TILE VAULTED SYSTEMS FOR LOW-COST CONSTRUCTION IN AFRICA

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Abstract:

This paper discusses the potential of tile-vaulted structural systems to provide sustainable and low-cost construction for Africa, based on experiences both in academia and practice.

The proposed tile vaulting building technique adopts an unreinforced masonry construction method with a 600 year tradition in the Mediterranean, where the bricks have traditionally been made from fired clay. [1] The technique is now combined with the local tradition in Africa of cement-stabilized, soil-pressed bricks, which use locally available soil. In this context, Social and economic concerns were jointly addressed with local leaders and inhabitants to ensure that the structure is relevant to the local culture and successfully implemented. The proposed vaulting technique has the potential to meet three primary objectives: to provide an environmentally-sound building solution using mainly local materials, to engender social cohesion and pride within the local communities by drawing upon traditional methods, and to stimulate economic growth by providing local jobs, while reducing dependence upon imported materials.

Keywords: tile vaulting, soil-pressed bricks, low-cost construction, capacity building

1. Introduction

With an annual growth rate of almost 7%, Ethiopia is one of the fastest growing countries worldwide, yet it also remains among the poorest ones. In 2008, Ethiopia was home to approximately 81 million people and by 2025 this number could reach more than 125 million. There is an immediate need to enhance indigenous construction capabilities and create more awareness of the economic value of local materials to meet the urgent need for housing. This is of particular concern to poorer areas, where dwellings are often constructed from corrugated metal. These dwelling units cannot be expanded upon for multi-story construction, yet sprawl outward, consuming limited resources including wood, expensive imported materials, and land (Figure 1). Innovative solutions are necessary to address these pressing issues in a sustainable manner, considering the shortage of building materials, economic resources, and skilled labour. While the urgency for action might be extreme in Ethiopia, its socio-economic conditions are nevertheless comparable to other parts of Africa and throughout the developing world.

Historical methods of vaulting have remained economically viable in the contemporary construction markets of Spain and Mexico, mainly because tile-vaulting is also being reinvented as a contemporary construction technology [2]. One such example, the Mapungubwe National Park Interpretive Centre in South Africa, which was built using tiles pressed from local soil, was named the World Building of the Year at the 2009 Architecture Festival [3, 4]. The impressive forms of the Mapungubwe vaults demonstrate the elegance of the design possibilities using structural tile (Figure 2.a), and even more extravagant forms are possible. More recently, a similar methodology was used to build a prototype vault for a more modest (and more repeatable) tile floor system in Ethiopia (Figure 2.b). [5, 6] These two buildings signify the re-emergence of a technology, which could provide a solution to sustainable low-cost housing.

Fig. 1. b-c a) Traditional dwellings/huts as they can be found in rural Ethiopia (Amhara region); and two versions of newly built houses: b) built with found corrugated metal, and c) with Eucalyptus wood and plastered mud with a corrugated metal roof.

Fig. 2. a) First completed vault of the Mapungubwe project in South Africa (Image credit: James Bellamy); b) Unreinforced thin-tiled floor system of housing prototype for Ethiopia: simple barrel vault with stiffening diaphragms (Image credit: Lara Davis).

This paper discusses the potential of tile-vaulted systems which make use of local material, and follow the tradition of compressed earth block (CEB) construction in Africa to meet the need for more sustainable construction technology in the field of low-cost housing.

An introduction to the structural and construction principles of tile vaults will be presented, followed by a discussion of the engineering advantages and challenges of tile vault construction. Ethiopia will serve as a case study to exhibit the challenges of implementing this historic construction technology in a rapidly urbanizing society.

2. Tile vaulting: Origins, methods and structure

2.1. Origins and method

To construct a brick vault between parallel walls, one of several different vaulting methods may be considered (Figure 3). European-style vaults (Figure 3.a) would provide a durable solution from local materials, though excessive formwork (centering) should be avoided to protect scarce timber resources in many African locations. Mediterranean tile vaulting (Figure 3.c) makes use of thin ceramic tiles for structural vaults in which minimal centering is required during construction. This type of construction flourished in medieval Spain, and was successfully imported to the United States by the Spanish immigrant, architect and engineer, Rafael Guastavino (1842-1908). [1] The R. Guastavino Company built thousands of thin-shelled masonry vaults in the late 19th and early 20th century, including such prominent buildings as the Terminal of Grand Central Station and the Cathedral of St. John the Divine in New York City and the Boston Public Library. With high load capacity, fire resistance, and long spans, these structures were a cost-effective solution to spanning space.

Tile vaulting is a construction technology requiring little to no formwork as well as minimal material for the shell. The technology was developed during a period in which building with local material was a necessity, and not

Fig. 3. Three methods of brick vault construction [7]: a) Northern European vaults require extensive wooden centering; b) pitched brick vaults, built in North Africa and Mexico, eliminate the need for centering; and c) Mediterranean tile vaults may be constructed without centering.

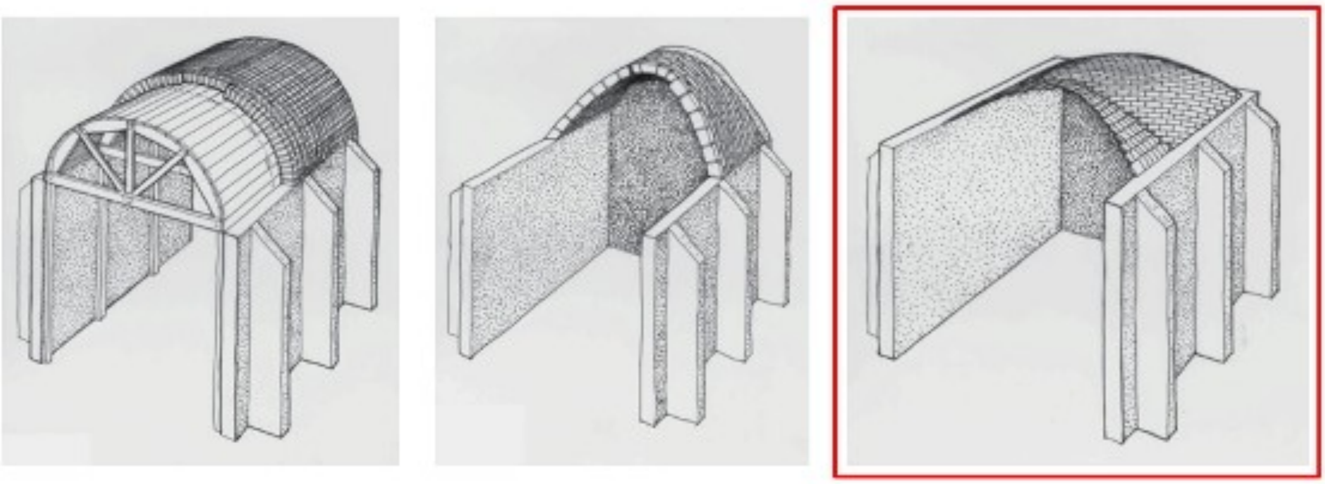
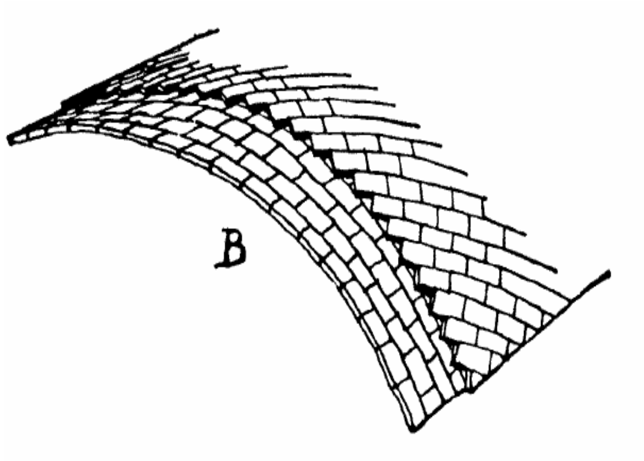


Fig. 4. a) Layered tile construction at Mapungubwe (Credit James Bellamy) b) Tile vaulting, built from multiple layers of thin bricks laid flat [9]



merely fashionable. Such frugal practice is rapidly becoming a necessity again. This system employs typically 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 typical cementitious mortar. The tiling pattern is altered in each layer to prevent tile joints from being continuous between layers and to establish a strong structural bond (Figure 4). The flat bricks are typically 3cm thick.

2.2. Structural capacity

The layered tile vault can be remarkably thin when it has a suitable structural form. A funicular shape is the most efficient geometry to resist loads as it acts in pure axial tension or compression. One example of funicular geometry is the hanging chain, which acts in pure tension (with no bending moments) and takes the shape of a catenary under self-weight only. Bending moments require a great deal of material to carry loads, so structures without bending moments can be very thin. Another funicular geometry is created when the hanging chain is inverted. However, the inverted structure acts in pure compression rather than pure tension. Thus, the same catenary geometry may be used to form a funicular arch, which carries loads in pure axial compression for the specific loading condition, i.e. self-weight only [7, 8]. In order to develop arch action in this compression structure, the arch needs to be properly supported at its ends, able to resist the outwards “thrust”.

The proposed vaulting system takes advantage of funicular geometry to limit the amount of material required, and to avoid tensile reinforcements. Stresses are low within the structure, so soil tiles with relatively little material strength can be utilized. However, the geometry is only funicular for one specific loading condition, so the vaults must have additional support to account for other possible loading conditions. This is achieved for example by adding thin stiffening walls on top of the thin vault to give the vault additional structural depth (Figure 3.b).

Such a floor vaulting system is not entirely new. Indeed, the Guastavino Company was particularly successful with their very efficient floor system (Figure 5). Its reinvention in the African context is quite appropriate as it requires minimal steel reinforcement and formwork and makes use of readily available, low strength, soil materials. Most critically, it allows for a structurally sound, multi-story construction to address urban density.

2.3. An African floor system

For the vaulted floor prototype in Addis Ababa, the two different systems for stabilizing thin, funicular vaults used by the Guastavino Company (Figure 6.b), has been implemented. The left approach adds structural depth to the vaults by adding lightweight stiffening walls, and the right approach adds a stabilized fill. The latter does two things: it adds structural depth, but also adds extra weight to the floor system, causing asymmetric live loads to have less effect in comparison to the more dominant self-weight of the floor system. By combining the two systems, the stiffening walls can be made very thin, as they are stabilized by the compacted fill. The continuous fill furthermore prevents that the vault can is point-loaded locally, which is not recommended for single curvature vaults. Instead, these point loads are nicely distributed over an area of the vault and the stiffeners.

The material of the first thin layer of tiles is Trachyte stone, the same type of stone used for the interior of Cologne Cathedral in Germany, which has a high compressive strength (≈150MPa) and is locally available in Ethiopian quarries. This stone tile layer was laid with locally produced gypsum mortar, which was custom-produced by a manufacturer and burned at higher temperatures to meet our optimal requirements for the speed of setting. The vault was designed with the subsequent layers of soil masonry units, produced with a press and stabilized with an 8% inclusion of cement. Because the masonry vault is designed to have an efficient, funicular geometry (a catenary curve derived from a hanging chain, see Figure 7.a), the compressive strength required for these tiles is only 4

MPa. All masonry on the upper layers was laid with a cementitious mortar, a mixture of sand, cement, lime and water. The spacing between the tiles set with plaster was on average 4mm (varying between 1-7mm), and that between the tiles set with cementitious mortar was on average 8 mm.

The span of the structure is approximately 5.8 meters, with a vault thickness of less than 10 centimeters. This does not include the fill for the floor system, which is a lightweight, semi-hard composition of pumice and lime. The theoretical line of thrust, which represents the path of compressive forces through the masonry vault, must travel through the cross section of the masonry for the vault to be stable without tensile reinforcements. The vertical diaphragm walls of masonry, built at intervals of 0.9 meters, provide reliable, alternative load paths for the masonry vault, effectively resulting in a structural depth at the supports of the full rise of the vault (50cm). This becomes important when the vault is heavily asymmetrically loaded (e.g. a group of people standing on one side of the vault), resulting in asymmetric thrust lines which no longer fit in the thin section of the vault. It is very important to note that such diaphragms are critical structural components for a barrel vault, which has only a single degree of curvature. Single-curved vaults are very vulnerable for asymmetrical loads, particularly applied at the quarter point of the arch. A vault with double-curvature is more stable.

For this prototype housing unit, the vault was nonetheless designed as single-curved barrel so that no thrust would be directed into the terminal edges of the vault, in order to reduce the reinforced concrete edge supports and to allow stop the vault at any point to allow for a stair well to the second floor. A simple barrel vaulted shape also has as important advantage that the guidework for building the vault can be minimized to two stiff arch profiles on each side with strings tied between

Fig. 3. a) Rafael Guastavino standing on a newly built arch during construction of the Boston Public Library, Boston, Massachusetts, 1889. [10] b) Guastavino Rib and Dome System, New York, 1902. [11]

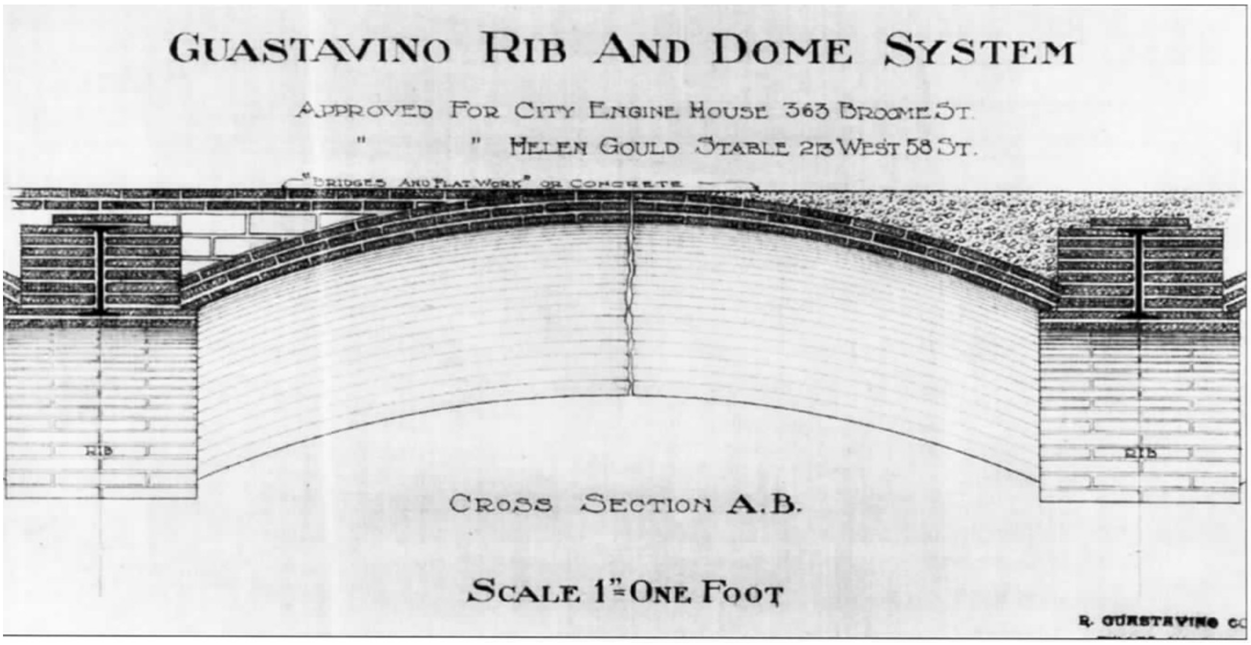


Fig. 6. Unreinforced thin-tiled floor system of housing prototype for Ethiopia: simple, single-curved barrel vault with stiffeners (Image credits: Lara Davis).

them (Figure 7.b-c).

A barrel vault needs linear edge supports to receive the horizontal thrust exerted by the vault. To avoid the transmission of these horizontal forces in the walls, the two reinforced concrete edge "beams" are tied back with four steel tension ties, spaced at intervals of approximately two bays.

For estimated sizing of the required tension ties and thickness of the vault at the crown, the following calculation can be used to calculate the horizontal thrust (H) in the vault,:

$$H = wL^2/8f,$$

where *w* is a linear, average line load representing the self-weight of the vault (including fill) for a 1 meter strip, *L* the vault span, and *f* the rise of the vault at midspan.

3. Implementation: Ethiopia as a case study for social context

3.1. Challenges of low-cost housing in Africa

In rural areas of Ethiopia, there is no sufficient building practice which would allow for the construction of towns to proceed with minimum standard, multi-floor living units. Many of these present dwellings – essentially vernacular huts – are still built incorporating traditional techniques such as mud plastering, known as "Chikapet" in Amharic (Figure 1.a). These vernacular construction techniques contribute to a fairly well-developed common knowledge base of the diverse local soils.

Current demand for new housing, however, is answered with the construction of poorly made shacks, assemblages of (eucalyptus) wood, straw and mud, utilizing sheet metal for roofs, doors, openings, and occasionally for walls (Figure 1.b-c). Inhabitants of rural areas resort to these fast, low-quality solutions, because of a lack of available building materials, constructional know-how, and financial resources. It is not unlikely that the local construction market is ignoring the needs of the inhabitants as many of them cannot afford to pay for the services they could. These constructions typically result in very low standard living conditions. The use of thin sheet metal with poor acoustic and thermal qualities for example cause extreme temperatures during day and night. These constructions furthermore do not utilize Ethiopian resources in a sustainable manner (e.g. the abundant use of wood contributes to deforestation and resulting erosion, a perennial environmental concern in Ethiopia with important, corresponding economic implications) [12]. An interesting phenomena is that the dependency on imported sheet metal has not only economic reasons. This inappropriate building component bestows upon the rural people a sense of 'quality' and assurance associated with modernity and development [13]. This building practice though precludes the possibility for safe, multi-story construction.

Fig. 7. a) Inverted hanging chain to find the shape of the compression-only vault, b) simple guidework and mason's line, and c) building the vault into space without the need for formwork (Image credits: Lara Davis).

Fig. 8. A selection of imported – hence expensive – building materials in current "low-cost" projects: a) Precision timber for formwork; b) precision formwork for columns and edge beams; c) interior panels (Made in China); and d) reinforcement steel and Portland cement for concrete.

3.2 Effective Low-Cost Housing

To make housing truly low-cost – with specific consideration to the Ethiopian condition – we must identify what makes traditional "low-cost housing" prohibitive by Ethiopian means. To this effect, elements of a low-cost construction need to be reduced even further in order to make low-cost housing accessible for low-income inhabitants.

Imported building materials commonly used in low-cost projects, such as steel, cement, and construction timber, are scarce in Ethiopia, both as natural resources and in terms of industrial manufacturing prevalence (Figure 8). Scaffolding and formwork for concrete construction are expensive, produce excessive building waste, and put strain upon the scarce natural resource of trees.

'Low-cost' for Ethiopia is classified as less than 1000 ETB/m² (≈ 75 USD/m²). Currently, large construction companies who are heavily subsidized by the government to build western concrete frame/slab construction dominate low-cost government housing. Low-cost housing is expensive because of the cost of imported materials. Compared to the Western paradigms they copy, the only improvement has been the use of precast ribbed beams and prefabricated concrete floor elements – again, both produced by heavily government subsidized programs – resulting in less concrete and simplified formwork. At the end, the cost of the housing provided by the government as 'low-cost' still costs the buyer 2500-3500 ETB/m² (≈ 185-260 USD/m²), and this after heavy subsidies on different levels.

In addition to the need for being more independent from imported materials and minimizing building waste, a 'low-cost' strategy also implies that the construction process should employ local labour. In Ethiopia, the workforce is large, unskilled, and mainly agricultural. Therefore, a structured training program (e.g. in form of formal apprenticeship) to impart the knowledge and practice of new building technique would allow for an upgrade in skills of the local workforce in constructing low-cost housing.

4. Appropriateness of tile vaulting in context

Soil and stone are the primary materials, which can be considered as sustainable in the Saharan/African context, where precision construction wood is often scarce. As stone or soil have limited tensile capacity, building with these materials demands compression-only structural solutions. For walls carrying dominantly vertical loads, this criteria is easily satisfied; however, once a space must to be spanned, beam elements, which work in bending, are typically required and can thus not be built using stone or soil, but in timber, steel or reinforced concrete – all materials that are not readily available in most parts of Ethiopia. A beam, as a structural system, demands that its section can accommodate tension and compression forces, which is not possible when building in stone or soil only.

As outlined previously, structural vaulting provides a solution to this constraint by allowing for compression-only solutions to span space. There are different techniques to build compression-only vaults, but tile vaulting allows for the construction of compact floor systems with a depth of less than a tenth of the span, without the need for any formwork or internal tension reinforcements. Other techniques result in much deeper structures which are inefficient and economically unfeasible for multiple story buildings.

It is important to point out though that soil-pressed tile vaulting is not necessarily an appropriate building technology anywhere in the world. In places where wood or bamboo are not scarce, these materials may be much more sensible construction materials than earth-based architecture, particularly in seismic areas. Fired clay tiles may be preferred where clay is abundant because they are more durable. In Pakistan, for example, there is a tradition of baking bricks using small kilns, and custom bricks are produced in local kilns directly adjacent to the building site.

The proposed technology has the potential to generate successful local entrepreneurship that generates income and employment for the local economy. The structural elements can be produced by people from local commu-

Fig. 8. The floor system in the Mapungubwe project uses a) structural vaults as permanent formwork for b) a mass concrete floor. c) This floor can be built without formwork and significantly reduces the amount of reinforcement steel necessary. In the Mapungubwe project, the edge beams are made in reinforced concrete. (Image credits: James Bellamy.)

nities, and local labourers can easily be trained to master the constructional practices required. The main challenge is to set up the necessary institutions that support training programs and entrepreneurial activities and improve access to credit and investment. Furthermore, political and cultural aspects must be taken into account to enable such a building technology to take root on a regional scale, including the social, political and religious structure of local leadership.

Most importantly perhaps, the discussed vaulting method is not far off from achieving the very tough 'low-cost' limit set at ETB 1000/m². Taking data from previous projects and translating the costs to the Ethiopian context, the method is still 30-40% too high, but this is largely due to the dependency of the technique on the fast-setting mortar. This mortar is not available yet on the Ethiopian market and is thus costly. If such a vaulting method were to become standard practice in Ethiopia, the cost of this product would obviously be reduced.

5. Challenges of tile vaulting in context

5.1 Supervision and Training:

Abundant local labour is clearly a tremendous advantage in the implementation of a technology such as thin-shell vaulting. However, the lack of a reliable skill-base must be comprehensively addressed. Technology-related capacity building and training must be implemented at universities as well as in vocational training centres to guarantee a safe and durable transfer of technology and skills. It needs to be integrated into the curriculum of architects and engineers to design for these new technologies. Moreover, universities should collaborate closely with construction managers in the private sector to manage safe construction of such buildings and ensure quality standards.

This vaulting technique, which allows one to build out into space without any support, may give the false impression that there is no risk. The first basic level of tile vaulting is very easy to learn, yet this tremendous advantage may be deceptive or even dangerous. A brick laid does not necessarily mean that the bond is sufficiently strong to ensure that the position of the brick does not compromise the structural form, or that it does not propagate errors in tiling geometry, which require skill and time to correct.

The learning curve is quite steep when one considers all of the critical aspects of construction. It is extremely important, for example, to understand the sequence of construction. One must always build in stable sections, carefully following geometrical guides throughout the construction. A partial or full collapse may occur (and have occurred) when these important aspects are forgotten. A fully constructed masonry vault is structurally robust if designed properly, but certain states in the construction sequence are less secure than others. Thus, critical supervision, quality control, and a robust training program are necessary.

The authors recommend and have had good experiences with mockups to educate and train for further construction, and to provide the possibility for structural load testing. However, it is important to control those very carefully. An uncontrolled structural failure is unacceptable. On the other hand, it is important to be able to do full-scale load testing to give everyone involved the necessary confidence of this new construction and material combination. Therefore, the authors typically demand two full-scale prototypes to be built on site, the first one to be load tested to failure and the second to remain as a demonstration.

It is critical to address the repeatability and the tolerance of this system to unintended appropriation for the purpose of structural safety. Without the means to hire experienced professional supervisors, it is often unavoidable that others merely appropriate the technique and shapes of tile vaulting. To this end, the vaults at Mapungubwe were a daring precedent, as they are complex shapes obtained and verified with the latest 3D structural form-finding techniques [14]. Such forms cannot simply be repeated without some risk.

Nevertheless, by simplifying the form-generation method, the prototype may serve as a robust and repeatable model. The design of thin-tile vaults may be reduced to ultimately simple structural concepts and constructional methods. In the case of a single-curved vault, a hanging chain may be used to derive the geometry of the vault. This catenary geometry may then be used at the full scale to fabricate a simple, inexpensive, non-structural guide, which serves to describe the geometry of the vault for the masons. Construction may be repeated as a controlled sequence in 1m strips – including an additional diaphragm wall as stiffener for asymmetric loads – to construct a very simple, single-curved barrel vault. On account of this simplified vault form and constructional process, robust constructional systems could be more reliably copied and repeated.

5.2 Technical Challenges of thin-tiled vaulting in developing context

Because the tiles are made from local soils, locally available soils have to be assessed, as soil can differ significantly from location to location. Finding the correct soil and mix proportions is a fairly delicate matter, which depends largely on experience acquired through working with soils. There is a lot of knowledge of soils in Africa, but it is imperative that the "engineering" of the tiles can be controlled and verified. [15] and [16] give a comprehensive manual on how to select good soils for the specific purpose of making soil-pressed tiles, nevertheless, one cannot learn about handling a natural material merely from a book.

This addresses a critical concern regarding material testing. Simple procedures, standards and building codes need to be developed to test tiles, which should not be dependent on expensive laboratory equipment, which is often not readily available. The thin-tiled vaulting technique depends entirely on the use of fast setting mortar, or plaster of Paris, which is a special type of gypsum mortar. This material is typically not readily available and its specific properties are critical for the application of thin-tiled vaulting. Gypsum mortar is also in comparison quite expensive, as it is not a typical material for the construction process. In Addis Ababa, we worked with the plaster manufacturer to custom-produce in a separate batch for our unique material requirements. Of course, this cost could be reduced if demand rises due to a new market based on this technology.

If it is not necessary to have shallow vaults, other vaulting techniques which do not rely upon the fast-setting mortar should be considered. For a roof, deeper structural systems with greater double-curvature are in any case preferred to the asymmetric loads. The Mexican style vaulting technique (Figure 3.b), built with regular mortar, may be more appropriate for these cases. Waterproofing is a very delicate point which still requires a great deal of attention and further research. As the building materials are basically stabilized soil, special care needs to be taken to protect these materials from the natural elements. In the Mapungubwe project this was achieved by continuous layers of cement and tar. Obviously, local materials would be preferred if possible. Special care or even best standard detailing needs to be developed for key details such as gutters or overhangs.

Ethiopia is situated near a fault line in the Rift Valley, causing some parts of the country to be susceptible to moderate seismic action. However, throughout most of the country there are no building codes or requirements to account for seismic loading. In this context, building with 'advanced' materials such as reinforced concrete allows for the construction of taller structures and gives an impression of safety and technological progress. In reality, these buildings require advanced reinforcement design as well as quality construction and detailing. The results can be devastating. For example, the 1999 Kocaeli earthquake in Turkey caused the collapse of thousands of steel-reinforced concrete buildings, and the recent earthquake in Haiti underlines the importance of proper construction techniques to prevent fatal collapses. Thus, concrete frame buildings, although they are becoming popular in big developments in Ethiopian and African cities, must be built properly or they will not perform well should an earthquake occur.

Unreinforced masonry buildings also have a reputation for being susceptible to earthquakes, particularly if constructed poorly. Earthquakes may induce bending loads in vaulted structures which cause tensile stresses within the structure. Thin-tile vaults with single curvature have very little geometric resistance to bending and therefore very little material strength to resist lateral loading if their tensile strength is ignored. Thus, they have a relatively low seismic capacity, and construction of unreinforced tile vaults in high seismic areas should be avoided. However, in moderate seismic areas they remain a viable option if they are designed properly and reinforced as necessary.

To increase seismic capacity, the first option is to build vaults with double curvature. While these vaults may be more difficult to design and construct in some respects, and therefore require more skilled labour, the double curvature provides a cross-section with greater effective structural depth, which thus increases bending capacity and resistance to lateral loading.

For further seismic resistance, reinforcement may be necessary. Steel reinforcement is one obvious option, however, it is not optimal because it must be imported. Furthermore, it is particularly susceptible to corrosion in soil-pressed vaults which are more permeable than concrete. Alternative reinforcement methods are the subject of current research. One possible option is to place a geogrid mesh between the tile layers. Although geogrid also must be imported, it is lightweight, easy to transport, and provides the necessary ductility to allow tile vaults to withstand significant bending action without collapse. [17] Ideally in this context, techniques of natural reinforcement, which use locally available materials (e.g. hemp fibers, rice fibers, bamboo), could be used and are also being explored.

6. Conclusions

This paper has discussed tile vaulting as a viable, alternative construction system for low-cost construction for an African context, while offering the advantage of work for local labour, transmission of skill and material scarcity. As vernacular methods in earth construction are prevalent, this method would not merely suggest the use of local materials, but confer also the advantage of local material expertise. To this end, local labor and entrepreneurship may be mobilized, while enhancing the value of local knowledge and thus pride associated with vernacular construction.

The material economy and structural efficiency of thin-tile vaulting enables the construction of vaulted floor systems without the excessive use of formwork material. These structures, which may be rapidly built, have a capacity to answer the housing demand by being produced at the community level.

Realistic implementation of such methods may occur in various degrees to immediately impact local construction towards economically and environmentally sustainable means. Already, having a tile floor in a reinforced concrete frame structure is a significant improvement to the full reinforced concrete alternative, as it would remove the expense of formwork, reinforcement steel and the cement for the concrete. It might even be preferable in certain contexts to keep a reinforced concrete frame for seismic safety reasons.

We demonstrated the potential of tile vaulting as an appropriate building technology for Africa by designing and implementing a first prototype in Addis Ababa. This experience also confronted us with the multiple challenges related to such an approach. If tile vaulting is to be successfully implemented in building practice in a country like Ethiopia, a lot of further careful research and (controlled) experimentation is required.

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