Philippe Block · Jan Knippers
Niloy J. Mitra · Wenping Wang *Editors*

Advances in Architectural Geometry 2014

Springer

Gaudi's Puffy Jacket: A Method for the Implementation of Fabric Slump Casting in the Construction of Thin-Wall Funicular Vault Structures

Iain Maxwell and Dave Pigram

Abstract This paper describes a method for the production of thin-wall funicular (compression-only) structures from unique double-curved concrete components via a novel slump casting technique. The technique deploys fabric formwork within simple two-dimensionally cut frames to enable the efficient production of the unique parts necessary to tessellate form-found funicular geometries. Through the realisation of a high-tech / low-tech ecology of production, the paper seeks the reestablishment of generative pathways between each domain in the design-to-production cycle: architecture, engineering and fabrication. The method and resulting case study pavilions are situated within the historical trajectory of architectural form finding, specifically, the realisation of masonry vault structures.

I. Maxwell (✉)
Architectural Association School of Architecture, London, UK

University of Canberra, Bruce, Australia

Architecture & Technology, University of Technology Sydney [UTS], Ultimo, Australia

Sydney Visiting School, Architectural Association School of Architecture, London, UK

Supermanoeuvre, 42/56-60 Foster Street, Surry Hills, Sydney, Australia
e-mail: maxi@supermanoeuvre.com

D. Pigram (✉)
University of Canberra, Bruce, Australia

Supermanoeuvre, 42/56-60 Foster Street, Surry Hills, Sydney, Australia

Graduate School of Architecture, Preservation and Planning [GSAPP], Columbia University, New York, NY, USA

University of Technology Sydney [UTS], Ultimo, Australia
e-mail: dave@supermanoeuvre.com

P. Block et al. (eds.), *Advances in Architectural Geometry 2014*,
DOI 10.1007/978-3-319-11418-7_5

1 Introduction

Through the realisation of good structural form, poor materials transcend their apparent limitations. This paper describes a novel method for the production of thin-wall funicular (compression-only) vault structures from discrete double-curved precast concrete tiles. In the method and case studies that follow, the deliberate pursuit of a high-tech / low-tech workflow ensues. The method is high-tech with regard to the adoption and development of algorithmic approaches to the production of geometry, one that digitally computes form through the mechanical simulation of material to ensure optimal structural shape and material placement. It is low-tech due to the establishment of a bespoke production method that seeks an efficient approach to the fabrication of unique, thin wall, doubly curved, resilient tile elements. Critically, the coupling of design, engineering and fabrication strategies allows for feedback between each domain and thereby increases the number and nature of design influences providing opportunities for innovation. The method is demonstrated through two case study pavilions.

2 Masonry: Material, Structure and Construction

2.1 *Form: Innovation Through Material Constraint*

Good structural form (geometry) reduces the existence of stresses within the materials that compose it. Equally, good structural form must also resist bending under live loading. Throughout the history of architecture and building, we find many examples where limited material resources have set the context for significant innovation in order to meet evolving spatial (span) demand. The theory of arch stability via the development of the catenary thrust line (hanging chain) in the seventeenth century serves as a primary historical example, while the work of Eladio Dieste in the twentieth-century exemplifies the imperative for structural innovation borne out of resource limitations. For Dieste, it was the predominance of extruded clay blocks and the rarity and expense of concrete and steel in his native Uruguay that led to the development of his seminal Gaussian vaulting technique (Fig. 1). Dieste's method, primarily used form to resist buckling, where the *"Gaussian vault can be thought of as a series of connected catenary arches with varying rises that share a common springing. At any longitudinal cross section the vault is subjected to axial compression, but the magnitude will vary between sections as the rise of the catenary changes. The variation in axial compression generates shear stresses between the segments, resisted by steel reinforcement placed between the brick units."* (Pedreschi and Larrambebere 2004). Dieste built many such vaults, the largest example of which, the Port Warehouse, spanned 50 m longitudinally.

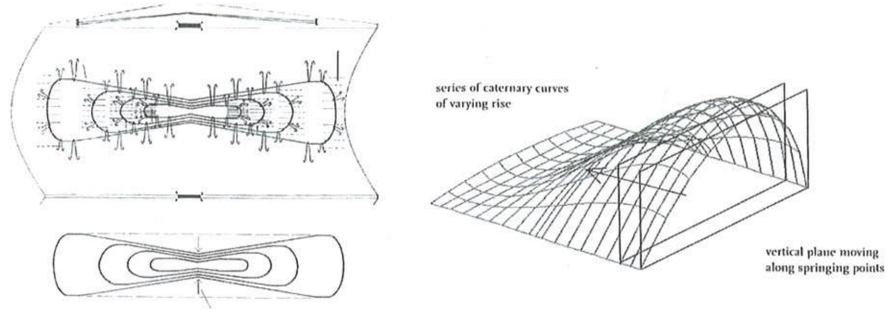

Fig. 1 Eladio Dieste's Gaussian vaulting technique (Pedreschi and Larrambebere 2004)

2.2 *The Stability of Masonry Structures*

Robert Hooke (1635–1703) is generally credited with the theoretical establishment of the thrust-line (catenary) method through the principle of inverting a uniformly loaded suspended rope or chain: *"As hangs the flexible line, so but inverted will stand the rigid arch."* However, as Karl-Eugen Kurrer substantiates, the first mathematical description of the catenary-shape is attributed to the English mathematician David Gregory (1659–1708). Jacques Heyman provides the most extensive review of arch theory and in doing so outlines the historical and theoretical development of the discipline of civil engineering more broadly (Kurrer 2008).

The contemporary rise of computational (algorithmic) modelling, analytical and optimisation techniques has vastly empowered the engagement of design with matters of material and structural stability and sets the platform for an expanded conversation on the nature of architectural form. An extension of architecture's rich history of form-finding that speculatively couples space, geometry, structure and material. A paradigm as familiar with the work of the Master Builders and Gothic masons as it is with the work of Antonio Gaudi and Robert Maillart, Heinz Isler and Frei Otto. Key contemporary figures include: Mike Barnes and Chris Williams (University of Bath), David Wakefield (Tensys), Mutsuro Sasaki (SAPS), John Ochsendorf (MIT), Philippe Block (ETH) and Sigrid Adriaenssen (Princeton University).

2.3 *The Challenge of Thin-Walled Masonry Vaulting*

The fundamental trait of any stable arch or vault is the containment of the thrust-line within the thickness of the structural surface. In confirming Hooke's method David Gregory elaborated: *"none but the catenaria is the true figure of a legitimate arch…And when an arch of any other figure is supported, it is because in its thickness some catenaria is included"* (Heyman 1972). Yet, throughout history we find many examples where a masonry arch does not take the ideal form of the catenary. Their stability, as Gregory observed, is only ensured by the fact that within their massiveness the true thrust-line is captured. T.M. Charlton relays, *"since arches carried heavy dead load, due to superstructure, in comparison with which live load was small, elementary statics was sufficient to ensure that the distribution of dead load and arch shape were such that the locus of the resultant of the total shear force at any section and the horizontal thrust, nowhere passed outside the masonry"* (Charlton 1982). Thus, assuming basic mechanical action (element slippage) was accounted for; a number of less-than-perfect shapes may have been tolerated owing to the massiveness of stone construction.

Within a lightweight and thin-walled paradigm such implicit redundancies do not exist. Simply, without the excessive thickness (depth) or latent benefits of over-compression (mass) inherent to historical masonry construction, there is neither margin nor material to spare a thin-shell vault from exposure to non-uniform externalities and ultimately catastrophic failure. As such, shape control and the realisation of better techniques of shape production are paramount!

2.4 *Historical Methods of Masonry Construction*

There are two primary historical approaches to the construction of masonry arches and vaults: Voussoir and Catalan. Irrespective of the approach, neither method is considered completely stable until the entire vault is complete. The Voussoir method is exemplified by the arches and vaults of the Roman, Byzantium and Gothic periods and denotes the assemblage of individual cut masonry elements. A necessary demand of Voussoir construction is the erection of temporary falsework (centring) to support each block until the overall assembly is complete. The significance of this temporary structuring is further exacerbated by the immense weight of the material used and the limitations its presence places on overall site access.

Conversely, the Catalan method is constructed from small, relatively thin (20–25 mm) and dimensionally similar clay shingles or tiles and produces significantly lighter structures. The use of rapid setting mortar allows Catalan vaults to avoid extensive centring, as such; they are typically built in free-space with minimal guide work. This, together with the use of standardised rather than custom elements, makes them much faster to construct than their Voussoir counterparts. Arising from the brittleness of the tiles and their resulting vulnerability to impact, increased orders of safety – structural redundancy – must be obtained through constructing multiple layers in a cross-laminate manner. Generally three layers are sufficient resulting in an overall thickness of between 75 and 100 mm dependent on curvature and layup. The Catalan method is exemplified by Rafael Guastavino (1842–1908) whose construction company built over a thousand such examples (floor systems and roofs) in North America, the most notable being Boston's Public Library and New York's Grand Central Station (Fig. 2) (Ochsendorf 2010).

Fig. 2 Catalan vaulting employed by the Guastavino Construction Company (Allen 2004)

In the method that follows, a mixed mode approach to masonry assemblies is outlined. One that privileges Voussoir logic in so much as each tile is geometrically unique – and complete falsework is required – yet operates through a lightweight, thin-walled and thereby materially efficient tile strategy. The technique operates on the simple assumption that if the form of the catenary imbues structural capacity and resilience at the scale of the overall structure, then such logics may afford an equivalent resilience at the grain of the tile itself.

3 Form Finding

3.1 *Analogue Form Finding*

Like traditional design techniques: cutting, carving, folding, weaving; form-finding techniques harness the positive limitations of a given media, here material and physical forces, to resolve formal characteristics in consistent ways. Unlike traditional methods however, form-finding processes embed a considerable level of material and structural intent within active design modelling processes. Robert Hooke's inversion of the suspended rope or chain sets the context for a technique-based

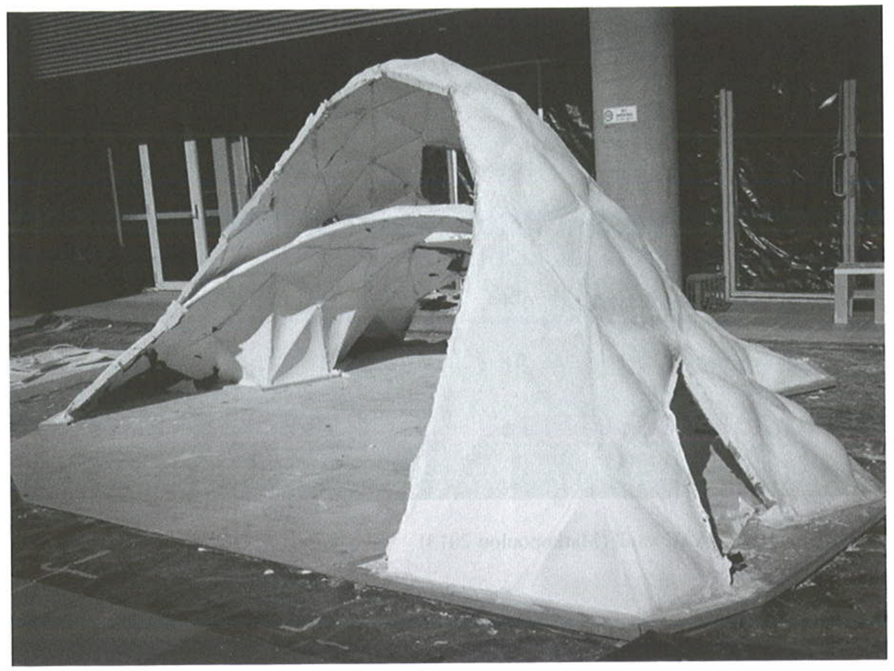

Fig. 10 Completed vault, University of Technology, Sydney (Wibowo 2013)

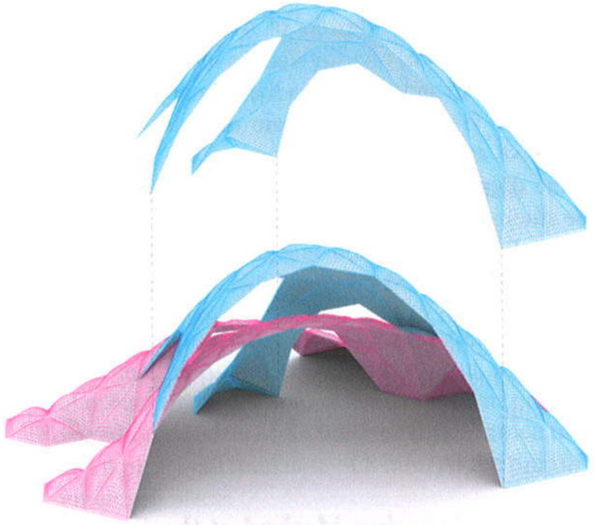

Fig. 11 Drawing demonstrating nested lamina approach to UTS vault (Maxwell 2013)

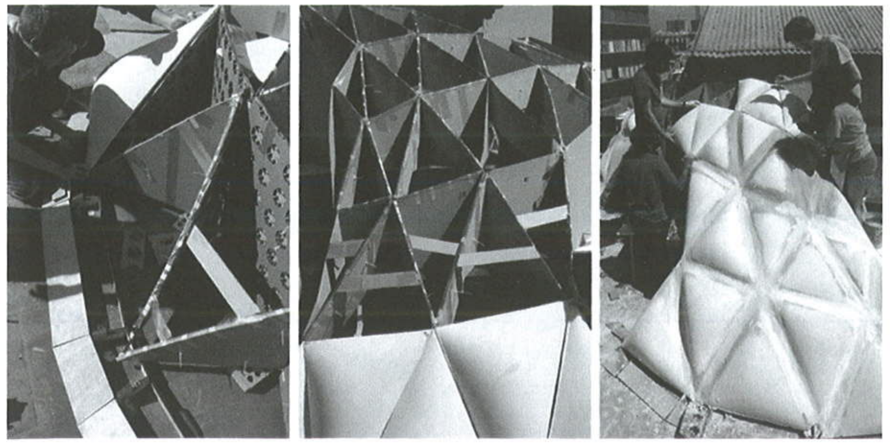

Fig. 12 Construction: use of cardboard scaffolding to position and support fabric-formed precast panels prior to joining (Maxwell 2013)

deflected significantly and the fabric stretched too much. A simple solution was to double-up both the fabric and the frame resulting in a tile that was 16 mm thick.

5.5 *Pavilion Assembly*

Given the thinness of the tile elements used (8 mm), it is extremely important that the built structure closely matches the computationally found-form so that all load paths remain within the computed thrust line. As is typical in all non-Catalan approaches to vault construction, the structure is not stable in an incomplete state and it was necessary to use extensive construction falsework to ensure the exact positioning of each tile and to support them during assembly. Like the precast tiles, each scaffold element was unique (Fig. 12). The scaffolding was produced from cardboard, laser cut and assembled into triangular tubes, reflecting the geometry of the digitally form-found 'parent' geometry. Again, simple Python scripts were developed to automate this routine task.

5.6 *Destructive Testing*

Destructive testing of the second pavilion prototype was conducted via non-uniformly loading the upper lamina (Fig. 13). The vault demonstrated complete stability under a sustained 1,000 kg + point-loading of sand bags. Catastrophic

Fig. 13 Successful point loading (1,000 kg +) of 8 mm thin-wall funicular vault structure (Maxwell 2013)

failure was only achieved through violently severing the load paths at the vault's leading edge using a metal bar.

6 Future Work

Future work will concentrate on two areas: firstly, material testing of the doubly-curved tiles in order to numerically validate their increased performance over an equivalent planar tile of the same area and thickness. Secondly, to employ finite element analysis in order to digitally examine the stability of the construction method under dynamic and non-uniform loading cases such as wind or impact. The purpose of the latter would afford a direct point of comparison to the cross-lamina approach to redundancy exemplified by traditional Catalan vaulting techniques.

7 Discussion

The pursuit of good structural form permits poor construction materials to transcend their apparent limitations. The traditions of form-finding within architecture trace our discipline's efforts to embed material as an active agent within the design process. Enacted digitally, form-finding methods afford an interactive context for the accelerated evolution of design. When developed in parallel with methods of production, a real opportunity exists to establish generative feedback loops across the allied domains of architecture, engineering, fabrication and construction. Thus increasing the number and nature of design influences enabling extended opportunities for design confidence and ultimately innovation.

The method described permits the low-tech construction of simple unique molds and in turn unique parts that can be used to produce novel, thin and lightweight compression-only structures as demonstrated by the two case-study pavilions.

References

Addis, B.: A history of using scale models to inform the design of structures. In: Huerta, S. (ed.) Essays in the History of the Theory of Structures: In Honour of Jacques Heyman. Instituto Juan de Herrera, Escuela Técnica Superior de Arquitectura de Madrid, Madrid (2005)

Allen, E.: Guastavino, Dieste, and the two revolutions in masonry vaulting. In: Anderson, S. (ed.) Eladio Dieste: Innovation in Structural Art. Princeton Architectural Press, New York (2004)

Barnes, M.: Form finding and analysis of tension structures by dynamic relaxation. Int. J. Space Struct. **14**(2), 89–104 (1999)

Block, P., Veenendaal, D., West, M.: History and overview of fabric formwork: using fabrics for concrete casting. Struct. Concr. **12**(3), 164–177 (2011)

Bourke, P:. Particle system example. Available at: http://paulbourke.net/miscellaneous/particle/ (1998)

Charlton, T.M.: A History of the Theory of Structures in the Nineteenth Century. Cambridge University Press, Cambridge/New York (1982)

Day, A.: An introduction to dynamic relaxation. Engineer **219**, 218–221 (1965)

Heyman, J.: Coulomb's memoir on statics: an essay in the history of civil engineering. Imperial College Press, London (1972)

Hooke's law. Available at: http://en.wikipedia.org/wiki/Hooke's_law

Kilian, A., Ochsendorf, J.A.: Particle spring systems for structural form finding. Int. J Shell Spat. Struct. **46**(2), 77–84 (2005)

Kurrer, K.: The History of the Theory of Structures: From Arch Analysis to Computational Mechanics. Ernst & Sohn, Berlin (2008)

Larsen, N., Pedersen, O., Pigram, D.: A method for the realization of complex concrete gridshell structures in pre-cast concrete. In: ACADIA 12: Synthetic Digital Ecologies Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture, pp. 209–216, 18–21 Oct 2012. San Francisco (2012)

Ochsendorf, J.: Guastavino Vaulting: the art of structural tile. Ernst & Sohn/Princeton Architectural Press, Berlin/New York (2010)

Pedreschi, R., Larrambebere, G.: Technology and innovation in the work of Eladio Dieste. In: Anderson, S. (ed.) Eladio Dieste: Innovation in Structural Art. Princeton Architectural Press, New York (2004)