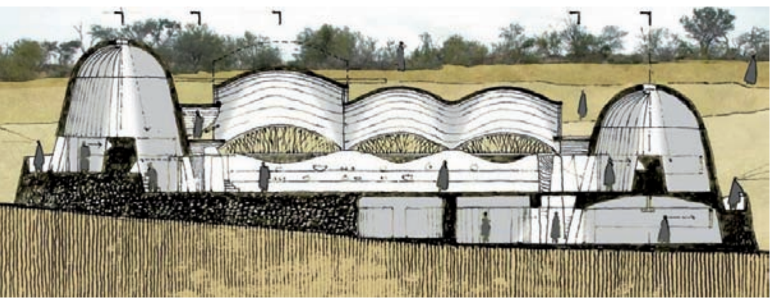

Advanced Geometry, Rudimentary Construction: Structural form finding for unreinforced thin-shell masonry vaults

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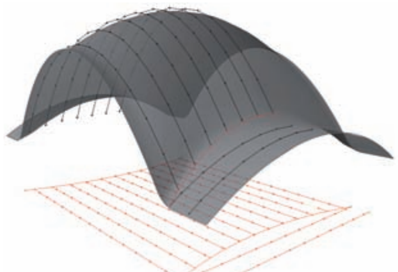
Form finding based on equilibrium thrust line analysis allows the design of thin unreinforced masonry shells that act in pure compression. Digital models let us translate advanced geometry into simple guides for construction. Traditional timbrel vaulting, using locally-made, pressed soil-cement tiles, allows the complex shapes to be built without extensive formwork. This merging of novel structural geometry with traditional craft has resulted in a new interpretation center for a transfrontier national park in South Africa.

Keywords: *form finding, thrust line, masonry vault, graphic statics*

Thin-Shell Structural Geometry



The new Mapungubwe Interpretive Centre uses the Mediterranean tradition of timbrel vaulting, a 600-year-old construction system that uses thin bricks to create lightweight and durable buildings. In particular, the load-bearing masonry is used to construct roof vaults achieving high structural strength with minimal material. We replaced the traditional use of fired-clay bricks with less energy-intensive stabilized earth tiles, which have a well-established tradition in sustainable practice. At Mapungubwe a hand-press is used to locally manufacture tiles of sufficient strength for structural vaults.

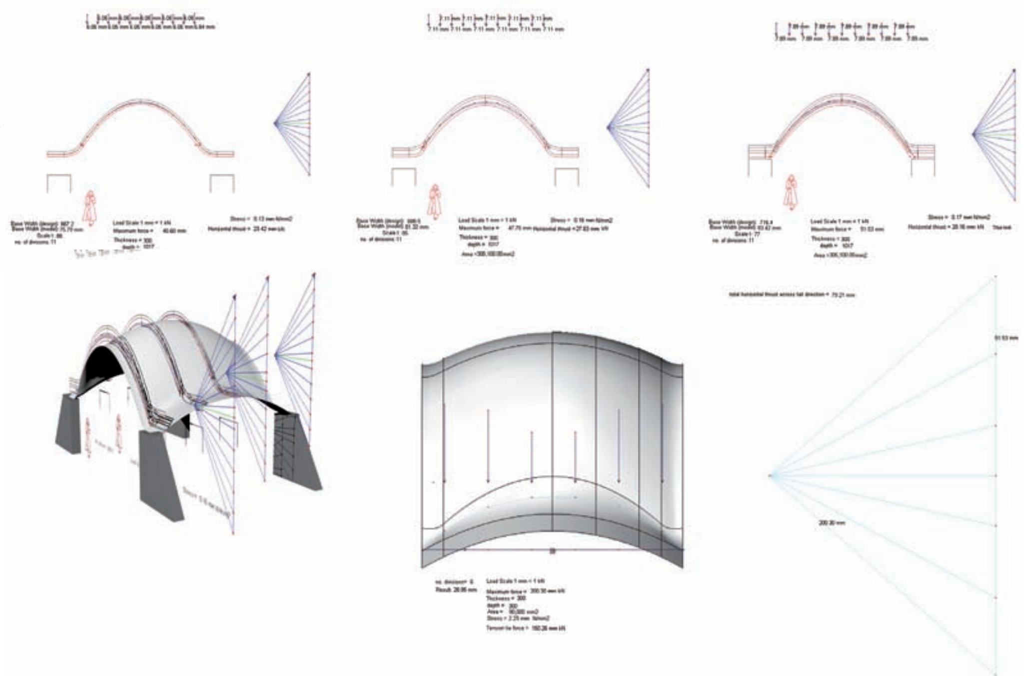
We designed the shells to have low stresses of about 1.5 MPa acting in compression only, because the soil-cement tiles can only withstand about 5 MPa. We use real-time lower-bound equilibrium analysis based on interactive graphic statics [Block et al. 2006] to find the form of the vaults.

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.

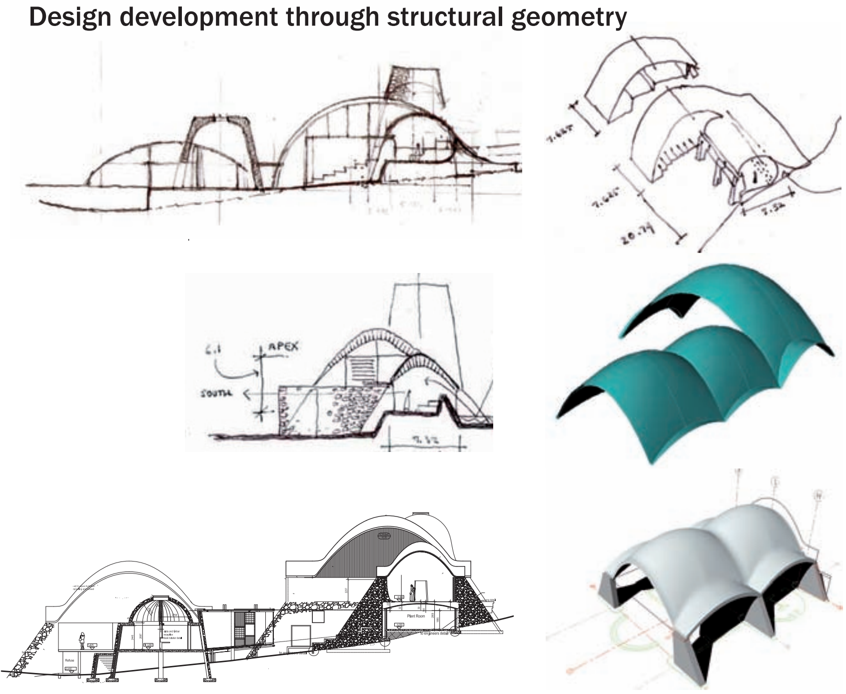
Using the dead and live loads to develop the initial structural geometry, we then apply reasonable asymmetric loads to determine the thickness and degree of curvature for the vaults such that we can always find a line of thrust that fits within the masonry [Heyman 1995]. The areas of high internal force are then checked against the allowable stress for the tiles to make sure there is a sufficient margin of safety. The three-dimensional thrust surfaces are based on two dimensional thrust lines cut through the high apex which are then aggregated in the perpendicular direction to span across the lower edge vaults.

We check for buckling using Heyman's approximation of span to thickness for a sphere, on the conservative basis that the Mapungubwe vaults have more curvature than a sphere. The static equilibrium of these surfaces is then checked with recently developed thrust network analysis [Block and Ochsendorf 2008].
The project incorporates ten free-form masonry vaults, ranging in span from 5 meters to 20 meters, and a similar number of regular barrel vaults and domes

Structural form develops from aggregated two dimensional thrust line analysis



Design development through structural geometry



Mapungubwe Interpretive Centre

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 recently held a competition to design the Interpretive Centre. The design by Peter Rich Architects, with structural vaults designed by J. Ochsendorf and M. Ramage, is now under construction.

In designing the vaults we were faced with typical constraints of budget and construction time, but also unusual constraints of minimizing steel (which is both expensive and scarce due in part to South Africa's building boom), making use of local materials and putting 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.

Our structural form-finding relies on techniques of graphic statics [Zalewski and Allen 1998] to define the envelope for possible lines of thrust under dead load and asymmetrical loads. The line of thrust is a theoretical line, which 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.

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. 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 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.

Tiles are laid using limited structural formwork and geometrical guidework to define the shape

Translation to Architecture

Timbrel vaults rely on fast-setting gypsum mortar and thin tiles laid on edge. This type of vaulting 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 1968, Ochsendorf 2009]. The tiles are stuck together using limited structural formwork and geometrical guidework to define the shape [Ramage 2007]. 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.

Section cuts through the digital model produce a lightweight network of guides to define the shape. More typical forms of masonry vaults rely on standard masons' tools of lines and string (although when thoughtfully applied, the range of forms possible with these is large and exquisite).

Conclusion

Compression-only form-finding for thin-shell masonry can result in new geometries that do not require high technology or extensive machinery to construct. New developments in structural analysis allow a return to traditional craft construction for contemporary design.

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