enough, as the tile structure will begin to crack, requiring the work to be redone. Initially, this inaccuracy would need pointing out to the builders, but once they could see where the vault was not flowing right, they knew exactly where they went wrong and would easily correct it with a trained eye.

Table 1 - Vault Costs

Mapungubwe Visitor Interpretation Centre Material Qauntities and Costs

vault type	vault area (m^2)		material cost per m² vault	labor cost per m² vault	Rand cost per m² vault	$ cost per m² vault	Hours per m² vault	$ cost per ft² vault	Hours per ft² vault
All	617	Total figures for all Vaults	R 518	R 311	R 829	$111	31	$10	3.6
		Summary by vault type							
BV	218	Barrel Vaults	R 381	R 228	R 609	$81	24	$8	2.3
D	93	Domes	R 622	R 264	R 886	$118	28	$11	3.7
PV	297	Parabolic Vaults	R 582	R 385	R 966	$129	38	$12	4.8

10. Costs

The vaults cost about $110/m² of vault, at a construction rate of 31 hours/ m². By comparison, the Pines Calyx, a vaulted building in England designed by some of the same team members, took 20 hours/ m² and cost about $450/ m² [10]. A more detailed quantification of the construction rates of each type of vault is included in Table 1. [TABLE 1 - Vault Costs] On an individual basis, however, the construction in South Africa used about 3 times as much labour per m² as at the Pines Calyx, but overall was a quarter of the cost. The handmade tiles of the Pines Calyx were expensive at about £2.50 (30 Rand) each, while the tiles in South Africa cost about 2 Rand each. Compared to conventional tiles in the UK, the South African construction is about 1/3 the cost of the UK construction.

Figure 8 - Human Ladder

11. Architecture and Development

11.1 Professional Arrangements

The design and construction at Mapungubwe suggest a new model for the interaction of architecture and development. SANParks specifically requested a labour-intensive building process, which led to a project driven by simple materials made on site and the possibilities for using them. This decision required foresight and courage on the part of the client, as more than a year of work went into making the materials themselves. The adaptation of material, structure and form required close collaboration between architect, engineer, and construction supervision, which in general requires a team founded on mutual respect for all players. This is particularly necessary as material and construction constraints often drove design decisions. An engaged client and a highly collaborative design and construction team are part of what is needed for successful completion of novel development projects. These close relationships suggest a new way of working, which could lead to new contractual procedures. While this project was completed using standard South African contracts, there is an opportunity to innovate in the professional arrangements. Building procurement, design fees and contractual values are generally based on a percentage of a buildings' total cost. Throughout the world this is a perverse incentive for architects and engineers to increase costs, since that would result in higher fees. In developing economies where labour is inexpensive and many materials are imported, a lot of a building's value is embedded in the material it is made of, so when a building is made from the earth it sits on, the value of the construction drops. This is beneficial overall, but lowers the professional fees. Moreover, simplifying buildings and building processes requires more thoughtful design, because they are not part of conventional practice. Fee structures based on value percentages are not the correct way to encourage more professionals to take on projects that are intentionally inexpensive and often time-consuming. An alternative approach could be to base professional fees on savings from typical costs, value delivered to communities, or simply time expended. A solution using conventionally manufactured materials, standard construction and typical architectural forms would have been faster to build, but would have had significantly less impact on the park, the region, and the possibilities for architecture and development.

11.2 Sustainability

Sustainable practice is essential for development, and especially an approach that recognises social sustainability alongside environmental sustainability. Money expended on a project should first and foremost go towards people rather than products, and time should go towards reducing energy in materials and performance. Reducing costs is an equally important aspect of construction, but must be considered over the whole life of a building, rather than just the short period of design and construction, which can often justify higher up-front costs that are offset over time. At Mapungubwe, the labour intensive construction reduced polluting machinery (sourced from far) and replaced it with small format construction methods that have minimal impact on the surrounding environment. This intensive construction involved skills training which has had a positive impact on the socio- economics of the local area, consistent with government strategies for targeting development to local communities. The government-funded poverty reduction programme employed a 60 people to make tiles for a year. Constructing the vaults trained over 100 people and employed 10-40 people at any one time over the course of 8 months. By using thin tile vaults instead of reinforced concrete at Mapungubwe, we saved an estimated 9 m^3 of steel, resulting in an embodied energy savings of almost 120,000 kg CO_2 emissions for manufacture alone, and using local earth bricks instead of fired clay obviously saved the energy that would have been used to fire over 200,000 tiles. A further significant amount of CO_2 was saved by radically limiting transportation of materials. While conventional reinforced concrete construction is responsible for embodied carbon emissions of approximately 150kg/m2, thin earthen vaults are responsible for only 40kg/m2 of carbon emissions, a reduction of nearly 75%. The design proposal uses high thermal mass and exposed construction which has passive environmental benefits leading to lower operating energy as well. Here the exposed, thick construction absorbs thermal shock and acts as a radiant surface, transmitting the 'coolth' from the night time ambient temperatures over the day. A displacement ventilation system, introducing tempered air (cooled from the ground), allows air to rise naturally as it heats to be expelled at the apex of the vaults. The vaulted forms allow natural light to penetrate deeply into the building, further reducing energy expenditure.

12. Conclusions

The chosen technologies for the remote site of the Mapungubwe National Park Interpretive Centre avoid the potential large embodied energy and high costs of conventional solutions by using predominantly local materials. Except for the cement added to the earth to give the tiles strength, and used in the mortar beds between the layers of tiles, all materials (earth, sand, gravel and stones) came from within a few kilometres of the building site. By reducing or eliminating steel in the vault construction, we aim for a longer life span without concern for deterioration due to corrosion. The heavyweight construction has passive environmental benefits over a more conventional solution. The building costs at least 30% less than a conventional solution, and benefits the local population through using predominantly local labour with the added benefit of a tangible skills transfer. The project has provided insight into ways to improve the process for next time, both from mechanical aspects such as the efficiency of tile making (we can now make them 3 times as fast) and from architectural and engineering aspects (we have a better understanding of which forms are better for training and skill-building). We hope to be able to replicate the model with institutional projects in other parts of Africa and East Asia. The building has been recognised with numerous international awards, including the David Alsop Sustainability Award from the Institution of Structural Engineers in 2009, a Holcim Award for Sustainable Construction in the region of Africa/Middle East in 2008, and the World Building of the Year in 2009 at the World Architecture Festival.

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Biodata

Michael Ramage has a degree in architecture from The Massachusetts Institute of Technology and currently teaches structural engineering in the Architecture Department at Cambridge University in England. Prior to studying architecture, he had a Fulbright Fellowship to Turkey to study geology and archaeology. He is one of the designers of the masonry vaulting for the Mapungubwe Interpretive Centre in South Africa which won the World Building of the Year award in 2009. He also designed the domes for the Pines Calyx, the first Guastavino-style vault to rise in the United Kingdom, and the 20-meter span vault for Crossway, one of Europe's lowest-energy houses. His most recent work is The Bowls Project, a contemporary architecture and music installation at the Yerba Buena Centre for the Arts in San Francisco.

John Ochsendorf is a structural engineer specialising in the analysis and design of masonry vaulting. He is Associate Professor at the Massachusetts Institute of Technology, and holds a joint appointment between the Departments of Architecture and Civil and Environmental Engineering. At MIT, he directs a research program with an emphasis on historic masonry structures (see http://web.mit.edu/masonry/). Ochsendorf studied engineering at Cornell University and Princeton University before earning his PhD in the structural mechanics of traditional masonry from the University of Cambridge in England. He studied masonry vaulting in Spain in 1999-2000 on a Fulbright Scholarship, and in 2007-2008, he spent a year studying vaulting in Italy after becoming the first engineer to win a Rome Prize from the American Academy in Rome. In 2008, he was named a MacArthur Fellow by the John D. and Catherine T. MacArthur Foundation.

Peter Rich: For thirty five years, Peter Rich has been rigorously engaged in four key areas of architectural practice. As researcher, Peter Rich pioneered the documentation of African settlements so others can learn from them. As an activist, he brought what he has learned to a wider audience. As a teacher, he developed an architectural vocabulary that builds on tradition and has empowered successive generations of young architects. As a practicing architect in his wide variety of work, he has given structure to his discoveries, creating architecture that is deeply embedded in its time and place.

James Bellamy is a sustainable builder and director of Re-vault, a socially responsible construction company based in New Zealand, specialising in earth construction methods with a focus on public facilities. Bellamy's most recent projects include the Pines Calyx in Dover, England and Mapungubwe National Park Interpretation Centre, South Africa. With a passion for ecological systems and a degree in Parks and Recreation Management, his efforts are to design and build structures that resonate with and utilise the local natural setting. He is currently involved in two significant projects in New Zealand, designing and constructing a series of buildings for a social change agency and a sustainable refurbishment exemplar of a commercial interior space for a community owned business and environment centre.

Philippe Block is a structural engineer and architect and is Assistant Professor of Structural Engineering at the ETH-Zurich in Switzerland, where he directs a research group in masonry structures and new structural design and fabrication approaches (see http://block.arch.ethz.ch/). He studied architecture and structural engineering at the Free University in Brussels and earned his PhD from MIT in 2009, where he developed a revolutionary computational method for masonry vault assessment and design. In 2008, he studied at the Institute of Lightweight Structures and Construction Design (ILEK) in Germany on a DAAD Scholarship. For his PhD research, he was awarded the Hangai Prize from the International Association of Shell and Spatial Structures.

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