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Fig. 1: MADA vault, Melbourne, Australia, 2013. (Photo: Peter Bennetts.)

RIBBED TILE VAULTING: INNOVATION THROUGH TWO DESIGN-BUILD WORKSHOPS

PHILIPPE BLOCK (ETH ZURICH), MELONIE BAYL-SMITH (UTS, SYDNEY), TIM SCHORK (MADA, MELBOURNE), JAMES BELLAMY (REVAULT), DAVE PIGRAM (UTS, SYDNEY)

Traditional tile vaults are typically constructed springing off from walls or straight arches built from support element to support element on falsework. From these, the vault's surface can be built in space with minimal or no guidework. Built on previous research and focusing on continuous surface expression and fully representing three-dimensional equilibrium surfaces in compression, this research explores the design potential of three-dimensional networks of structural ribs, made possible by new funicular form-finding approaches. This new structural typology for tile vaults was investigated and tested through two intensive, design-build workshops in Australia, the first at the University of Technology, Sydney (UTS) in October 2012, and the second at Monash Art Design & Architecture (MADA), Melbourne in May 2013.

INTRODUCTION

With indebtedness to projects such as the Mapungubwe Interpretive Centre in Limpopo, South Africa,[1] the 600-year-old Mediterranean construction technique known as tile or Catalan vaulting is undergoing an important revival and attracting increased interest. Tile vaults are unreinforced masonry vaults made of thin tiles, built in multiple layers, with the typical tile unit size approximately 24 × 12 × 2 cm. Traditional tile vaults are constructed by building off of walls or from arches, straight in plan and built on falsework, from support element to support element. Taking a wall or these arches as boundary supports for the vault's surface, the first layer of tiles can be built in space using a fast-setting gypsum mortar, commonly known as plaster of Paris. By mortaring the tile units on two thin sides, the masonry is able to temporarily cantilever until stable sections are formed. When complete, this stable first layer serves as permanent or 'lost' formwork for a second, and typically also, a third layer of tiles in order to build up sufficient structural depth. These subsequent layers are laid using regular mortar and are placed at different angles to each other, and to the first, in order to create a good bond and avoid obvious hinge lines.

Unreinforced masonry has negligible tensile capacity, therefore the shapes of vaults need to result in a state of compression only. These can be obtained through the process of form finding, recent developments of which allow a controlled exploration of funicular form. Thrust Network Analysis (TNA) uses geometrically linked form and force diagrams, representing the force flow and its force equilibrium, which give the designer explicit control over the distribution of forces in order to shape three-dimensional compression-only shells.[2] The concepts of TNA have been implemented in a free plug-in for the CAD software Rhinoceros, called RhinoVAULT.[3]

Previous research, such as the prototype vault built at ETH Zurich in 2011, focused on continuous, flowing tiled surface expressions that respond to the fully three-dimensional equilibrium solutions, possible due to these advances in form-finding approaches.[4] A key objective of that earlier research was to avoid the subdivisions created by the arches in traditional tile vaults that emanated from a mainly two-dimensional design approach. These do not exist in a spatial network of forces, and can disturb the spatial continuity of the new compression shapes.

In comparison, this research explores the potential of a design approach that uses a spatial, interacting network of ribs as the form-driving element for tile vaults. Whilst the vaulted infills or 'patches' between the ribs are undertaken in a traditional manner, the structural ribs no longer only span linearly between supports. The design possibilities of this new structural typology for tile vaults, combining the structural action of a Gothic net vault, the constructional logic of traditional tile vaulting, and novel TNA-generated equilibrium form, were investigated and tested in two intensive design-build workshops in Australia.

The first series of investigations was undertaken at UTS and explored fully spatial, interacting ribs, curving both in plan and elevation. Specifically, investigations were concerned with the fluidity of a hexagonal pattern and the aesthetic of non-intersecting (kissing) strips of ribs of greater structural depth. At MADA, a second set of investigations rationalised the network of ribs, constraining them to form straight segments in plan, forming quadrilateral subdivisions. These constraints resulted in simplified and more realistic, scalable falsework constructions for the ribs, reducing the logistical challenges of the UTS vault. The MADA prototype specifically aimed to demonstrate that a vault of complex geometry could be obtained from a simple underlying structural topology that respected construction sequencing.

FORM FINDING

To explore the new rib vault typology, in the first instance, the structural action of the vaults was abstracted to just the equilibrium of the ribs. The coarse subdivision allowed the controlled and fast exploration of different form diagrams, i.e. rib layouts in plan, using only few controls. Consequently, the distributions of internal force were represented in an agile, comprehensible manner by the simple force diagrams.

In the UTS vault, continuous undulating strips of hexagonal units were obtained with ribs that only just touched, with spacer links included in the network topology to maintain the necessary (rib) offset during the form finding. For the MADA vault, the explorations favoured intersecting ribs and thereby adopted a stretched grid strategy as the rib layout, resulting in pleasing intersections close to square angles. Further, to approximately model the arch and vault shapes in between those intersections, one subdivision was used, giving one mid-node per segment and a node in the middle of each quadrilateral patch.

In a second stage, the 'low-poly' designs were then refined. At UTS, a simple subdivision scheme was used to obtain a smoothly undulating and continuously arching solution. The shapes of the vaulted patches spanning the hexagonal units were obtained separately. These post-processing steps were enabled by the use of selected deep, wide structural ribs comprising stiffened U-channels (see below) in which the structural lines of action could be nicely contained. For the MADA vault, the final geometry could be easily obtained by constructing interpolating curves through the nodes of the top-level form finding. The rib arches in between patches were straightened, made possible through the in-plane arch action achievable in the ribs' widths.

CONSTRUCTION

FALSEWORK

A key motivation for varying the design approach of the MADA vault from the UTS vault was the rationalisation of the falsework. For both vaults, falsework was only constructed to support the ribs, with infill surfaces subsequently built unsupported and in space in the traditional Catalan manner. The UTS project had ribs that curved in both plan and section, demanding a relatively complex curved falsework system. MADA rationalised the undulating ribs to a stretched quadrilateral grid, constrained to be straight in plan piece-wise. Both vaults employed printed templates and manual cutting to translate the computationally defined rib profiles into material reality.

The UTS falsework system was constructed from a mix of volumetric EPS foam blocks beneath a curved network of cardboard profiles with columns providing intermediate support. Forming something of a voxelated mountain, the foam blocks were positioned to create a low-resolution offset of the vault, minimising the amount of cardboard (and cutting) required. A second, more significant advantage was that the foam easily supported human weight and that this falsework foundation thus also became a terraced access structure during all subsequent stages of construction, eliminating the need for ladders or conventional scaffolding. The curved cardboard profiles were constructed from three layers of cardboard with discrete foam blocks acting as spacers. Their shapes were defined via vertical extrusion of the centre line and (offset) edge lines of each undulating rib.

For the MADA vault, the form diagram was manipulated to obtain planar ribs, allowing the falsework to be built as a simple grid of planar stud walls. These constraints resulted in simplified falsework constructions for the ribs, further reducing the logistical challenges. Although straight in plan, the rib profile twisted in space as ribs were aligned tangentially to the obtained compression surface. To control this, the two different profiles were cut out of masonite and screwed against the studs. To further accelerate and streamline the falsework fabrication, a Grasshopper software tool was developed to extract the required length of each timber stud from the digital model, and automatically generate the cutting sheets for the ribs.

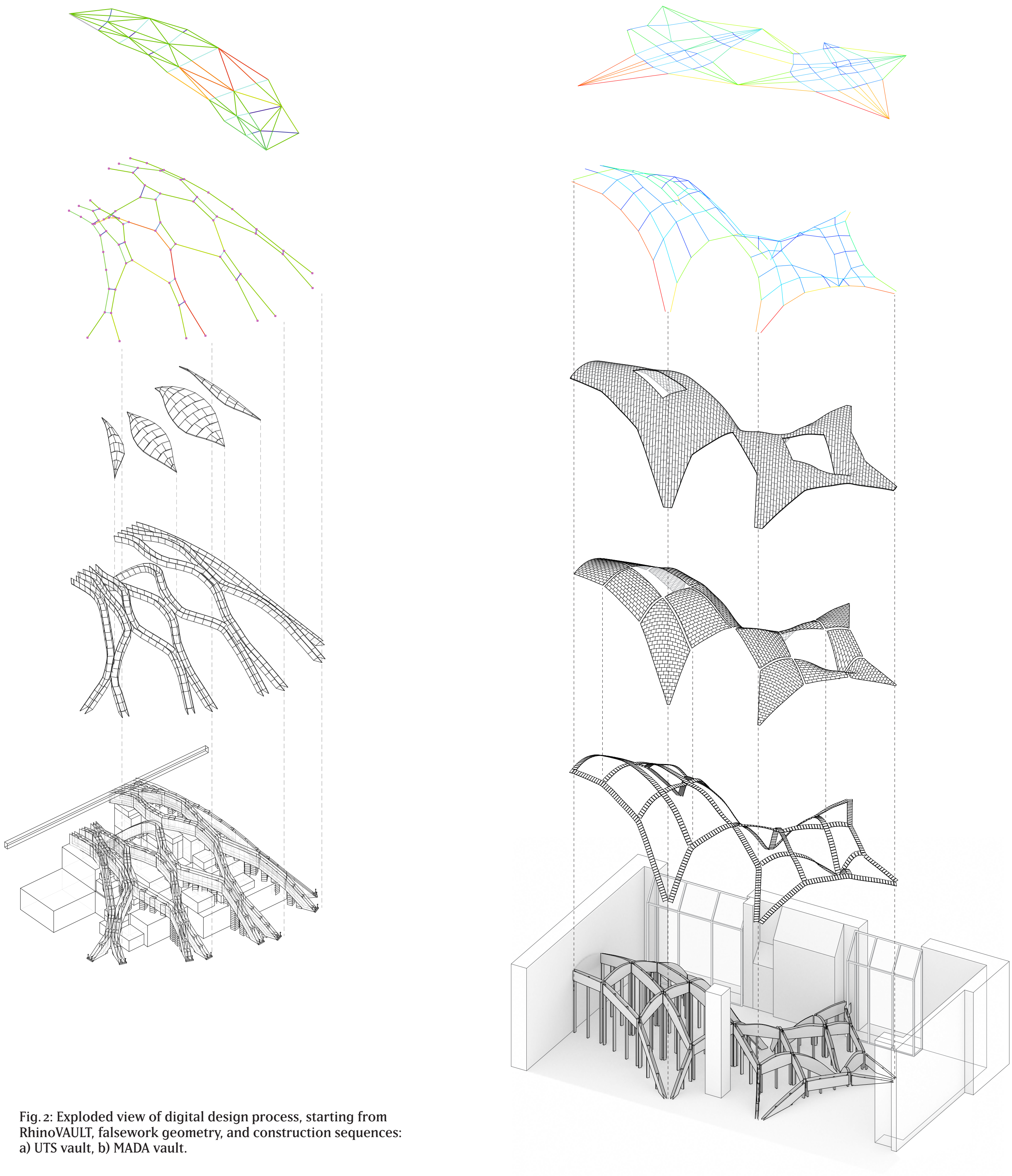


Fig. 2: Exploded view of digital design process, starting from RhinoVAULT, falsework geometry, and construction sequences: a) UTS vault, b) MADA vault.

SITE SET-UP

Because of the short timeframe for each workshop, the erection of the falsework was simplified by printing out 1:1 scale drawing sheets of the plan layout. These were positioned and taped on the floor of the respective spaces. These drawings included reference marks, element numbers and key dimensions, e.g. of the timber studs for the MADA falsework.

For the fabrication of the arch ribs, a similar strategy was employed with all fabrication information being extracted from the digital model and printed out at full-scale (1:1) for cutting templates.

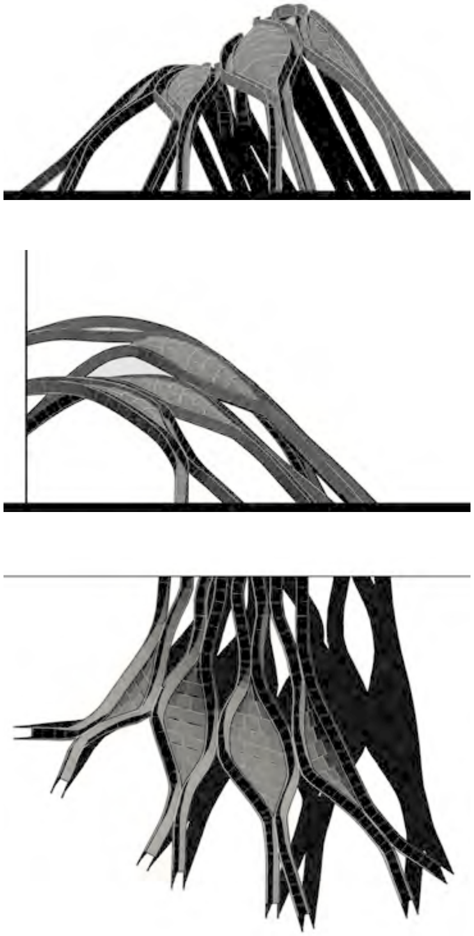
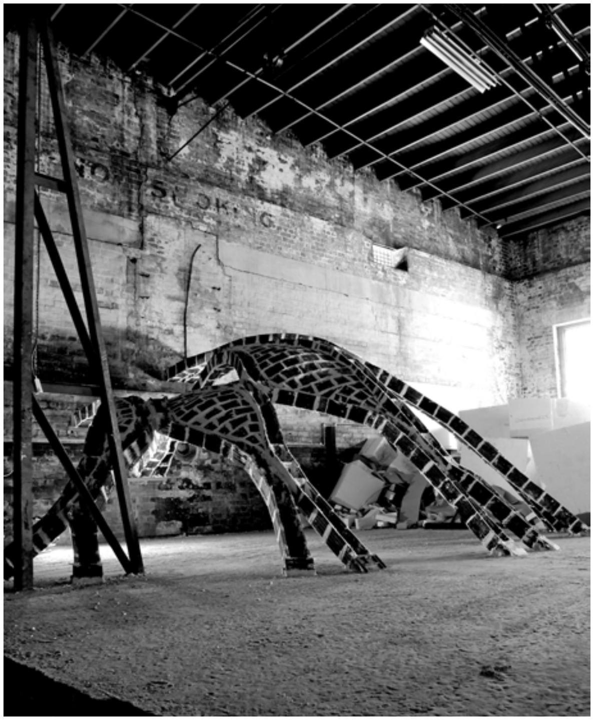


Fig. 3: As-built drawings of UTS vault:
a) front, b) side, c) top view.



Figs. 4, 5: Finished UTS vault, Sydney, Australia, 2012.
(Photo: Michael Ford.)

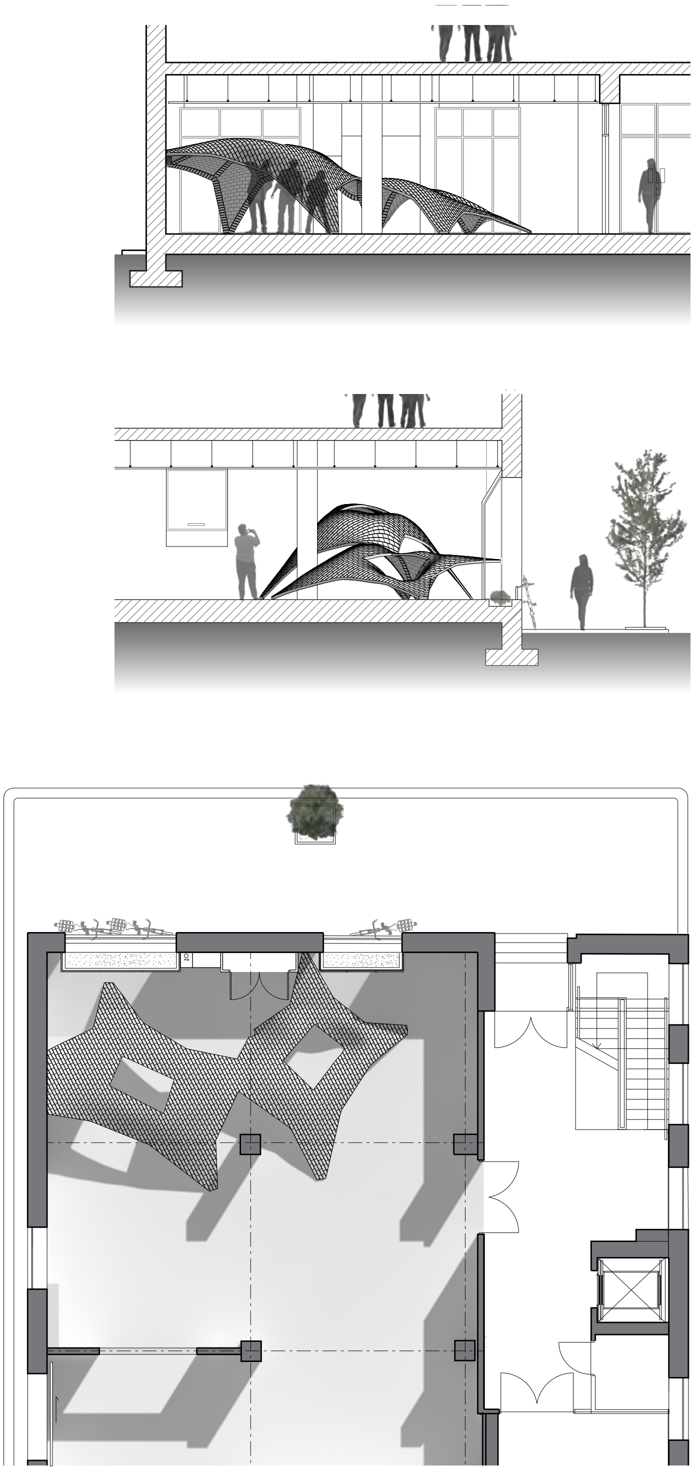


Fig. 6: As-built drawings of MADA vault:
a) front, b) side, c) top view.

MATERIALS

Tiles in the format typically used in Catalan vaulting are not readily available outside of Spain, and custom solutions needed to be found for both workshops. At UTS, concrete roofing tiles were selected for their relative flatness and thickness. These large tiles were then cut into quarters, enabling a sorting of the cut tile units according to the usefulness, or not, of the original lap features found on their underside. Whilst the tiles provided a highly divergent character to the inside and outside of the final vault, overall, they proved difficult to handle during the tile vaulting. For the MADA vault, non-profiled, hollow tiles (very similar to those used in note 4) were used. To provide clean tiles with continuous edge profiles, three cuts per tile were required. This ensured the cuts could avoid, and therefore not expose, the extruded hollows, which would give an uneven edge and thus be hard to work with.

For the fast-setting mortar, with a setting time of approximately 10 seconds, at UTS, a special high-strength gypsum-based mortar called Hydrocal®[5] was used. For the MADA vault, a readily available and relatively inexpensive dental mortar was substituted, with favourable results.

ASSEMBLY AND DECENTRING

Due to their three-dimensional undulation, the ribs of the UTS vault were constructed with increased depth via a U-shaped profile consisting of one horizontal tile and two upstanding tiles. This three-tile profile was repeated along the length of all curved supports, beginning from the bottom, with all joints staggered to avoid continuous mortar joints. Particular attention to the 'kissing' points was needed to ensure adequate contact and connection at the bottom of the 'U' for future load transference. The result was a stable spatial net of ribs, which were decentred prior to the addition of the infill surfaces. These infills were constructed in the traditional Catalan manner, i.e. without formwork, as described above. The undulating rib pattern and consequent irregular form of the vaulted patches demanded considerable custom tile cutting.

The MADA vault was also constructed ribs first. Tiles were first laid with their long sides next to each other chasing the planar falsework. These ribs remain visible on the underside of the final vault and form a strong aspect of its final character. Here, the entire vault was constructed before decentring and construction with three layers along the ribs, transitioning to two layers for the fills. For the reasons described above, each layer was laid at an alignment that differed from those below it. The intentional constraint to use only quadrilateral

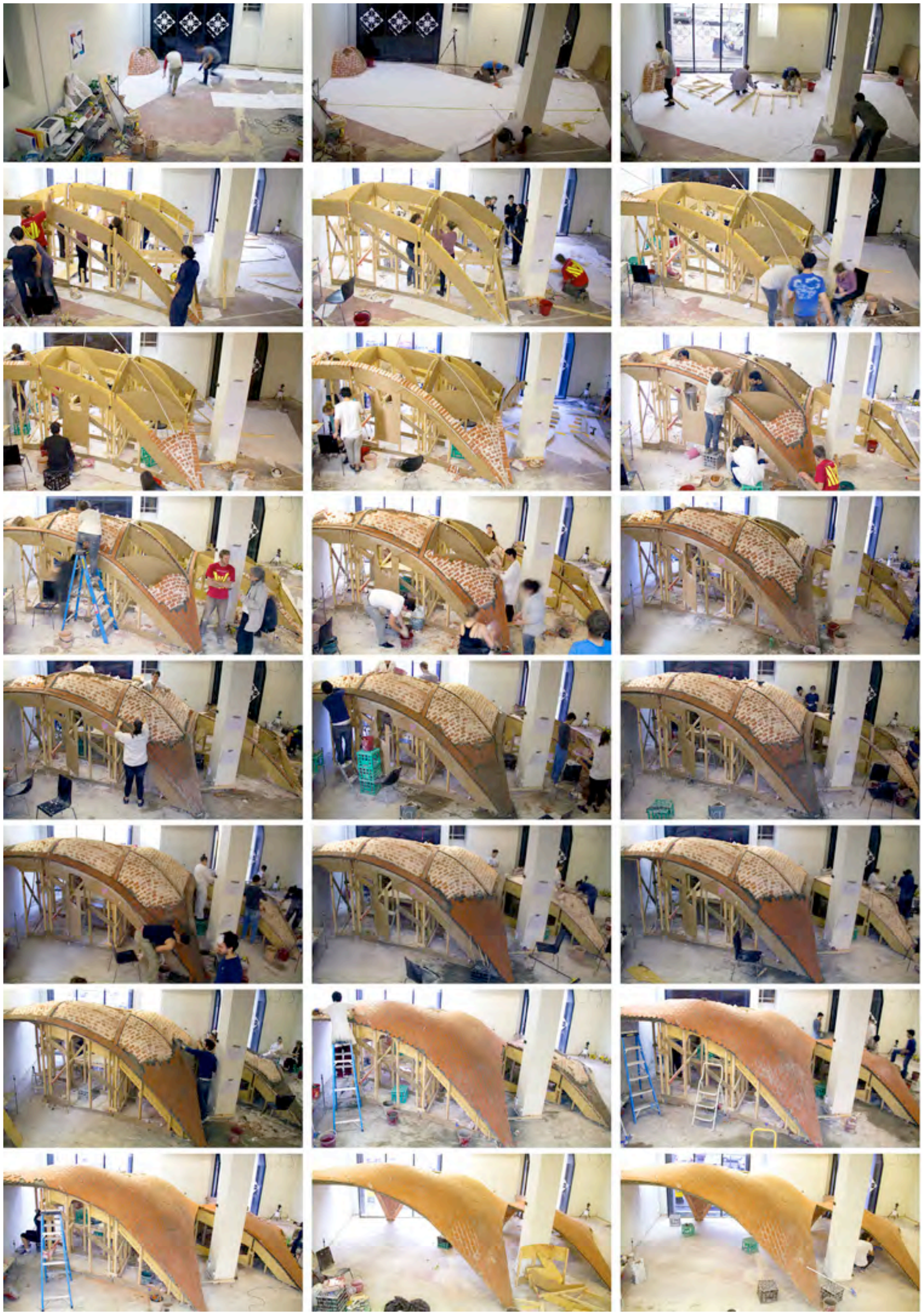
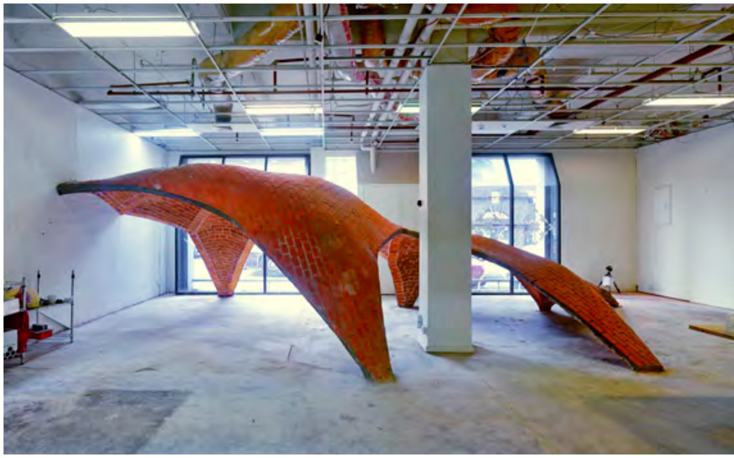


Fig. 7: Construction time lapse of MADA vault.
(Photo: Dean Lau Tim Ling.)

Figs. 8, 9: Finished MADA vault, Melbourne, Australia, 2013.
(Photo: Peter Bennetts.)



subdivisions meant that much less tile cutting was required for the vaulted infills.

CONCLUSION

The two case study projects demonstrate that the increasing contemporary interest in compression-only masonry vault construction is matched by increasing levels of control and formal possibility afforded by innovations in form-finding software paired with fabrication methodologies that expand upon traditional construction approaches. To the set of highly three-dimensional surface structures exemplified by the Block Research Group's earlier prototype at ETH Zurich is now added a new category of irregular and highly three-dimensional compression-only ribbed tile vaults as realised in two projects in Australia.

Significantly, these ribbed tile vaults retain the relatively sparse requirements for falsework enjoyed by their traditional tile vault ancestors without retreating to regularity of form or an increase in thickness. When taken as a pair, by displaying differing levels of rationalisation in the definition of the rib geometry, the two vaults clearly demonstrate the wide range of formal possibilities available as well as the ability to integrate fabrication concerns into the form-finding process.

The combination of computational form-finding approaches and traditional construction methods, as demonstrated via the design and construction of two ribbed tile vaults, can increase the links between design intent and materialisation, and as such is fertile ground for research and innovation.

WORKSHOP DETAILS / ACKNOWLEDGEMENTS

School of Architecture, University of Technology, Sydney (UTS):

INSTRUCTORS: Philippe Block, Melonie Bayl-Smith, David Pigram
STUDIO FUNDING: School of Architecture, University of Technology Sydney
MATERIALS AND SERVICES SPONSORS: Bijl Architecture, Lordell Trading P/L, Monier CSR Roofing, Hanania Quality Tiling Services
DATES: October 2–13, 2012
UTS STUDENTS (Master of Architecture): Amelia Pang, Domenico Ciccio, Francesco Bianchini, Hani Bafail, James Lauman, Jeah Loong Yeoh, Jordan Soriot, Laura Hinds, Natalie Ma, Philena Au Yeung, Sandra Mendonca, Sung Dae Chung, Timothy Cheung
AWARDS: 2013 Graduate & Student Awards of the Australian Institute of Architects NSW Chapter:

- Structural Innovation in Architecture Prize
- Digital Innovation in Architecture – Commendation

Department of Architecture, Monash Art Design & Architecture (MADA):

INSTRUCTORS: Philippe Block, James Bellamy, Tim Schork, Damon Van Horne
STUDIO FUNDING: MADA Department of Architecture in partnership with Grimshaw Architects, supported by the Victorian Endowment for Science, Knowledge and Innovation (veski)
Dates: May 27–June 4, 2013
MADA STUDENTS (Master of Architecture): Anna Black, Boden Davies, Chin Lien Anne-Lise Ip Sion Thoo, Damian Palamara, Dean Lau Tim Ling, Diego Arellano, Dinh Triet Nguyen, Gerard Turnbull, Mehrnoush Latifi Khorasgani, Michael Truong, Natalie Studdert, Radoslaw Buczek, Sara Sidari, Sheli Kuperman

NOTES

1 Michael Ramage, John Ochsendorf, Peter Rich, James Bellamy and Philippe Block, '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.

2 Philippe Block and John Ochsendorf, 'Thrust Network Analysis: a New Methodology for Three-Dimensional Equilibrium', *Journal of the International Association for Shell and Spatial Structures*, 48/3 (2007), pp. 167–73.

3 Matthias Rippmann, Lorenz Lachauer and Philippe Block, 'Interactive Vault Design', *International Journal of Space Structures*, 27/4 (2012), pp. 219–30.

4 Lara Davis, Matthias Rippmann, Tom Pawlofsky and Philippe Block, 'Innovative Funicular Tile Vaulting: a Prototype in Switzerland', *The Structural Engineer*, 90/11 (2012), pp. 46–56.

5 Proprietary product of the U.S. Gypsum Corporation.