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Tile vaulting in the 21st century

La bóveda tabicada en el siglo XXI

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ABSTRACT

New interactive equilibrium methods for the design and analysis of masonry structures have facilitated the construction of masonry structures with a formal language well beyond what is typically associated with compression-only architecture. These developments have also rekindled interest in tile vaulting, and led to a rediscovery of this traditional building technique.

To ensure that tile vaults with new, complex shapes can still be built economically, the construction processes involved in the realisation of these structures have adapted. For example, cheaper and simpler falsework systems have been introduced. In addition, a wide variety of materials have been experimented with to be able to build more sustainable vaulted structures with local resources.

This paper presents a review of the latest innovations in tile vaulting, based on the most representative works of the past few years with respect to shape, construction method and the use of materials.

Keywords: Catalan vault; Guastavino vault; tile vault; compression-only form; funicular form; brick architecture; RhinoVault; form-finding; masonry.

RESUMEN

Los nuevos métodos interactivos de equilibrio para diseñar y analizar estructuras de fábrica han facilitado la construcción de este tipo de estructuras con un lenguaje formal normalmente no asociado a las estructuras a compresión. Estos avances también han reavivado el interés por la bóveda tabicada, y han dado lugar a un redescubrimiento de esta técnica constructiva tradicional.

Los procesos constructivos han sido adaptados para garantizar que las nuevas bóvedas tabicadas de formas complejas puedan continuar materializándose de una manera económica. Por ejemplo, se han introducido sistemas de cimbrado más baratos y sencillos. Así mismo, se ha experimentado con una gran variedad de materiales que permitan construir estructuras abovedadas más sostenibles con recursos locales.

Este artículo presenta una revisión de las últimas innovaciones en técnica tabicada basándose en las obras más representativas de los últimos años con respecto a la forma, el método constructivo y el uso de materiales.

Palabras clave: *Bóveda catalana; bóveda de Guastavino; bóveda tabicada; forma a compresión; forma funicular; arquitectura de ladrillo; RhinoVault; form-finding; obra de fábrica.*

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1. INTRODUCTION

The contemporary renaissance of tile vaulting has been closely linked to the development of new interactive equilibrium methods for the design of masonry structures. Architects and engineers have found in tile vaulting an appropriate technique to build the expressive free-form structures designed with the tools related to these novel methods. The combination of tile vaulting with these tools has broadened the horizon of possibilities adding versatility and expressivity to a centuries-old technique that has succeeded in adapting to the current architectural trends.

The growing interest in the tile vaulting technique and the proliferation of projects worldwide have demanded new approaches to the design and construction to simplify construction of complex shapes and reduce costs and carbon emissions. After centuries of refinement through tradition and experience, tile vaults are currently undergoing an accelerated period of innovations.

This paper aims to identify the key contributions to the tile vaulting technique in the 21st century by presenting a review of the most relevant tile vaulted projects in the past few years regarding the novelty of their shape and the innovation in the fields of construction and materials. The identification of these contributions helps to understand the current state of the technique and gives a thorough overview of its possibilities.

2. ORIGINS

> "*... tile vaults are an effective constructive invention because, with bricks and plaster or fast cement, a skilled mason can do in a few hours, a huge variety of resistant forms, without any other tool than drawer and palette ...* " (1)

Tile vaults are masonry structures made with thin bricks (tiles) and mortar. The bricks are placed flat, building up two, three or more layers. Traditionally, tiles are used because of their lightness, which is a necessary condition to build the first layer "in space", without supporting falsework. The first layer is achieved through the quick adhesion of mortars such as gypsum or fast-setting cement. The bricks stick within seconds to the edge walls, or the already finished arches or stable sections, taking away the necessity of centering (2). Using this first layer as a permanent formwork, the second and subsequent layers can be set with lime or Portland cement mortar.

The origins of tile vaulting are not entirely clear and different authors have different opinions. Joan Bergós stated clearly that the Romans were the inventors of tile vaulting (3) and showed Choisy's drawings of Roman constructions to support his argument (4). Some doubts arise though when posing the question about the continuity of the technique until the first known constructions. Bergós gave importance to the region of Lleida in Catalonia (his birthplace), as a place where the technique would have endured and he presented some examples of "*flat deck vaulting elements*" (5) made with the tile vaulting technique, the first one already in the 13th century. The first tile vault that Bergós dated in his text is from the Hospital of Santa María in Lleida, built in 1352.

George R. Collins was more cautious on his statements about the origin of tile vaults (5). He presented his doubts about the Roman origin based on the absence of transitional examples. Like Bergós, he named some built examples with "*flat deck vaulting on or between stone ribs*" and dated the first reference to a tile vault in the beginning of the 15th century:

> "*The earliest reference of any sort of which I am aware is in a letter of King Martin I "el Humano" of Aragon in the early fifteenth century about the construction of the capilla real of the Cathedral of Barcelona in which the king praised the qualities of the Catalan vault. Certainly such vaults were common in mediaeval Catalonia-and very thin shell vaults.*" (5).

On the other hand, Philippe Araguas is clear in his statement that he "*was able to fix the date of the invention* [of the tile vault] *in 1382, in the archaeological sense of the term*" (6). It is worth to point out that the word that he uses is "invention" (also used by Bergós). This is fundamentally different from the opinion of, for example, Manuel Fortea. For Fortea, tile vaulting did not appear suddenly; it was the "*culmination of an evolutionary process in which the arising obstacles have been gradually overcome*" (7). He argues that this evolution required a place where gypsum, brick and vault construction without formwork are known and commonly used. His argumentation takes us on a very interesting trip starting in Mesopotamia and mainly through the Spanish regions of Valencia and Andalucía, where, as described by Fortea, there are built examples of tile vaults from before the 14th Century. He finally places the first references of the technique known as tile vaulting in Almería in Andalucía, in the 11th Century.

3. INNOVATIONS IN THE LATE 19TH CENTURY AND THE 20TH CENTURY

The tile vaulting technique experienced its first period of innovations mainly thanks to the Guastavinos and the Catalan Art Nouveau. Rafael Guastavino Moreno (1842 – 1908) started the modern application of the traditional technique in the late 1860s in Barcelona. He replaced the lime mortar by Portland cement mortar, obtaining higher and quicker strength, and introduced the iron as metallic reinforcement (8) (9). Guastavino managed to bring attention to tile vaulting and turned it into a genuine feature of the industrial architecture (10). A good example of this is the Batlló Factory in Barcelona, built in 1868. Guastavino built many other projects of several typologies featuring tile vaults in Catalonia, but his main innovations in the field would come during his "American episode", after emigrating to the United States with his son Rafael Guastavino Expósito (1872 – 1950) in 1881. The Guastavino Company, in which both father and son worked, was able to adapt the Spanish technique to the American construction market, fulfilling requirements such as fireproofing, soundproofing, sanitation and decoration (9). The Guastavinos developed a total of twenty four patents with new improvements or adaptations of the technique, covering the entire construction process, including construction details, new materials and structural issues, and making "*substantial contributions to the development of the traditional tile vault as an engineered structural system*" (9). They achieved enormous success in the US, where they built tile vaults in more than a thousand buildings, especially in the City of New York. Extraordinary feats of engineering were achieved with spans up to 40 meters and where the tile vault is at the core of buildings of great significance. According to Guastavino, tile vaults were to become more and more common constructions. However, that did not happen. In 1962, the Guastavino Company closed its offices and the technique became obsolete in the U.S. with the advent of steel and concrete.

The Art Nouveau in Catalonia learnt from the Spanish tradition and from the Guastavinos' experience and found in tile vaulting an appropriate technique to build their new expressive architectural forms. Within this movement, and in parallel to the Guastavino Company's work, tile vaulting reached a peak in terms of expressiveness, versatility and importance, with the works of, among others, Antoni Gaudí Cornet and Lluís Domènech i Montaner. The symbolic use of tile vaulting in Catalonia finished with the end of the Art Nouveau. However, the lack of steel after the Spanish Civil War offered again appropriate conditions for a new recovery of the technique (11). From this time, it is worth to highlight the work by the architect Luis Moya (1904-1990) who experimented, mainly in Madrid, with different features, shapes and configurations, such as series of contiguous tile vaults (avoiding the use of tension ties), their combination with crossed masonry arches (12) and, in a later period, with steel reinforcement (13). After this period, which comprised mainly the 40s and 50s (although Moya continued building tile vaults until the 60s), the technique was abandoned, with the exception of the construction of tile-vaulted stairs in Catalonia until the 80s (11). However, the study and use of tile vaulting for historical reasons or restoration purposes by a reduced number of academics or professionals continued, as can be seen from several publications in the second half of the 20th century (14).

4. THE CONTEMPORARY RENAISSANCE OF TILE VAULTING

The contemporary renaissance of tile vaulting had a clear beginning at the Masonry Research Group at the Massachusetts Institute of Technology (MIT) in Cambridge, USA, led by Professor John Ochsendorf (15). Ochsendorf first learned about the technique from Professor David Billington (a colleague of George R. Collins) at Princeton University in 1996. He further studied tile vaulting through the Spanish tradition, masons and scholars (such as Santiago Huerta, José Luís González and Manuel Fortea) during his academic stay in Spain in 2000-2001, when the exhibition, "*Las bóvedas de Guastavino en América*" (*Guastavino´s vaults in America*) (16), was being mounted (17).

The success of the MIT Masonry Research Group was in part due to the development of powerful new tools for the design and analysis of masonry structures using interactive equilibrium methods (18) (19) (20) (21) (22). These tools allowed them to create new architectural shapes and demonstrate their stability and structural safety.

One of their first relevant works in tile vaulting was the Pines Calyx (2004-2006), a conference centre at St. Margaret´s Bay, United Kingdom. John Ochsendorf, Wanda Lau and Michael Ramage of the MIT Masonry Research Group were involved in the structural design, analysis and construction of the two 12m-span, 12mm-thick, tile domes and a tile-vaulted stair. The building was built using waste materials and was awarded for its sustainability and low embodied energy. The tiles for the domes were made of waste clay, washed out of a local gravel quarry, and the walls were made with rammed chalk from the excavations for the building´s foundation (23).

The building does not make a substantial contribution to the tile vaulting technique, but it was a successful attempt to recover it into contemporary architecture, demonstrating its feasibility and exportability (it was the first tile vault in the UK) and drawing attention to its sustainability. Moreover, it marked the beginning of a series of buildings using tile vaults, many of which brought relevant contributions to the field. Most significantly, for its size and impact, the construction of the Mapungubwe National Park Interpretive Centre (2008) (Figure 1), covering more than 3,000 m² and using 200,000 locally-made, pressed, soil-cement tiles, marked an important milestone in tile vaulting construction (24).

Some MIT alumni continued their research on tile vaulting in different institutions, such as Michael Ramage at the University of Cambridge, and Philippe Block with the Block Research Group (BRG) at ETH Zurich (25). Particularly the innovations in "free-form" tile vaults by the BRG gave new possibilities to the old construction technique, resulting in novel, free-form, optimized tile vaults.

Since the above-mentioned revival, many tile vaults have been built in numerous workshops and projects all over the world. This paper tries to identify crucial milestones or key innovations in them. Many of the contributions in modern tile vaulting within its contemporary renaissance are related to the previously mentioned new formal language. This was possible thanks to the novel form-finding computational

Figure 1. Mapungubwe National Park Interpretive Centre, Peter Rich Architects, (2008), a) interior view, b) under construction (Photo: James Bellamy).

Figure 2. First free-form tile vault. BRG, ETH Zurich, 2011, *a)* finished vault (Photo: Klemen Breitfuss), *b)* form diagram (Γ), force diagram (Γ*) and 3D thrust network (G) (RhinoVault).

tools, whose application in different project is showed in section 5, and required new approaches to construction processes, explained in section 6. Research on the material alternatives has also provided substantial contributions, which are analysed in section 7.

5. NEW FORM-FINDING COMPUTATIONAL TOOLS

The Pines Calyx project served as inspiration for the architect Peter Rich, who proposed a tile vaulted structure for the Mapungubwe National Park Interpretive Centre in South Africa (2008) (Figure 1). Rich teamed up with, among others, Ochsendorf and Ramage for the design of the vaults.

The new equilibrium methods developed at MIT based on graphic statics were crucial for the design of the vaults. Interactive, two-dimensional thrust-line analysis (20) was used on the cross-sections of the doubly curved, parabolic vaults to define their final shape (26). Further 3D equilibrium verification was carried out using Thrust Network Analysis (21) (24).

Thrust Network Analysis was the result of Philippe Block´s PhD thesis under guidance of Ochsendorf at MIT (22), and it served as theoretical basis to develop the computational form-finding tool RhinoVault at the BRG (27) (28). RhinoVault is a plug-in for Rhinoceros that allows the design of compression-only, vaulted structures with high formal complexity. This tool is based on the simplicity of graphic statics and uses geometrically linked, reciprocal form and force diagrams that can be directly modified by the designer to produce different equilibrium solutions through an interactive and intuitive structural design process. RhinoVault has been key in the innovation in tile vaulting, since it has been the tool used to design some of the most relevant projects contributing to the field.

The first free-form tile vault was built by the BRG in 2011 (Figure 2) in a project by Matthias Rippmann, Lara Davis and Philippe Block (29). It was the result of combining the newly developed RhinoVault and the versatility and flexibility of the traditional tile vaulting technique. In order to test the method, the design of the project aimed to face several structural and construction challenges: a structural fold, different boundary conditions (including a point support), high degrees of curvature and multiple "open edge" boundary arches (30).

Inspired by the prototype built at the ETH by the BRG in 2011, the architects Map13 Barcelona (Marta Domènech, David López López and Mariana Palumbo) (31) used the form-finding tool RhinoVault to design the first human-scale, free-form tile vault at the International Festival of Architecture Eme3 in Barcelona in 2013. The multi-awarded pavilion, "Brick-topia" (Figure 3) (32), accommodated different activities such as concerts, colloquia and performances, and showed the relevance of the newly-developed form-finding computational tool to be able to build expressive, architectural projects that could be safely open to the public. This fact demanded an accurate structural analysis to fulfil the requirements of the Spanish Building Code (33). This analysis was based on pre-

Figure 3. "Brick-topia", Map13 Barcelona, 2013, *a)* finished vault (Photo: Manuel de Lózar & Paula López), *b)* form diagram (Γ), force diagram (Γ*) and 3D thrust network (G) (RhinoVault).

Figure 4. Workshop at MADA, Melbourne, 2013, instructed by P. Block (ETH Zurich), J. Bellamy (Re-vault), T. Schork (MADA) and D. Van Horne (Grimshaw Architects), *a)* result (Photo: Peter Bennetts), *b)* form diagram (Γ), force diagram (Γ*) and 3D thrust network (G) (RhinoVault).

vious research about the structural behaviour of tile vaults by the authors of "Brick-topia" (34). Although it could have been a permanent structure, "Brick-topia" was built at a festival of architecture and the permission to occupy that space was temporary. It was demolished in October 2013.

A new funicular form-finding approach by the BRG was applied in two hands-on workshops in Sydney and Melbourne, Australia (2012 and 2013 respectively), to create, using the tile vaulting technique, three-dimensional networks of structural ribs and infills or "patches" in between them (Figure 4). The ribs are created by modifying the reciprocal diagrams and attracting forces to the desired places in the shell (35). The final shape in both cases was achieved after two steps in the design process: an abstraction of the structural action to achieve the equilibrium of the ribs alone using a rough and simple form diagram subdivision, and the following refinement of the "low-poly" designs together with the addition of the infills. The layout of the ribs in the first workshop explored "*undulating strips of hexagonal units*" (35), whereas the second structure was based on a stretched, quadrilateral grid, in which each segment was straight in plan.

6. CONSTRUCTION

Traditional tile vaults are built without formwork as the non-completed arch or section relies on the adherence of the fast-setting gypsum or cement to the previous already stable arch or section. The building sequence, taking into account the stability during construction, is normally clear for a relatively experienced builder. However, this is not generally true for free-form vaults, because they rely on fully three-dimensional structural action in order to stand in pure compression. It may not even be possible to divide such vaults into stable sections that can be built independently and without falsework. Therefore, the presented new free-form tile vaults required novel approaches to construction processes.

The prototype by the BRG, built at the ETH Zurich in 2011, presented a novel falsework system using CNC-cut cardboard boxes to define the shape of the vault (Figure 5). The boxes were placed on an assembly of shipping palettes, which served as platforms to stand on while building and reduced the amount of required cardboard. The resulting thickness of two boxes together and the whole system of boxes in a grid provided enough stiffness to resist the weight of portions of the vault during construction. The dimensions of the boxes were such that they were compatible with the dimensions of the palettes and allowed the bricklayer to stand inside (30).

The project "Brick-topia" by Map13 Barcelona learnt from the first BRG´s prototype, but faced a new scale and very strong constraints in time and budget (32). These facts demanded some further developments that would allow to build a safe, large and cheap structure in a very short time. Another falsework system was explored that had three main elements: scaffolding, cardboard and thin steel rods (Figure 6). The modular scaffolding was used, as the palettes were used in the first prototype at the ETH, to reduce the amount of required cardboard and to reach a comfortable height for the bricklayers to work. The cardboard panels were cut following the shape of perpendicular cross-sections of the building. The

Figure 5. First free-form tile vault. BRG, ETH Zurich, 2011, *a)* under construction, *b)* falsework scheme.

Figure 6. “Brick-topia”, Map13 Barcelona, 2013, *a)* under construction (Photo: Manuel de Lózar & Paula López), *b)* falsework scheme.

intersecting panels created 2m by 2m, stable systems of four panels, which were placed on the scaffolding modules, defining the intrados of the vault. Following the cardboard’s upper edges, a net of steel rebars was placed. These rebars were bent in situ and linked together using steel wire. Once a stable and stiff net of steel rebars, effectively a low-tech gridshell, was achieved, the cardboard was removed to allow the bricklayers to work on the scaffolding (32). The main difference and advantage over the falsework of the ETH shell is, besides the obvious reduction of cardboard waste, that the masons could easily reach and check the underside of the brick layer during construction. This allowed a more comfortable construction process and the inspection of the joint´s quality for structural and aesthetical reasons.

Further steps were done in the two mentioned workshops in Australia, in which a high degree of formal expression was achieved simplifying the falsework radically. Only the ribs were built using a falsework, whereas the infill in both projects was built in the traditional way. The first workshop required a three-dimensional falsework to build the ribs curved both in plan and elevation, whereas the second one had straight ribs in plan, which resulted in a very simple and cheap falsework restricted to the ribs (Figure 7). These two projects, and then the last one particularly successfully, incorporate materialization in the form-finding process by designing to ease and speed up construction, simplify the falsework and decrease costs without losing expressivity (35). The overall goal of these experiments were to find a balance/compromise between the efficiency of traditional tile vaulting and the new expressive possibilities of free-form tile vaulting through the introduction of ribs that globally describe the geometry, but subdivide it in manageable patches for which a clear tile pattern can be followed.

7. MATERIAL

The revival of the technique and its exportation worldwide demanded research on new materials that would be produced locally, reduce costs and be more sustainable. The use of locally produced earth bricks instead of the typical fired clay was a successful novelty of the mentioned internationally-awarded Mapungubwe National Park Interpretive Centre (2008) (Figure 1). Besides, it includes other innovations related to economy and social and environmental sustainability. The use of local resources, i.e. workforce and materials, contributed to the activation of the local economy and the reduction of embodied carbon emissions. Local workforce was both employed to build the vaults (thus learning a new technique and acquiring new skills), and to produce the compressed, stabilized, soil-cement tiles (24) (26). A very important contribution of this project is that it showed that learning tile vaulting has a relatively low threshold, an idea that was very important in projects following, where tile vaulting was promoted as an appropriate construction technique for an African context. This project demonstrated the possibility of a safe technology transfer and was an example of sustainable construction.

Figure 7. Workshop at MADA, Melbourne, 2013, instructed by P. Block (ETH Zurich), J. Bellamy (Re-vault), T. Schork (MADA) and D. Van Horne (Grimshaw Architects), *a)* under construction, *b)* exploded 3D showing the falsework and construction scheme.

Figure 8. Tile vaults at SUDU project, BRG, ETH Zurich, (2010-2011), *a)* tile vaults with lightweight stiffening walls, *b)* tile vaults with lightweight stiffening walls and compacted fill.

Following this line, the SUDU project (Sustainable Urban Dwelling Unit, 2010-2011) was designed by Philippe Block, Lara Davis and Dirk Hebel (36) (37) (38). The BRG's tile vaults at SUDU in Addis Ababa, Ethiopia, are also part of a project that is entirely conceived from a sustainable perspective. The material of the first layer of tiles is the locally-available Trachyte stone, whereas the next layers are built using stabilized soil masonry units (36). The floor system solution is inspired by the Guastavinos, it combines two traditional ways to stabilize thin tile vaults: adding lightweight stiffening walls and adding compacted fill (Figure 8).

After Michael Ramage's collaboration with Peter Rich and John Ochsendorf in the Mapungubwe National Park Interpretive Centre in South Africa, his subsequent work at Light Earth Designs (39), together with Timothy Hall and Peter Rich, follows this line, using local earth to build the bricks for their tile vaults. Examples of this kind of construction are the Earth Pavilion in London (2010), whose bricks are made of waste soil from a close construction site, the FR2 Offices in Chicago (2013) (40), featuring 200 small-span tile vaults, and the recent Sussex Cellars in London (2015), in which English traditional fan vaults are built using the tile vaulting technique (39).

It is also worth to mention the contribution by Michael Ramage and Matthew DeJong in the reinforcement of new tile vaulted structures by applying a geogrid in between the layers of bricks (41). This kind of material (polymeric grids, glass-fibre mesh, basalt-fibre mesh, etc.) has been commonly used for the reinforcement of existing masonry structures, including tile vaults, in the field of restoration. The contribution in this case lies in the use of this material for new structures, to introduce tensile and bending capacity and the intention to export the technique to seismic areas where these kind of constructions are normally directly rejected. The system was tested in the Bowls Project in San Francisco and implemented in the Earth Pavilion in London, both in 2010 (42). The geogrid was used in the Bowls Project for seismic reasons, whereas in the Earth Pavilion it was justified as a way to reduce the thickness of the vault (40).

A recent "novelty" in tile vaulting in the field of new materials is the construction of the first tile vault in ice by the BRG on January 2015 (Figure 9). This one-layered, single-curved prototype was built following the traditional construction process of tile vaulting, i.e. "in space" after the first row of bricks, relying on the adherence of the tiles to the previous stable row. The only material used was water, in two different states, liquid and solid, using snow, water and ice. The fast-setting binder was the snow, which, under low temperatures, hardens very fast when a small quantity of water is added. Special care needs to be taken in the decentering process, since temperature changes may cause melting and refreezing of the intrados and some parts of the vault might get attached to the formwork, causing asymmetric loading from below, which could potentially produce cracking or failure. This prototype opens a wide range of formal and aesthetical possibilities in ice construction and shows a new sustainable way to build a different kind of tile vaults in specific contexts with low temperatures. The material used is local, cheap, easy to produce and has no embodied energy. Furthermore, once

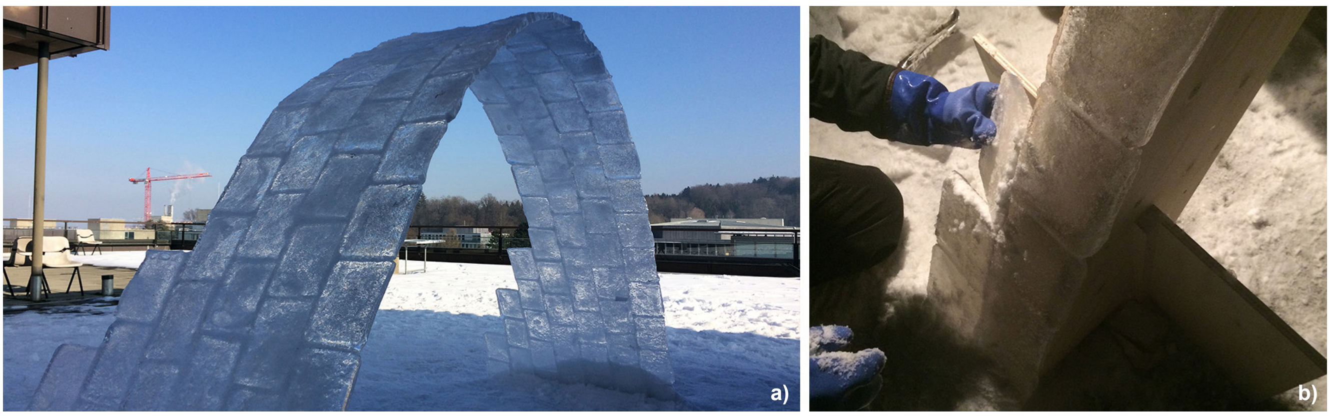

Figure 9. Ice tile vault, BRG, ETH Zurich, 2015, *a)* finished prototype, *b)* under construction.

the structure is demolished or melts there is no waste material other than water.

8. CONCLUSIONS

Tile vaulting construction is experiencing a renaissance since the beginning of the 21st century. The versatility and flexibility of the technique allow the creation of expressive, free-form structures designed with novel, computational form-finding tools. These powerful, equilibrium-based, interactive tools for the design and analysis of masonry structures have been key for the recent innovations in tile vaulting.

New structural shapes require new solutions for construction processes. The efforts on this field have been mainly addressed to come up with improvements that allow the reduction of the falsework, and thus also the costs, while maintaining a safe and easy construction as well as a sufficiently accurate description of a complex and specific geometry.

Tile vaults' intrinsic sustainability and the possibility of using local materials with low embodied energy to produce the tiles have also drawn attention from current architects, who appreciate the value of an economic and expressive technique that offers the chance to be exported. Several projects or prototypes have been built using compressed, stabilized earth tiles, tiles made of stone, or even ice tiles.

Given the current research on tile vaulting's new possibilities and the increasing interest in it, its current revival will likely still provide relevant contributions and interesting innovations.

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