



# BUILDING ETHIOPIA

SUSTAINABILITY AND INNOVATION IN ARCHITECTURE AND DESIGN



ZEGEYE CHERENET  
HELAWI SEWNET



**EiABC**

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# EARTHEN MASONRY VAULTING TECHNOLOGIES AND TECHNOLOGY TRANSFER

>> LARA DAVIS | PHILIPPE BLOCK

## TECHNICAL ASPECTS INTRODUCTION

In rural Ethiopia – where the annual population growth rate is 7%, congested cities increasingly cannot absorb the high rate of urban migration, and rural land is at capacity for subsistence farming, innovative methods are urgently needed to provide housing and encourage the growth of medium scale towns.<sup>1</sup> Solutions are required at the building scale, which may foster intermediate economies, ballast unemployment, and densify settlements so that it is affordable to introduce communal infrastructures for semi-urban dwelling such as, supply chains for access to food, potable water, electrification, crop irrigation, and access to social infrastructures like schools and health care facilities. This is born out of the belief that shared infrastructure is equivalent to affordable facilities. In these same regions demanding new approaches to semi-urban density, the only existing housing stock are roughly constructed dwellings disbursed widely throughout the landscape, which, critically, cannot accommodate strategies for multi-story housing. Such dwellings, while being economically sustainable for the typical poor, rural Ethiopian peasant, are also heavy consumers of limited domestic resources (eucalyptis wood) and imported materials (corrugated steel roofing). The imminent challenge is to enhance these vernacular construction methods – with consideration to the shortage of building material, capital resources, and skilled labor by applying the use of innovative techniques, to meet the urgent need for housing.

As such, timbrel vaulting and Mexican “leaning brick” vaulting are two historical masonry construction techniques, with demonstrated low-cost applications in construction markets of Spain and Mexico, which have been proposed as viable low-cost techniques in the Ethiopian context.<sup>2</sup> Why vaulting? Though these traditional, Mediterranean and Mexican vaulting techniques are both typically executed with fired clay bricks, both have been modified for more sustainable building practice in the African context through the application of cement-stabilized, soil-pressed bricks, or compressed earth block (CEB) technology. In the case of timbrel vaulting, this combination has been pioneered by the Mapungubwe National Park Interpretive Centre project in South Africa.<sup>3-6</sup> A more distant relative to the leaning brick method, Nubian vaulting, has a much longer history of application with the use of sun-dried, earthen Adobe construction.<sup>7</sup> This use of soil as a primary building material – locally abundant and inexpensive – has offered an environmentally sound, alternative building solution for low-cost housing, which reduces dependence upon expensive imported materials, and stimulates local economic growth through labor-based job creation. These methods have enabled the rapid construction of modest, repeatable tile floor systems, which directly answer the demand for multi-story construction in a rapidly urbanizing society. This two-part chapter discusses the implementation of these two vaulting construction techniques in the context of Ethiopia. Part I will describe the techniques of timbrel and leaning brick vaulting in their technical details, while addressing the arguments for their sustainable use in Ethiopia. This section will outline the construction methods, their structural principles, material properties, and applicable design tools and metrics. It will additionally present a comparative discussion of relevant selection criteria for the alternative building techniques, with attention to the challenges of resource constraint in the developing world context. Part II will juxtapose technical and social concerns of earthen masonry vaulting in Ethiopia, querying implications of the cultural relevance and uptake of this new technology, while setting forth strategies for sustainable technology transfer.

1 >> Läßle, Dieter. “Shaping Urban Ethiopia” Lecture. Lake Tana Region – Prospectives of Future Urbanisation, International Scientific Workshop, Bahir Dar University, Ethiopia, February 2011.

<http://www.hcu-hamburg.de/research/arbeitsgebiete/laepple/veranstaltungen/lake-tana-city-region-workshop/>

2 >> Block P., DeJong M., Davis L. and Ochsendorf J.[2010] Tile vaulted systems for low-cost construction in Africa, Journal of the African Technology Development Forum (ATDF), Vol. 7, Nr. 1-2, pp. 4-13.

3 >> Ramage, M., Ochsendorf, J., Rich, P., Bellamy, J. and Block, P. (2010) Design and Construction of the Mapungubwe National Park Interpretive Centre, South Africa. Journal of the African Technology Development Forum (ATDF) – Special Issue on Architecture for Development.

4 >> Ramage, M., Ochsendorf, J. A. and Rich, P. (2010) Sustainable Shells: New African Vaults Built With Soil-Cement Tiles. Journal Of The International Association For Shell And Spatial Structures (J. Iass), Vol. 51, No. 4 December n. 166, pp. 255-261.

5 >> Ramage, M., Ochsendorf, J., Block, P. and Rich, P. (2008) “Advanced Geometry, Rudimentary Construction: Structural Form Finding for Unreinforced Thin-shell Masonry Vaults” in Advances in Architectural Geometry 2008, Vienna, Austria.

6 >> World Buildings Directory, Online Database – Mapungubwe Interpretation Center (2009) World Architecture Festival 2009 - World Building of the Year. <http://www.worldbuildingsdirectory.com/project.cfm?id=1634>

## NEW APPROACHES FOR LOW-COST HOUSING—CAPITALIZING ON SOIL

To develop comprehensive alternatives for vernacular construction, it is necessary to identify what makes local housing typologies already socio-economically fit for their environments, and



a >>

7 >> Houben, H. and Guillaud, H., *Earth Construction: A Comprehensive Guide*. CRATerre-EAG, Intermediate Technology Publications, London, 1994.

8 >> UN Habitat, Regional and Technical Cooperation Division, *ETHIOPIA: ADDIS ABABA URBAN PROFILE*. United Nations Human Settlements Programme (UN-HABITAT), UNON, Publishing Services Section, Nairobi, 2008.

9 >> Jarzombek, M. "Lalibela and Libanos, The King and the Hydro-Engineer of 13th Century Ethiopia, A Connection to India?" in *Cities of Change: Addis Ababa*, Edited by Marc Angéllil and Dirk Hebel (Zurich: Birkhauser, 2009) pp.76-79

a<sub>1, 2 & 3</sub>>> Traditional Sar-bet dwellings in rural Ethiopia (Amhara region); 1) Traditional "Sar-bet"(grass hut) dwellings in rural Ethiopia (Amhara region) with Eucalyptus wood and plastered mud construction method; 2) Typical, roughly built Sar-bets showing lateral instability; 3) Corcoro-bet, rectilinear form with minimal bracing and a corrugated metal roof.

what makes typical low-cost housing alternatives prohibitive by Ethiopian means. The most common vernacular dwelling of the north is the 'Sar-bet' (or grass hut), a 'tukul' type construction of eucalyptus wood, thatch roofing and mud plastering (a >>). The 'korkoro-bet' is a slightly modernized version, which has an adapted, rectilinear form to suit the dimensions of the corrugated sheet metal used for roofing (a<sub>3</sub> >>). The increased cost of sheet metal in this housing type is offset by its benefit to its owners, as it is commonly collected and used as material capital in a practice of informal, rural banking. It could be said that these two typologies most economically utilize the limited, available building material, and constructional skill in the rural market. However, it is clear that these alone do not provide a strategy for the population increase projected in the coming decades (UN Report),<sup>8</sup> and further, do not utilize Ethiopian resources in a sustainable manner. Eg. With the addition of bracing techniques, the abundant



b >>



use of eucalyptus wood elements could certainly be reduced for lower cost targets and mitigating unchecked development, which contributes to a long history of unsustainable deforestation and soil erosion in Ethiopia.<sup>9</sup>

Typical low-cost alternatives to vernacular construction techniques, known primarily only in urban centers, are prohibitively expensive because of extensive inflation and the shocking, disproportionate cost of imported materials. Further, the industrial manufacturing of building materials such as steel, cement, and construction timber is extremely limited in Ethiopia (b >>). Yet, while steel, cement, and precision construction wood are scarce, soil and stone may be considered as abundant, accessible and sustainable construction materials in Ethiopia. These inexpensive alternatives may be considered the materials of choice for low-cost construction, where lesser quality material can be safely employed.

## TIMBREL & LEANING BRICK VAULTING BACKGROUND AND METHODS

As stone and soil have limited tensile capacity, spanning space with these materials demands new structural solutions: compression-only structures. Wall elements in masonry are relatively straight-forward; however, once a space has to be spanned for second story occupancy, beam elements are needed. Such elements, which work in bending, typically require timber, steel or reinforced concrete – all materials that are costly or not readily available in the rural Ethiopian market. Furthermore, while bending moments require a great deal of material to carry loads, compression-only solutions used to span space can be very thin and require comparably less material.

There are three primary, typological methods for spanning space with a masonry system: European, Nubian/ Mexican and Catalan vaulting (c >>).<sup>10</sup> European-style vaults (c<sub>1</sub> >>) may be immediately discarded as a viable solution for low-cost housing on account of the excessive formwork (or centering) required for construction, as material and labor for formwork is one of

b >> Imported building material: Portland cement for concrete and reinforcement steel.

c >> Three methods of brick vault construction [7]: 1. Northern European vaults require extensive wooden centering; 2. pitched or leaning brick vaults, built in North Africa and Mexico, eliminate the need for centering; and 3. Mediterranean thin-tile vaults may be constructed without centering.

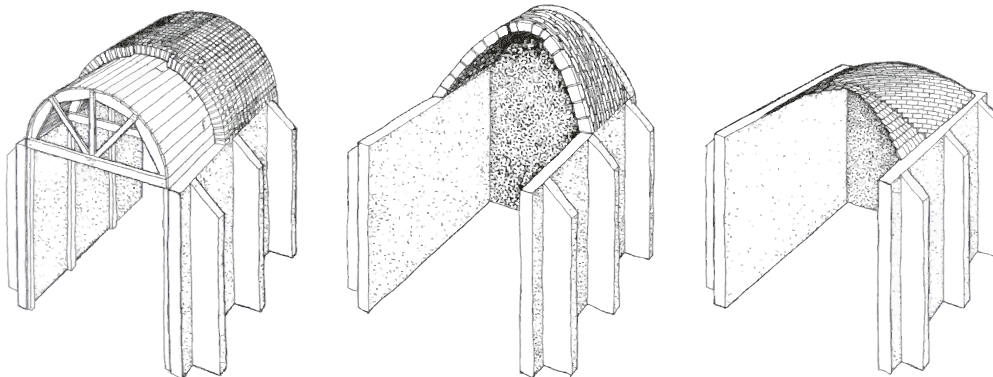
10 >> Ochsendorf, J. and Block, P. (2009). Designing unreinforced masonry. In E. Allen and W. Zalewski (Eds.), *Form and Forces: Designing Efficient, Expressive Structures*, Chapter 8. New York: John Wiley Sons.

11 >> Davis, L. (2010) Building the SUDU. <http://sudu1construction.wordpress.com/>

12 >> Hebel, D. *The Vernacular Rediscovered: Applying Local Construction Technologies and Materials in Ethiopia*. Ed. Ruby I. & A., Reinventing Construction, Ruby Press, Berlin, 2010.

13 >> Hebel, D. (2010) Appropriateness is a moving target: The re-invention of local construction technologies and materials in Ethiopia. *Journal of the African Technology Development Forum (ATDF) – Special Issue on Architecture for Development*.

14 >> Ochsendorf, J. (2010) *Guastavino Vaulting: The Art of Structural Tile*. Princeton Architectural Press, New York, NY.



the most significant hidden costs in the construction of vaults. Reduced formwork and scaffolding strategies are critical in Ethiopia, to reduce both cost and excess timber consumption. The other methods may be considered as “appropriate building technologies” in Ethiopia, and may complement a multi-faceted approach to the enhancement of vernacular construction techniques. This comparative study is intended to articulate the technical benefits, requirements and challenges of each, so that the resource constraints and site conditions of localized contexts may be taken into consideration when assessing their suitability. The following analysis is based upon lessons learned empirically through the construction of the Sustainable Urban Dwelling Unit (SUDU) at the EiABC.<sup>11-13</sup>



d >> Form and masonry pattern for typical double-curved 1) Timbrel vault; and 2) Leaning brick vault (groins marked red).

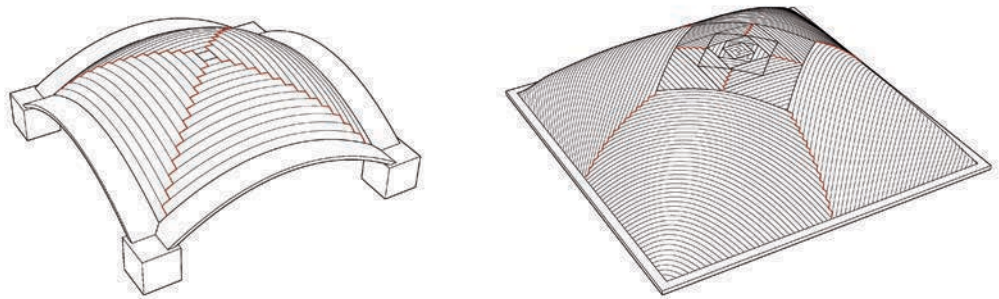
e >> Methods enabling formwork-less construction: 1) Timbrel vault gypsum adhesion; and 2) Leaning brick vault form/unit geometry.

f >> 1) Deep catenary geometry (compression above; tension below), 2) Shallow catenary geometry, and 3) Shallow funicular geometry for a timbrel vaulted floor system (note that the influence of the loading of fill in the floor system creates a funicular, but no longer catenary, geometry).

g >> Rafael Guastavino standing on a newly built arch during construction of the Boston Public Library, Boston, Massachusetts, 1889;<sup>19</sup> 2) Completed vaults; 3) Guastavino Rib and Dome System, New York, 1902.<sup>20</sup>

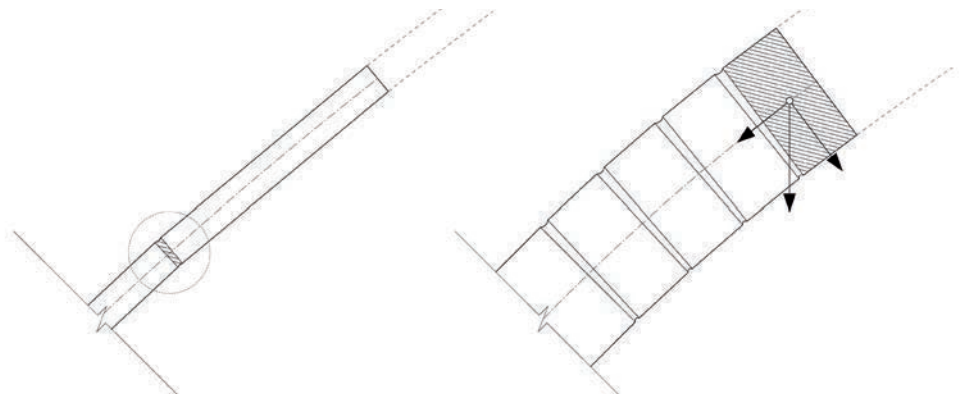
Timbrel vaulting also known as Catalan, Guastavino or thin-tile vaulting ( $c_3$  >>) is a historical Mediterranean technique which has made use of thin ceramic tiles for structural vaults, in which minimal centering is required during construction. The success of this technology, which has flourished in Spain since the 15th century and was also successfully imported to the United States by the Spanish architect and engineer, Rafael Guastavino<sup>14</sup>, is thanks to its extremely cost effective nature, given the context of a lower cost of labor and a prudent practice of building with local material. This system typically employs three layers of thin brick, the first of which is set with a fast-setting Plaster-of-Paris mortar, with subsequent layers built with a conventional cementitious mortar. The bricks are typically only 3cm thick, and the tiling pattern of each layer is rotated 45 degrees to break continuous joints between layers and to establish a sandwich of strong structural bondings. With long spans, high load capacity, and fire resistance, these structures are a cost-effective solution to spanning space.

Originally a Nubian vaulting construction technology c.1200 BC ( $c_2$  >>), which was developed just over 1000km from modern Ethiopia, this ancient vaulting technique was rediscovered and first introduced to Mexico by Hassan Fathy in 1980.<sup>15</sup> It was subsequently combined with traditional Central American vaulting techniques and adapted into its present form of Mexican leaning brick vaulting as practiced by the builder-architect Alfonso Ramirez Ponce.<sup>16</sup> Leaning brick vaulting is so named because, like Nubian vaulting, it employs full bed bricks which are laid face-to-face, to 'lean' into the cross section of the vault.



d >>

The primary distinctions between Nubian vaulting and Mexican leaning brick vaulting are the geometry and order of sequence in construction. Leaning brick vaulting is distinctive in that double curved vault forms are always begun from the corners, and worked progressively inwards to create groins where each corner 'squinch' meets ( $d_2$  >>). Most other vaulted types, including thin-tile vaulting, have groins which occur along 'diagonals' of masonry ( $d_1$  >>); whereas the groin of the leaning brick vault is turned 45°, to terminate at the mid-point of a span.

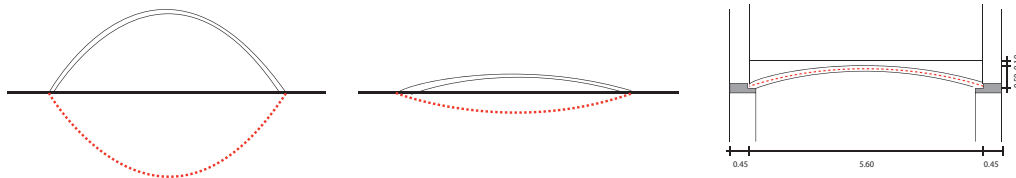


e >>

Vault curvature for either method may be single or double curved and adapted to a number of boundary conditions for various design considerations. On the whole, timber vaulting has greater formal flexibility, which, provided the mastery of the technique by more experienced builders, may be adapted for a broader range of design criteria (i.e. leaning brick vaulting is more commonly provided with continuous edge supports).<sup>(d<sub>2</sub>>>)</sup> Similar methods of light guide-work may be employed for both techniques. Note that “guidework” indicates a non-structural guide which describes for the mason where a surface must lie, whereas “formwork” indicates that the centering has a load-bearing capacity. For a single-curved vault, for example, two rigid arch profiles may be positioned at opposite ends of a space and connected with mason’s lines. Formwork-less construction is made possible in timber vaulting by the gypsum mortar, which adheres two sides of a thin-tile masonry unit to a masonry surface, holding it in cantilever until each masonry course is closed to insure its stability ( $e_1$ >>). Yet in leaning brick vaulting, it is primarily the ‘leaning’ geometry, along with the low weight of the masonry unit (1.5 kg / brick with typical dimensions of 10x20x5cm), that enables formwork-less construction ( $f_2$ >>). Each closed course then establishes stable sections, which prevent masonry units from sliding.

### VAULT DESIGN : SIMPLE STRUCTURAL PRINCIPLES, DESIGN TOOLS & RULES

The structural form of vaults for both techniques is funicular; it is able to resist the design loads and its self-weight, in pure axial compression. The hanging chain, taking the shape of a catenary, has a funicular geometry, which acts in pure tension under its own self-weight. The inverted catenary – the funicular arch with constant thickness – acts in pure compression rather than pure tension ( $f$ >>). The generation of a funicular vaulted form can either be accomplished by tracing a hanging chain at 1-to-1, or by a system of geometric rules for approximating a catenary.



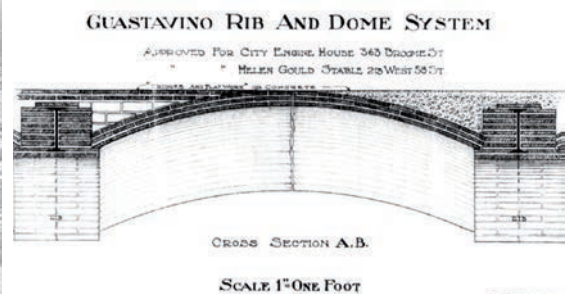
f>>

Leaning brick and timber vaulting allow for the construction of compact, efficient floor systems – such as that developed by the Guastavino Company ( $g$ >>)<sup>17,18</sup> – which may be used for multi-story construction. Since stresses are low within funicular vaulted structures, soil tiles with low material strength can be used, bending reinforcement can be omitted, and tension ties can be minimized.

A compression structure thrusts outward as its self-weight accrues and is directed through its geometry. This can be represented by a ‘line of thrust’, which is a theoretical line, describing the path of compressive forces through the masonry vault. This line of thrust, which has a catenary geometry (i.e. the shape of a hanging chain) only when the loading is proportional along



g>>



15 >> Alfonso Ramírez Ponce, *Curvas De Suspiro Y Barro. El Ladrillo Recargado: Una Técnica Milenaria Y Moderna.*

16 >> Alfonso Ramírez Ponce and Rafael Ramírez Melendez, “Curves of Clay: Mexican Brick Vaults and Domes”, pp. 143-154 in *Nexus V: Architecture and Mathematics*, ed. Kim Williams and Francisco Delgado Cepeda, Fucecchio (Florence): Kim Williams Books, 2004.

17 >> Morales, R. A. *Bóvedas Mexicanas.*

18 >> Ochsendorf, J. *ibid.*

19 >> Boston Public Library, Print Department.

20 >> Guastavino/Collins Collection, Drawings and Archives, Avery Library, Columbia University.



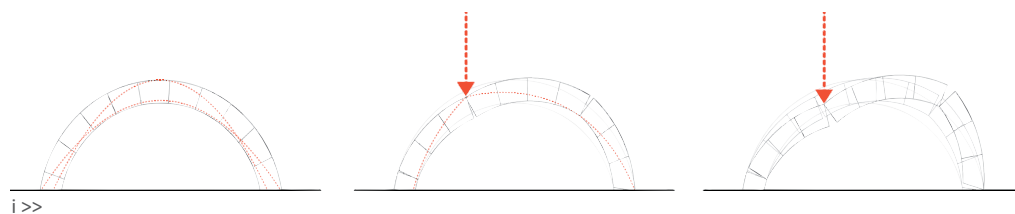
h >> Unreinforced timber vaulted floor system of the SUDU housing prototype: a) simple, single-curved barrel vault with stiffening diaphragms, to be stabilized with a pumice/lime fill.

i >> Masonry behavior (after J.Heyman):<sup>21,22</sup> 1) Maximum and minimum thrust lines which fit within the cross-section of masonry; 2) asymmetrical loading within cross-section of material; and 3) asymmetrical loading exiting material, to form a failure mechanism

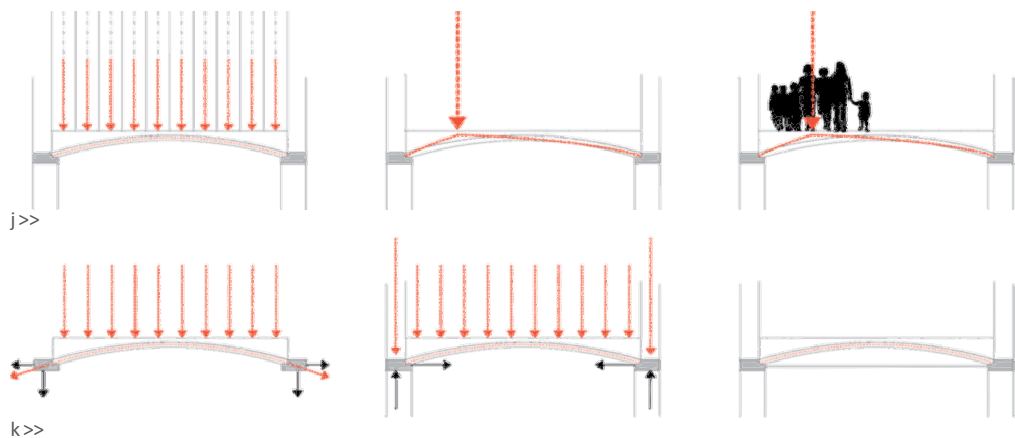
j >> Loading diagrams: 1) self-weight, 2 & 3) asymmetrical loading within cross-section of the floor system

k >> Thrust diagrams, 1) thrust of vault, 2) required reaction forces, 3) steel tension tie to resolve outward thrust

the center line of the arch, must travel through the cross section of masonry for a compression-only vault to be stable ( $i_1 \gg$ ). Heavy asymmetrical loading, for example, from a group of people standing on only one side of the vault, alters the position of a thrust line, and may result in a solution which no longer fits within the thin section of the vault ( $i_2 \gg, j_{2,3} \gg$ ). Thus, stiffening diaphragm walls and stabilized fill on top of the vault are needed to give additional structural depth to the vault, while providing a horizontal surface for a second story. Though typically either diaphragms or stabilized fill is used in such a floor system, the structural redundancy of this combination provides a safety factor against construction error and lower quality construction materials (e.g. soil elements which have absolutely no capacity for bending).



The floor fill furthermore adds self-weight to the vaulted floor system, so that the effect of point loads remains small. The diaphragm stiffeners and fill provide alternative load paths for point or asymmetrical loading and distribute these loads over a larger area of the vault. Diaphragms are critical structural components for a barrel vault. Such vaults have the important advantage, on account of their single curvature, that they can be easily geometrically described for construction. On the other hand, they are more vulnerable to asymmetrical loads than a double-curved vault, as the loads can only be carried down to the supports in one primary direction. A deep funicular structure has less horizontal thrust. A shallow form, with a greater horizontal thrust, must be resolved by providing steel tension members to tie back the vault ( $k \gg$ ). Regardless of the design requirements for tension ties, a vaulted structure can only be safe when stable, inflexible boundary conditions are provided.



### TIMBREL VS LEANING BRICK VAULTING: A COMPARATIVE ANALYSIS IN ETHIOPIA

The many parameters which vary between these two techniques – structural, material, constructional and tectonic – may be studied as elements in a cost-benefit equation, as a function of local human and material resource availability. Criteria for structural performance include, general structural efficiency of the system (e.g. thrust value) and resistance to asymmetrical live-loading. Material criteria include, mortar type and soil properties for the masonry units. Constructional criteria include, ease of masonry block production, guidework method, error margin for laborers, and stability during construction, speed of construction, and cost of labor.



Tectonic and typological criteria include, appropriateness for multi-story floor or roof systems, capacity for higher degree curvature (single/ double), and formal adaptability. It should be noted that this is not a comprehensive list of challenges associated with vault construction in the developing world context – including site conditions, waterproofing, and seismic concerns – which the authors have previously addressed.<sup>23</sup>

## STRUCTURAL EFFICIENCY

Generally speaking, leaning brick vaulting is more structurally efficient. The height to span ratio, according to Ramirez Ponce's rules,<sup>24</sup> produces a steeper form. Thus, its load action transmits more vertically, with a horizontal thrust smaller than that of timbered vaults. This means that it may be designed so that no or minimal reinforcing is needed to tie back the outward thrust of the leaning brick vault. It is, however, less efficient as a floor system for multiple story buildings, due to the deeper vault form (e.g. the greater total vault surface and floor height requires additional vault and fill material). According to Ponce's rules, which are formulated in part to insure that formwork-less construction is possible, the leaning brick floor system can only reach a reasonably shallow rise and floor depth if the span is small or if an intermediate wall or beam system is provided (e.g. vaulting between steel I-beams). Thus a leaning brick floor system of shallow rise could require, depending upon the span, much more steel than timbered vaulting. Timbered vaults, the naturally shallower structures, transmit greater horizontal thrust, yet use less material as a floor system. Tension ties are sufficient to tie in the thrust of the timbered vaulted floor system, mitigating the need for a more pronounced steel support. As steel is the greatest component expenditure for masonry construction in the Ethiopian context, this material expense governs the economic sustainability equation. Thus, the timbered technique may be advantageous where it is necessary to have shallow floor systems. The leaning brick vaulting technique may be more appropriate for roof systems, with its deeper structural system and greater double-curvedness, conferring more advantage against asymmetric loading.

## SOIL SELECTION & TILE PRODUCTION

The manufacture of stabilized soil tiles requires intensive study of the quality and properties of local soils, including particle fraction, clay fraction plasticity and stability (expansiveness and shrinkage). The authors will refer here to the excellent, comprehensive manuals on soil selection and CEB block production produced by CRATERre EAG, and will treat this complex subject only as it applies to the comparative analysis.<sup>25,26</sup> The most stable soils for CEB's have a very robust and well-distributed skeleton (gravel and sand) to prevent silt and particularly clay par-



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21 >> Heyman, Jacques, *The Stone Skeleton: Structural Engineering of Masonry Architecture*. Cambridge University Press, Cambridge, 1995.

22 >> Block, P., DeJong, M. and Ochsendorf, J. (2006). As hangs the flexible line: Equilibrium of masonry arches. *The Nexus Network Journal* 8 (2), pp. 13-24.

23 >> Block P., DeJong M., Davis L. and Ochsendorf J. *ibid*.

24 >> Alfonso Ramirez Ponce, *ibid*.

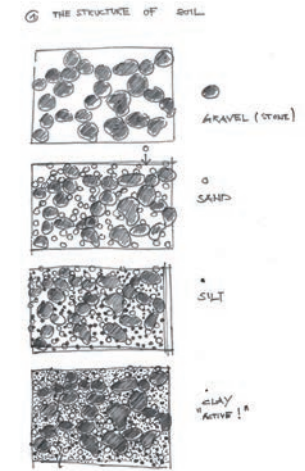
25 >> Rigassi, V. and CRATERre-EAG (1985) *Compressed Earth Blocks: Volume I. Manual of production*. A Publication of the Deutsches Zentrum für Entwicklungstechnologien - GATE in: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH in coordination with BASIN.

26 >> Guillard, H., Joffroy, T., and Odul, P., CRATERre-EAG (1985) *Compressed Earth Blocks: Volume II. Manual of Design and Construction*. A Publication of the Deutsches Zentrum für Entwicklungstechnologien - GATE in: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH in coordination with BASIN.

I >> Field testing of various soil types and mix proportions ("cake test" for a comparative measure of shrinkage)



m<sub>1</sub>>>



m<sub>2</sub>>>

m<sub>1</sub>>> Soil samples from the Amhara region; m<sub>2</sub>>> testing for adequate sand/gravel skeleton for stable block production. (Image credits: LKD, drawing by Benjamin Stähli, PB)

n >> Soil bricks produced at ZOMA Contemporary Art Centre, Harla Village: 1) Full-bed adobe bricks; and 2) thin-tile masonry units (for timbrel vaulting).



n >>



articles from expanding. Clay should be minimized for cement stabilized tiles, providing only sufficient adhesion for bricks before curing, because the cement stabilizer binds with gravel and sand particles. Overly clayey bricks are prone to expansion, contraction, and associated cracking when exposed to moisture variation.

Soil masonry units are generally compressed with hand or hydraulic presses and stabilized with a typical 5-13% inclusion of cement. Particularly applicable for this comparative analysis, the production of very thin tiles is much more difficult – timbrel bricks are brittle and prone to fracture before curing. The robust dimensions of the leaning brick block, however, save time and labor with less statistical breakage. Additionally, since timbrel vaulted systems are a sandwiched composite of many smaller masonry units, more masonry units must be produced, cured, prepared and then laid onto a masonry surface to cover the same surface area of a leaning brick vault, a more massive brick construction system. This indicates the inherent efficiency of leaning brick vaulting with respect to the speed of construction and thus cost of labor. Nevertheless, the extremely low cost of labor in Ethiopia, and the valuable investment of labor for job creation, could make optimizing this factor counter-productive in many respects.

### MORTARS

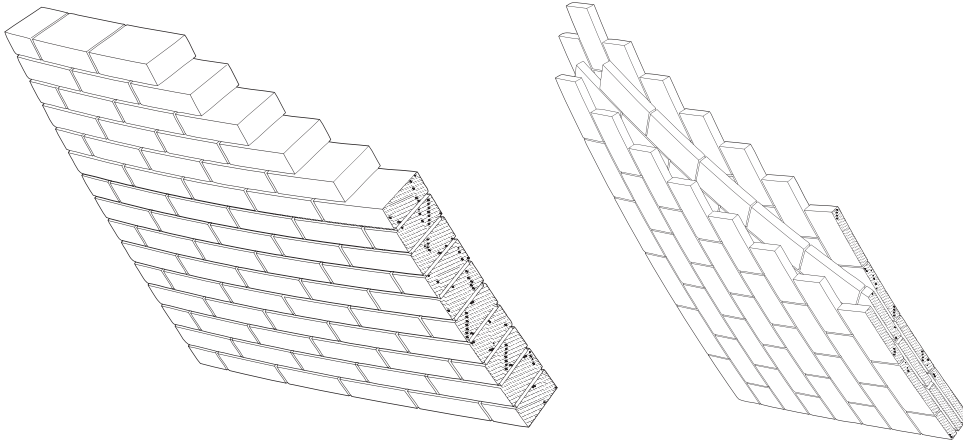
Timbrel vaulting relies upon the availability of fast setting gypsum mortar, which is needed to set the first layer of tiles. Since it is typically not readily available on the market and must be custom-produced by a manufacturer to meet the material requirements and specific properties for speed of setting essential for the technique, it is thus expensive in comparison to even typical cementitious mortars (sand, cement, lime and water). While most industrial scale production of gypsum is currently concentrated in Addis Ababa, the cost of the material could eventually decrease if and when industrial plants become more available in rural regions, or if partnerships are developed with smaller scale manufacturers. Leaning brick vaulting, on the other hand, has the advantage of not using a gypsum mortar. Either a readily available cementitious mortar may be used, or even mud mortars with sufficient adhesive properties would suffice.

It is necessary to maintain cohesion between the various layers of a vault with consistent expansive properties of masonry bricks and mortars, both in beds between masonry layers and joints between the masonry units. For this reason, cementitious mortars are typically utilized for the upper layers of a timbrel vault, incurring yet further expense with respect to mortar. Also on account of the sandwiched structure of timbrel vaulting (and the bedding between each layer), it is evident that the proportion of mortar to masonry blocks, and the total amount of mortar used, is greater. In any case, the potential for the use of mud mortars in the leaning brick method confers greater advantage in resource efficiency and overall expense.



## SKILL, EXPERIENCE AND TOLERANCE FOR ERROR

The first layer of timber vaulting is very thin, and laid in cantilever; thus, this technique is relatively error-prone for unskilled laborers who have insufficient experience to accurately achieve its funicular geometry. For instance, if there is a local flattening or region of negative curvature built in error, this section of masonry can cause failure mechanisms induced by local bending. Because timber vaulting relies upon the tensile capacity of the mortar for stability during



o >> construction, rather than the geometry of the vault, masons must follow very careful rules of sequencing to insure stability before each masonry course is closed. If masonry is not laid carefully in stable sections, it is prone to collapses. The first and only course of leaning brick vaulting, essentially full bed bricks (q >>), immediately confers a greater thickness; this method thus accepts error more readily, as the initial load path has a greater cross section to move within. Additionally, because leaning brick vaulting is stable during construction more so on account of its geometry than of its material property, its construction-phase stability is more optimal. While nevertheless demanding attention to stable building sequencing, leaning brick vaulting has inherently more tolerance for error than timber vaulting.

o >> 1) Timber masonry systems (3 layers with thin-tile bricks); and 2) Leaning brick systems (1 layer with modified full bed bricks).

p >> Teaching vaults: 1) Timber vaulting; 2) Nubian vaulting.

## CONCLUSIONS: WEIGHING EFFICIENCIES



p >>



## CREDITS

The Mapungubwe National Park Interpretation Centre, South Africa was designed by architect Peter Rich of Peter Rich Architects, in collaboration with Michael Ramage, James Bellamy, Henry Fagan, Anne Fitchett, Matthew Hodge and Franz Prinsloo, as well as one present author (Block).

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In terms of the application of floor systems for multi-story construction, timbrel vaulting provides the best-fit solution. This floor system, with a shallow structure and a reduced floor height, is more economically feasible; since it requires much less material than that (is) needed for a leaning brick floor system. Timbrel vaulting is also advantageous with respect to its formal flexibility. In terms of structural efficiency, ease of tile production, efficiency in mortar use, minimization of most critical cost factor (steel), tolerance for error and stability during construction, it is evident that leaning brick vaulting provides the best solutions. An insightful compromise may, however, combine the two systems within one structure, such as in the example of the SUDU prototype (r >>). Towards these aims, the SUDU has served as an applied research project, which has tested the application of these two appropriate building technologies in a context-specific manner.

It is evident, however, that we must better qualify the descriptive “appropriate building technology” for developing countries, and carefully interrogate the criteria for “sustainable” construction technologies in Ethiopia. While such terminology is used to frame the problem of economical construction practice in resource-constrained contexts, it radically oversimplifies the complex dynamics of human and material resource constraints as they apply to new technologies. In comparing material efficiencies, structural efficiencies, and labor-based efficiencies, a reductive logic cannot determine what is the best-fit for any given locality. In rural Ethiopia for example, it is not necessarily natural resource scarcity, but constraints with respect to infrastructure for production, supply and transportation of building materials, which govern the logistical and economic challenges for construction. Since import and material transportation comes at tremendous cost, material constraint becomes highly localized. This contingency upon local conditions requires a multi-faceted and flexible approach to adapt to available material, labor skills, and the constraints of a given locality. One must proceed then, along careful lines to understand what the critical efficiencies are. Whether constraints consisting primarily of capital, material, energy, transportation infrastructure, or skilled labor, extremely local cost-benefit analyses are necessary to ascertain which constraints (and which design goals), most govern the “sustainability” equation in all of its economic, environmental, social, and political



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facets. When the design goals are identified, such construction technologies may be used as flexible tools to respond to conditions of constraint, to mobilize labor economies in production, manufacture, and construction, and to generate modest but desirable outcomes in critical investments for rural Ethiopian towns. >>

q >> Teaching vault: Leaning brick vaulting

r >> SUDU 1) 1st floor Thin-tile vault, 2) 1st floor vault and 2nd floor Leaning brick vaulting, c. SUDU Sectional drawing –Composite of type

s >> Material transport in rural Ethiopia (Image credits: Benjamin-Stähli)



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unreinforced thin-tiled floor system of the SUDU housing prototype



