

Much of our architectural heritage today is built out of unreinforced masonry. It is often unclear why historic masonry structures still stand when conventional analysis tools have predicted their failure. In order to ensure the safety of these existing structures, there is an acute need for innovative tools that can accurately analyse their stability. Associate Professor **Philippe Block, Tom Van Mele and Matthias Rippmann** of the Block Research Group, part of the Institute of Technology in Architecture at ETH Zurich demonstrate how computational form-finding methods and design tools for masonry structures that stand in pure compression, such as arches and vaults, make it possible to design expressive and efficient surface structures that can be built with very little or low-quality material. By studying the techniques of medieval master builders, the Block Research Group has also developed new ways of building with masonry, enhanced by current construction and fabrication technologies. These new tools and reinvented construction methods can be applied in different contexts: for instance, by studying the structure of Gothic cathedrals, they manage to dramatically reduce the use of materials in office construction.

Structural Stone Surfaces

New Compression Shells Inspired by the Past

Philippe Block, Tim Schork, James Bellamy and Damon Van Horne, MADA (Monash Art Design & Architecture) prototype, Monash University, Melbourne, 2013

Using RhinoVAULT, the design potential of ribbed tile vaults was explored in a 10-day design-build student workshop run by Philippe Block with Tim Schork of Monash University, James Bellamy of Re-vault, and Damon Van Horne of Grimshaw Architects.



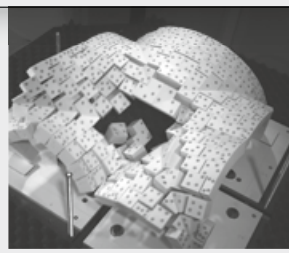
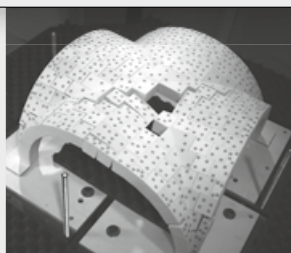
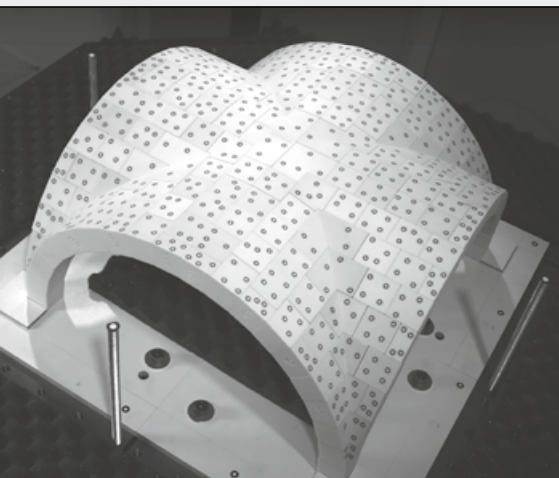
Masonry structures are essentially stable assemblies of discrete rigid blocks. They can stand in pure compression when arched, or be balanced and generate friction when stacked or corbelled. Their structural equilibrium can also be the result of a combination of these actions. This article focuses on structures that stand through arch action.

The forces in masonry structures are typically such that stresses are well below the capacity of the material of the individual blocks. For example, with a typical limestone used in cathedrals, in order for the bottom stone of a column to be crushed by the weight of the stones above it, the column should be 2 kilometres (1.2 miles) tall. In general, 'good structural form', that is, a geometry that follows the three-dimensional flow of compressive forces to the supports, results in low stresses. As a consequence, historical structures in masonry collapse mostly due to the instability caused by large displacements, for example differential settlements of the supports. Static equilibrium of assemblies of rigid blocks is thus a problem of stability rather than stress.

Conventional structural analysis tools used in engineering practice are not suited to deal with these types of structural problems. The Block Research Group has been developing different strategies and tools to better assess and preserve historical structures.

For example, Thrust Network Analysis (TNA) is an extension of traditional thrust line analysis to 3D vaults. It is based on the safe theorem formulated by Jacques Heyman, which states that a masonry structure is guaranteed to be in equilibrium under given loading conditions if a network of compressive forces can be found that is in equilibrium with these loads and entirely contained within the geometry of the structure.¹ Assessing the stability of a masonry structure with TNA consists of finding contained equilibrium networks for all relevant loading cases and combinations.

Structural scale models can also be used for a first validation of the structural behaviour of an unreinforced stone structure. All voussoirs are printed as discrete pieces using 3D printing technology, and with a CNC-milled foam falsework, they are assembled without adhesive. As stresses are very low, these models behave similarly to their full-scale equivalents, unless friction is a dominant aspect for the stability or collapse. Therefore, they allow the investigation of stability and collapse mechanisms of discrete vaults or any other masonry assembly under different support displacements and concentrated live loads. They are also instrumental in examining strategies for decentring. Furthermore, experiments with physical models serve to better define the relevant, digital



Block Research Group,
3D-printed structural
masonry scale model,
Institute of Technology
in Architecture,
ETH Zurich,
2012

For the stability analysis of unreinforced cut-stone vaults, collapse mechanisms under large displacements of supports were investigated using 3D-printed structural scale models.

Structural scale models can also be used for a
first validation of the structural behaviour of an
unreinforced stone structure.

parameters in discrete element modelling (DEM), which allows inclusion of the effects of friction, the elastic properties of the stone or seismic events.

New Graphical Methods for Exploring Equilibrium

An equilibrium form, in which no bending moments occur for the chosen loading case(s), is a necessity for unreinforced masonry. As is well known, one can find such funicular networks through inversion of a hanging model subjected to the to-be-expected design loading – as hangs the flexible line, so but inverted will stand the rigid arch. However, finding compressive networks of forces that balance given loads and fit complex Gothic vault geometry is a tough inverse optimisation problem. The development of algorithms that can do exactly that has resulted in a very powerful framework for rationalisation of any input surfaces and, when used in the opposite direction, in flexible and comprehensible design tools for shaping expressive and efficient self-supporting surfaces.

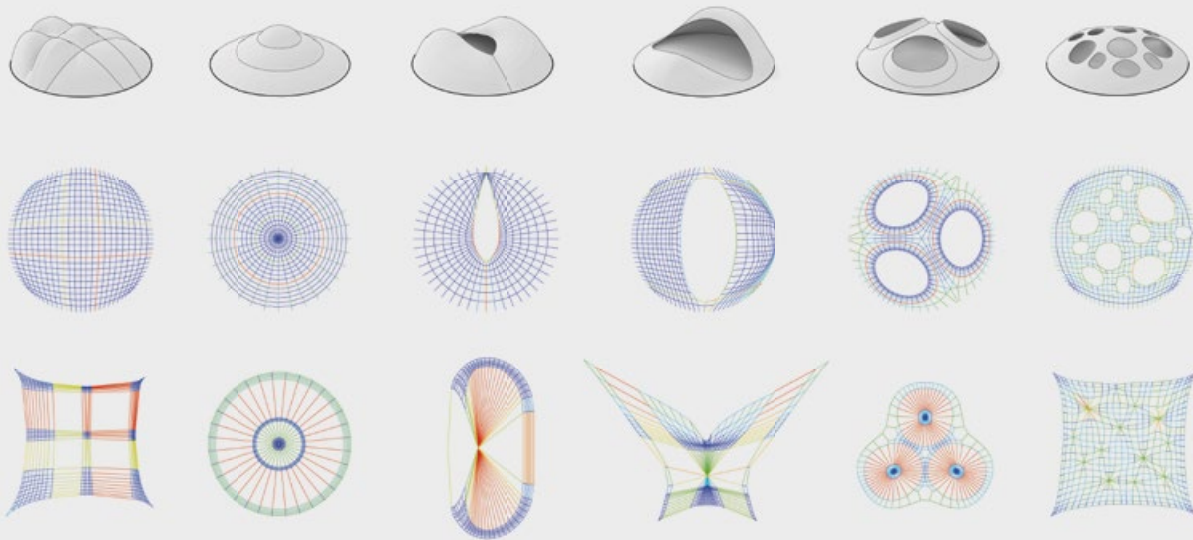
Rather than using (digital) hanging models, which focus on the geometry of the results, are challenging to control and do not allow a force-driven approach, TNA form-finding extends 2D graphic statics to describe the layout of loads and forces and the internal (horizontal) force distribution of possible equilibrium shapes using an explicit representation with geometrically linked diagrams. The designer manipulates the form and force diagrams to explore the infinite compressive solutions for given loading and boundary conditions in a very controlled and force-aware manner.

To share the insights into three-dimensional equilibrium obtained in the development of equilibrium analysis of unreinforced masonry, the Block Research Group developed RhinoVAULT, a robust implementation of the TNA approach for funicular form-finding in the CAD software Rhinoceros.

Vaults Using Minimal or Low-Quality Materials

Structures with funicular geometry and sufficient curvature have low stresses. Combining this principle with compression-only stiffening schemes, it is possible to build very thinly or with very low-quality material. For example, the soil-pressed tiles used in the vaults of the Mapungubwe National Interpretive Centre in South Africa have a compressive strength of only 2 MPa and break in bending when held on one side.² Using these same locally produced earthen tiles, and inspired by historic applications of unreinforced tile vaulting, which can be built without the need of falsework, the Block Research Group used compressive tile vaults for its Sustainable Urban Dwelling Unit (SUDU) prototype in Addis Ababa, Ethiopia (2010), to span space without bending and thus without the need for reinforcement steel.

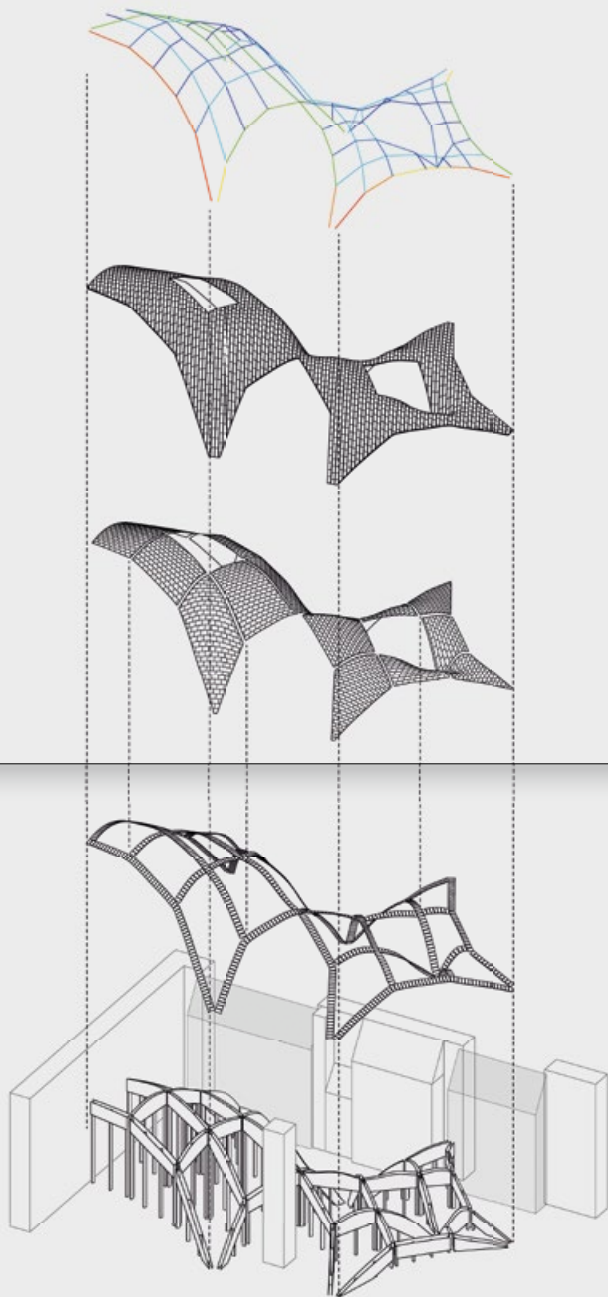
This approach is very different from current 'low-cost' housing solutions in many cities in developing countries that depend heavily on the typical building materials used in developed construction industries, such as concrete, steel and timber. In Ethiopia, for example, these materials are all not, or no longer, available, and thus need to be imported, which is



Block Research Group, RhinoVAULT, Institute of Technology in Architecture, ETH Zurich, 2014

RhinoVAULT, an implementation of Thrust Network Analysis (TNA), allows exploration of an infinite number of compression-only solutions, for example how to span a circular space using geometrically linked form and force diagrams.

An equilibrium form, in which no bending moments occur for the chosen loading case(s), is a necessity for unreinforced masonry.



Philippe Block, Tim Schork, James Bellamy and Damon Van Horne, Construction sequence, MADA (Monash Art Design & Architecture) prototype, Monash University, Melbourne, 2013

The structural design of the ribbed tile-vaulted prototype incorporated the constraints of construction sequencing such that the expressive form could be realised using only a sparse falsework onto which the ribs are laid before the infill patches could be built using only geometrical guides.

expensive and unsustainable. Thanks to this shift in structural system and construction, a modern, high-standard housing unit was achieved using mainly local materials and labour. Moreover, with a cost of less than 60 euros per square metre, the SUDU was built below the Ethiopian low-income threshold.

Designing Expressive Surface Structures

The precise and explicit control over the infinite possible shapes of funicular compression networks offered by the form and force diagrams of TNA can be used to design expressive and efficient surface structures that go beyond what is typically associated with good structural form. For example, the tile-vaulted prototype designed and built by the Block Research Group at ETH Zurich (2011) had curvature never seen before in unreinforced masonry.³ Its curved appearance was further enhanced by the continuous and flowing tiling patterns that corresponded to the fully three-dimensional equilibrium solution. One of the project's key objectives was to avoid the subdivisions created by the arches in traditional tile vaults that emanated from a mainly two-dimensional design approach. This required a descriptive geometrical guiding system, which was furthermore used as falsework for the masonry bond that did not follow the construction constraints of building in stable sections.

Building upon this research, the researchers reintroduced structural ribs and explored their design potential in the context of 'freeform' expression. When using networks of structural ribs, the vaulted



Block Research Group, Soil-pressed tile-vaulted floor, Sustainable Urban Dwelling Unit (SUDU), Addis Ababa, Ethiopia, 2010

The structure and construction of the unreinforced masonry floor system of the SUDU prototype is based on local materials and labour, and was inspired by the Guastavino Company's tile vaults, stiffened by spandrel walls and a stabilised fill.

infills between them can be built in a traditional manner, reintroducing one of the key advantages of traditional tile vaulting, that is, to be able to build large-span structures with very sparse falsework and simple geometrical guides. By rationalising the network of ribs to form straight segments in plan and favouring quadrilateral subdivisions, a simplified and more scalable solution could be offered for the falsework constructions for large, expressive tile shells with complex geometry. The MADA (Monash University Art Design & Architecture) prototype in Melbourne (2013), for example, demonstrated how a vault with complex geometry could be obtained from a simple underlying structural topology that respected construction sequencing.

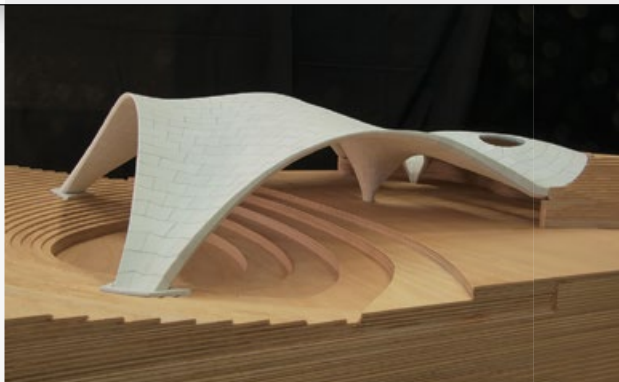
The Block Research Group's MLK Jr Park Stone Vault in Austin, Texas (2012) pushes the boundaries of what is possible with masonry by combining the new form-finding approaches and fabrication innovation. This expressive freeform vault is a unique, unreinforced, dry-set, cut-stone masonry shell planned to cover an area of approximately 600 square metres (6,500 square feet) with a maximum span of 30 metres (98 feet).

The Gothic builders mastered the art of cutting up large vaulted geometry into separate stone blocks. Their rules were based on experience and informed by stone-cutting constraints, drawing skills and structural intuition. Because of the complexity of the vault geometries now possible, the Block Research

Group is currently entering into the relatively new research field of 'digital stereotomy' that revisits and extends traditional stereotomy by introducing computational strategies and optimisation techniques to address structural requirements and fabrication constraints.

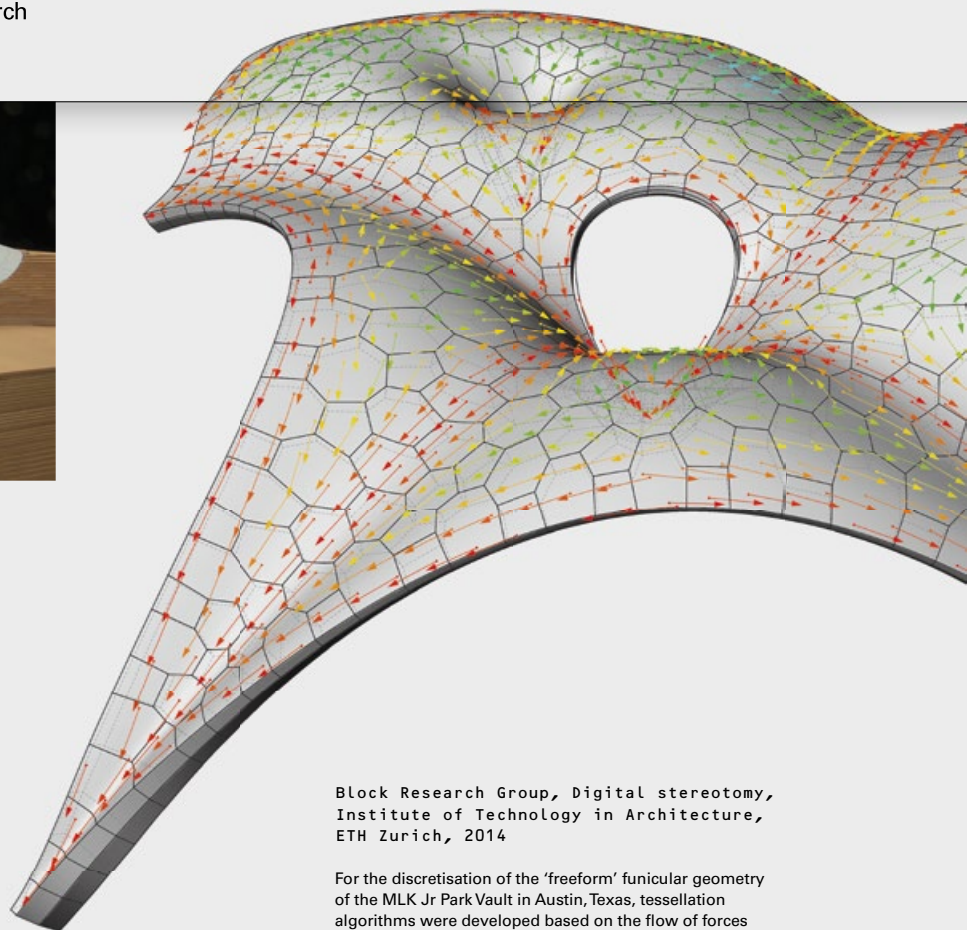
For discrete vaults, the tessellation geometry needs to be laid out on the thrust surface such that contact faces of adjacent voussoirs are orientated as perpendicular or as parallel as possible to the local force flow. Furthermore, considering fabrication requirements and the need for an 'interlocking bond' to allow for fully three-dimensional structural action and to prevent sliding of individual voussoirs, all these hard-to-control, interrelated criteria are negotiated in an optimisation scheme. Implemented in a digital design tool, this offers an interactive, flexible and user-driven design process; regulated and cut-stone vaults can be monitored automatically in real time.

An additional aspect of the research is the development of efficient strategies for the machining of complex voussoirs that take into account material waste, tool degradation, cutting time, geometrical accuracy and tolerance control.



Block Research Group, MLK Jr Park Vault, Austin, Texas, 2012

An early, discrete, 3D-printed scale model of the unique, unreinforced, cut-stone vault.



Block Research Group, Digital stereotomy, Institute of Technology in Architecture, ETH Zurich, 2014

For the discretisation of the 'freeform' funicular geometry of the MLK Jr Park Vault in Austin, Texas, tessellation algorithms were developed based on the flow of forces and the fabrication constraints.

Building New Shells

The hard constraints of masonry, a compression-only structural material system without the typical redundancy offered by bending capacity, has pushed the development of methods that exploit full understanding of the dependencies in complex equilibrium systems. This focus on masonry has provided validation for the novel form-finding approaches that the Block Research Group has developed in the last few years; 'masonry does not lie', so a non-proper form will collapse. However, equilibrium through structural form is material independent. Therefore, the approaches developed for the analysis and design of masonry can be translated to other materials and structural types to explore their material-specific possibilities, advantages and challenges, and to become the base for innovation in efficient structures in general.

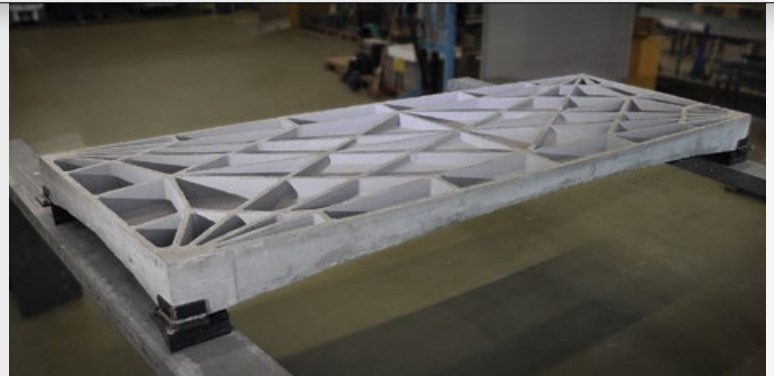
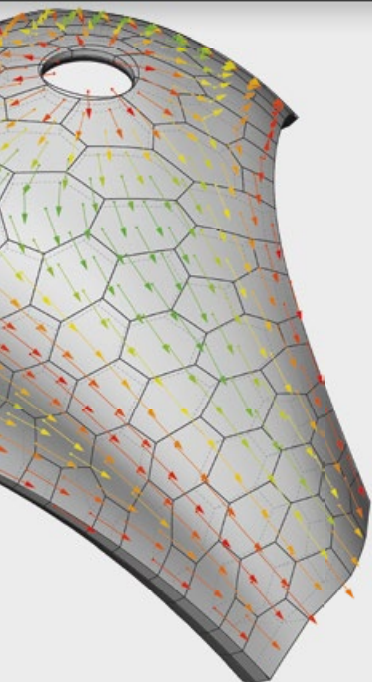
The research group's unique approach in the development of several built prototypes has revealed surprising shapes for masonry. However, its current research seeks to go further than these intriguing exhibitors to prove the relevance of innovation in masonry beyond the obvious applications, such as small-scale pavilion structures and projects in a developing context where labour is inexpensive. For example, by reinterpreting the Guastavino Company's tile masonry floor systems using modern materials, it is developing ultra-lightweight prefab floors without reinforcements for the NEST-HiLo project, which will be built in Dübendorf, Switzerland, in early 2016. Similar

to the SUDU project, this floor system uses stiffened, unreinforced funicular vaults to produce weight savings of more than 70 per cent compared to traditional concrete floor slab construction. It can be erected on site quickly and dryly, optimising the costs associated with on-site and labour-intensive work and waiting times. The hollow structural depth of the floor system and the large, ultra-thin shell surface also allow for a natural and efficient integration of services and low-energy heating and cooling systems.

The NEST-HiLo project is representative of the potential of learning from the past and from historic master builders to provide novel, resource-efficient solutions for the built environment. Furthermore, it shows that the Block Research Group's approaches to structural innovation combined with novel fabrication and construction concepts can be the trigger for a natural and symbiotic integration of energy-efficient building systems with efficient structures. ▽

Notes

1. Jacques Heyman. *The Stone Skeleton: Structural Engineering of Masonry Architecture*, Cambridge University Press (Cambridge), 1995, p 12.
2. Michael Ramage *et al*, 'Design and Construction of the Mapungubwe National Park Interpretive Centre, South Africa', *Journal of the African Technology Development Forum*, 7, (1-2), 2010, pp 14-23.
3. Lara Davis *et al*, 'Innovative Funicular Tile Vaulting: A Prototype in Switzerland', *The Structural Engineer*, 90 (11), 2012, pp 46-56.



Block Research Group, Funicular floor for NEST-HiLo research and innovation unit, Dübendorf, Switzerland, 2014

'Learning from the past' was central to the development of the structural concept of the ultra-thin, unreinforced concrete, stiffened vaulted floor system for the NEST-HiLo research and innovation unit.