V–2. Modern Applications of an Ancient Method of Roofing

Vilhelm Trier Frederiksen
Institute of Building Design
Technical University of Denmark

ABSTRACT

The vaulted roof of bricks is widely used in the Middle East and in the Mediterranean countries. Traditionally these structures are closely connected with heavy walls or buttresses. However, the curved structure with its stiffness combined with tension stringers along the edges can give considerable savings of materials. A pilot-project in scale 1:1 for university buildings in a developing country is discussed from an "Appropriate Technology" point of view. In the appendix is proposed a method of calculating yield-loads for unreinforced masonry shells.

La toiture voûtée maçonnée a eu une grande diffusion dans les pays du proche Orient et dans la region méditerranéenne. Traditionellement ces constructions sont liées aux murs épais ou aux piliers d'arcs-boutants. Cependant la raideur propre des voûtes combinée avec des barres de tension au long des bords peut signifier une réduction importante de la consommation de matériaux. On discute une construction expérimentale d'habitations pour une université dans un pays en voie de développement a base de "technologie appropriée". Dans l'appendice est proposé une méthode pour le calcul de charges de rupture pour des coquilles maçonnées non armées.

Gewölbte Dachbauarten aus Mauerwerk haben grosse Ausbreitung in den Mittelostgebieten und den Ländern um das Mittelmeer gehabt. Traditionell gehören diese Bauarten mit schweren Mauern oder Strebepfeiler zusammen. Indessen kan die Eigensteifheit der Bogen in Vereinigung mit Zugbändern der Kanten entlang bedeutende Ersparungen im Materialverbrauch geben. Aus Betrachtungen über "angepasste Technologie" wird ein Versuch im Skala 1:1 als Wohnungen an einer Universität in einem Entwiklungsland behandelt. Im Anhang wird eine Methode zur Berechnung der Bruchlast für unarmierte gemauerte Schalen vorgeschlagen.

La copertura voltata della muratura e molto usata nei paesi mediteranei e Medio Oriente. Secondo la tradizione questa costruzione e portata di mure pesante o di contrafforti. Ma la costruzione voltata con la sua rigidità combinata con armature concentrate lungo i bordi liberi puo dare risparmi considerabili di materiali. Un primo progetto a scala 1:1 per edifici universitari in un paese in corso di sviluppo e discutato da un punto di vista della tecnologia adattata. Nel appendice e proposto un metodo per calculare carichi di snervamento per involucri della muratura non armata.

INTRODUCTION

The ancient method of roofing by masoned vaults or cupolas either in burned bricks or natural stones is well known throughout Europe and especially in the Mediterranean countries. Whether it was a Roman invention or the Romans took it over from Africa or they refined an inheritance from the Nuraghes is not altogether clear. Whatever the origin, the method has been used ever since, not only in the sacred buildings of the Gothic but also for secular purposes as can be seen in Catalonic structures of our time. The most outstanding examples are the contemporary works of the well known Spanish architect Gaudi[1].

The method is also used today throughout the Middle East and North Africa, where both burned and sun-dried bricks are used for vaults and domes. In these arid areas the sun-dried brick vault constitutes a genuine alternative to wooden roof-structures in rural[2] and village surroundings[3]. In cities burned brick vaults have proved economic and practical in comparison with reinforced concrete slabs for roofs as well as horizontal divisions.

The traditional structures of vaults and domes are always combined with heavy wall structures or buttresses in order to transmit the horizontal component of the arch effect to the foundations. However, if one wants to do without these heavy structures a means is to be found to absorb the horizontal forces. Suitable means will be either cross ties or (when this is not considered applicable) rigid edge beams which can carry the load to gables, where either beams or embedded cross ties may produce the reaction. Several such structures have been made, all fitted with rather heavy (and heavily reinforced) beams because of large moment either horizontal at edges or vertical where two neighbour arches outbalance each other horizontally but give a large vertical moment[4].

However, the edge beams can be made much slenderer and also some reinforcement can be saved if the vault is considered not as an arch spanning between the beams, but as a shell supported at corners. In this case the prime purpose of the beams is to act as tension affected stringers holding the corners in place. Thus the structure through its corners delivers only vertical forces to walls or columns.

STAFF HOUSES AT NATIONAL UNIVERSITY OF LESOTHO (NUL)

In 1978 a contact to N.U.L. was established through World University Service (W.U.S.) which is an international organisation administering funds for educational purposes in developing countries. N.U.L. was about to start a project comprising two new institutes and at the same time was building a number of staff houses.

Lesotho, covering an area of 30,000 km^2, is an independent kingdom in Southern Africa and has the unique feature of being completely surrounded by another country—the Republic of South Africa. Lesotho is rated among the 13 poorest countries in the world. It lies between latitudes 28° and 30° south and rises from the lowlands at about 1,500 m above sea level to mountains of up to 3,400 m. The climate is warm temperate with well marked seasons. Main geologic features are sandstone mountains and fine clay lowlands. Thus climatically and geologically Lesotho resembles very much the countries of North Africa. Bricks and other ceramics are among the few productions taking place in Lesotho besides agriculture. The largest part of the GNP comes from the remittances of migrant workers in the mines of the Republic of South Africa. For construction purposes all material other than bricks must be imported from the Republic. That goes for cement, steel, to some extent aggregates and wood for formwork, all kinds of technology and skilled labour.

Hence W.U.S. found it both logical and feasible to introduce to Lesotho the North-African vaulted structures which are labour-intensive and at the same time saving on imported materials. Lesotho suffers from a rapid growth of population and a high rate of unemployment so it needs any boost of local production it can get.

Design

Since brick shells was a new and untested method of roofing in Lesotho it was decided to carry out a test in scale 1:1 by roofing two new staff houses which were to be built at the university campus. At the largest, a family house, the roof consisted of four shells, while at the smallest, a bachelor/couple quarter, the roof was a two-shell construction. All shells were 9.2 m long, including overhang, and 3.5 m wide.

The shell design comprised one layer of brick-on-edge (110 mm thick) with bed joints perpendicular to the cylinder generatrix. Over this was placed 25 mm polystyrole plates being spaced 30 mm from each other in order to create ventilation ducts. The second layer of bricks was placed on the flat side (75 mm thick) and given a glass fibre reinforced rendering of sand and cement, topped by a coat of cement-based paint (Figure 1).

Besides the structural purpose of the inner shell it serves as a heat accumulator, while the outer shell with rendering serves as shield against sun and rain, both of which are of great intensity in Lesotho.

The design of the beams is shown in Figure 2. The inner beam was poured in two sequences, leaving the upper rebar free until the shells were completed and the second pour could be done.

Construction took place during the dry winter time of August 1978. At the start of the shell construction the beams had cured for about two weeks. Prior to the bricklaying the beams were supported vertically by 100×100 mm timber, and horizontally by 12 mm rebars spaced two metres and tying the beams together. After the shells were finished and cured and thus had given the whole structure the required rigidity and stiffness, the provisional supports were removed. (Photo 1)

Two forms were used. Each being 900 mm "long" it supported 11 courses of bricks. While one form was being filled the other was removed, cleaned and wedged in place. Forms were removed as soon as the mortar had been sucked dry. After a couple of days the team of two bricklayers and one assistant was able to do four formsettings a day, corresponding to 13 m^2 covered area, time consumption thus being comparable to that of a normal half brick wall.

Economy

As far as economy is concerned, one cannot directly compare the actual costs for these roofs with European or American prices. On this particular site the monthly wages for skilled labour was about R.80 and for unskilled about R.60 (1.00 Rand corresponds to $1.10). These wages were among the highest paid in Lesotho. Prices on building materials are also substantially lower compared to European prices. However, the bids for the two staff houses proved to be quite interesting. A local contractor submitted a bid for two equal houses with corrugated sheet metal roofs amounting to R.28,000, while the winning price for the houses with roof shells in masonry was R.22,000. The difference in these prices is not significant though, because prices were for "turn key" houses including water and sanitation, electric installations, solar heating and decoration. But it shows that a fine and durable construction of local materials can compete with a less durable one of imported materials.

APPROPRIATE TECHNOLOGY

More important than the sheer price in Rands and Cents is the fact that the use of local materials (and labour) ensures that the money stays within Lesotho and may create more jobs. This applies especially to foreign aid meant for development purposes in Lesotho, and not (as quite often seen) for buying technology from the neighbouring, industrialized Apartheid South Africa.

Modern houses in Lesotho normally have roofs of either corrugated sheet metal or reinforced concrete. Compared to these roofs the brick shells represent an import saving of about 75%. The only local alternative is the thatched roof, which unfortunately is being ousted by corrugated metal.

CONCLUSION

The pilot project with vaulted roofs on the university staff houses showed the method to be suitable in Lesotho. It proved to be competetive as far as economy and time-consumption are concerned. In addition to this it represents advantages over reinforced concrete in import savings and job-creation, and over sheet metal in durability and esthetics.

The two new institutes, Institute of Labour Studies and Business Training Center, were designed with vaulted roofs. When the method sould be decided the Quantity Surveyor figured the cost of brick shells to equal that of the form-setting alone for reinforced concrete shells. The institutes are now under construction.

5. APPENDIX

Method of calculating uniformly distributed yield-loads for cylindrical brick shells[5].

It is assumed that the yield load is carried to the corners by diagonal arches with constant compression over the width b. (Some small parts of the load which cannot be transferred to the diagonal arches are carried to side beams by transverse arches, but this is not taken into consideration.)

If (Figure 3)

- p = load uniformly distributed over horizontal projection of shell
- w = width of shell (length of chord)
- ℓ = length of shell
- t = thickness of shell
- β = inclination of shell at edges
- R = vertical reaction at each corner
- b = width of the diagonal arches
- F = force along the diagonal arches
- σ = compression in the diagonal arches

then

$$R_w = \frac{p\,w\,\ell}{4\tan\beta} = \text{force along end-chords.}$$

$$R_\ell = \frac{p\,\ell^2}{4\tan\beta} = \text{force along edges.}$$

$$F = \frac{p\,w\,\ell}{4}\sqrt{1 + \frac{1}{\tan^2\beta}\left(1 + \frac{\ell^2}{w^2}\right)} = t\,b\,\sigma'$$

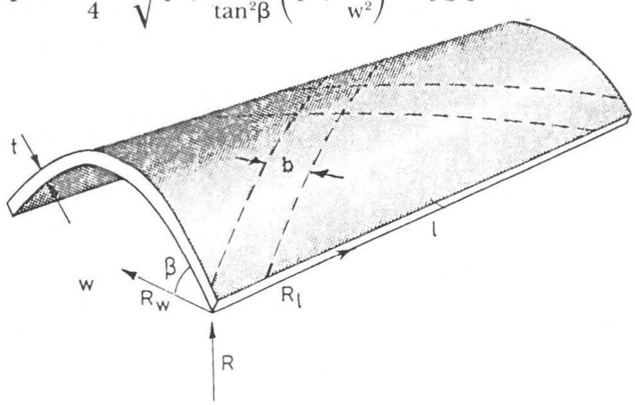

Figure 3.

b, the width of the diagonal arches (in which compression is assumed to be constant), has to be estimated. In Francker & Thomsen's report on laboratory tests[5] this is discussed in relation to the extent of cracks along edges. A width of about one tenth of the length ℓ seems to be reasonable.

To establish the failure compression, σ', one has to consider the bond and the angle, φ, between σ' and the bed joints (Figure 4).

Condition of failure in the bed joints:

$$\tau \leqq \tau_{oj} - f_j\,\sigma$$

Condition of failure in the brick work

$$\tau \leqq \tau_{ob} - f_b\,\sigma$$

Experimental values of τ_o and f are given in Reference 6.

Failure occurs at the minimum σ', either σ_j' or σ_b'. Point I represents failure in brickwork. II and III represent failure in joints ($\varphi_{II} \geqq \varphi \geqq \varphi_{III}$). For $\varphi > \varphi_{IV}$ failure will occur in the brick work (Figure 5). Coulomb's friction hypothesis is shown in Figure 5.

The laboratory tests showed that this method, however simple, gives good estimates of the bearing capacity of such shells.

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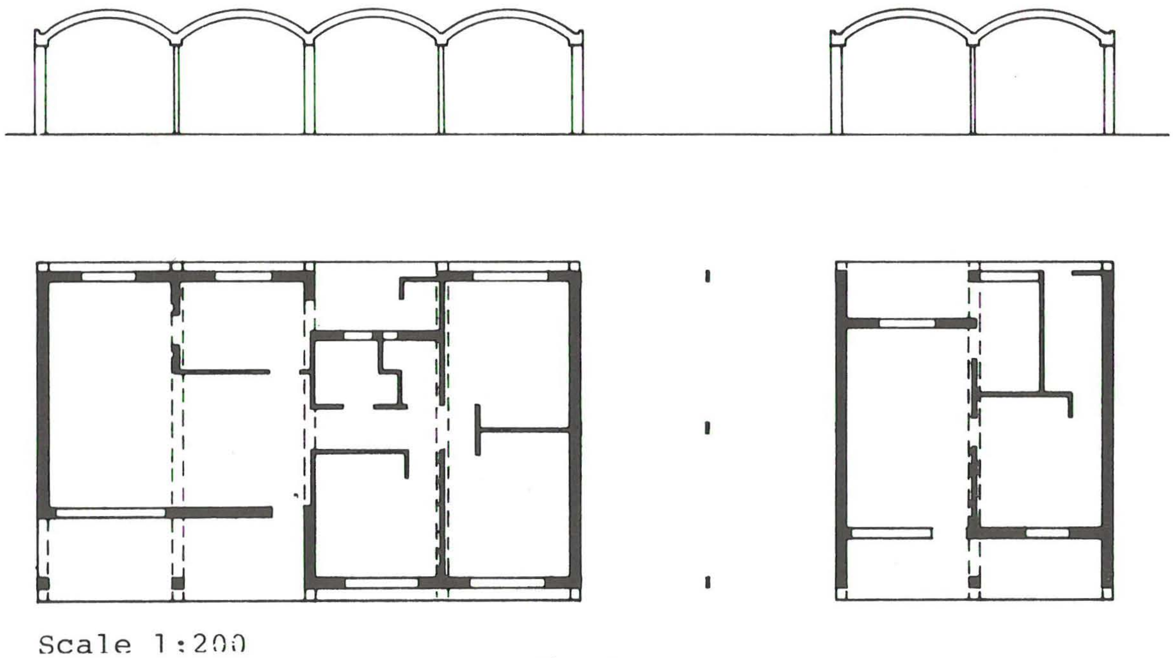

Figure 1.

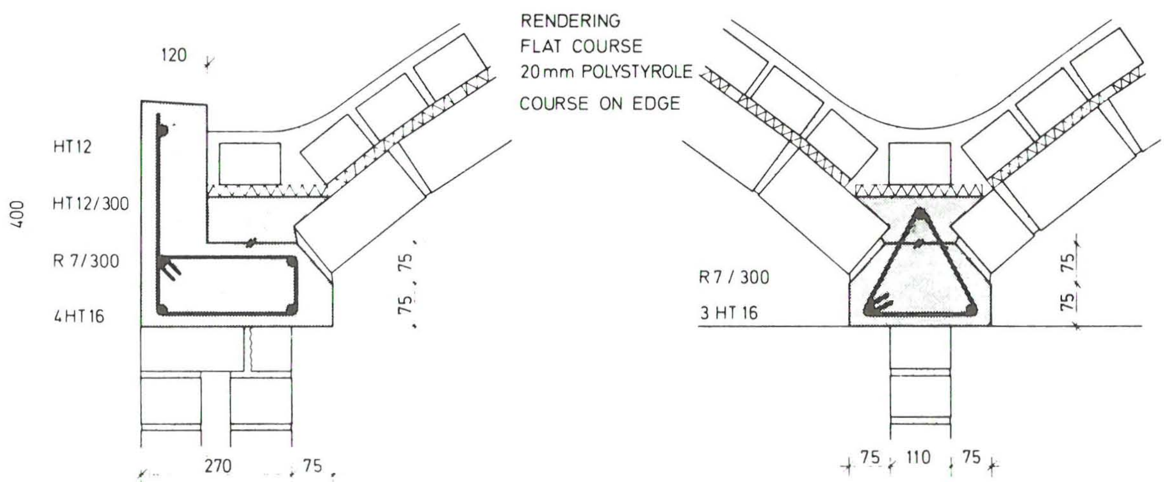

Figure 2.

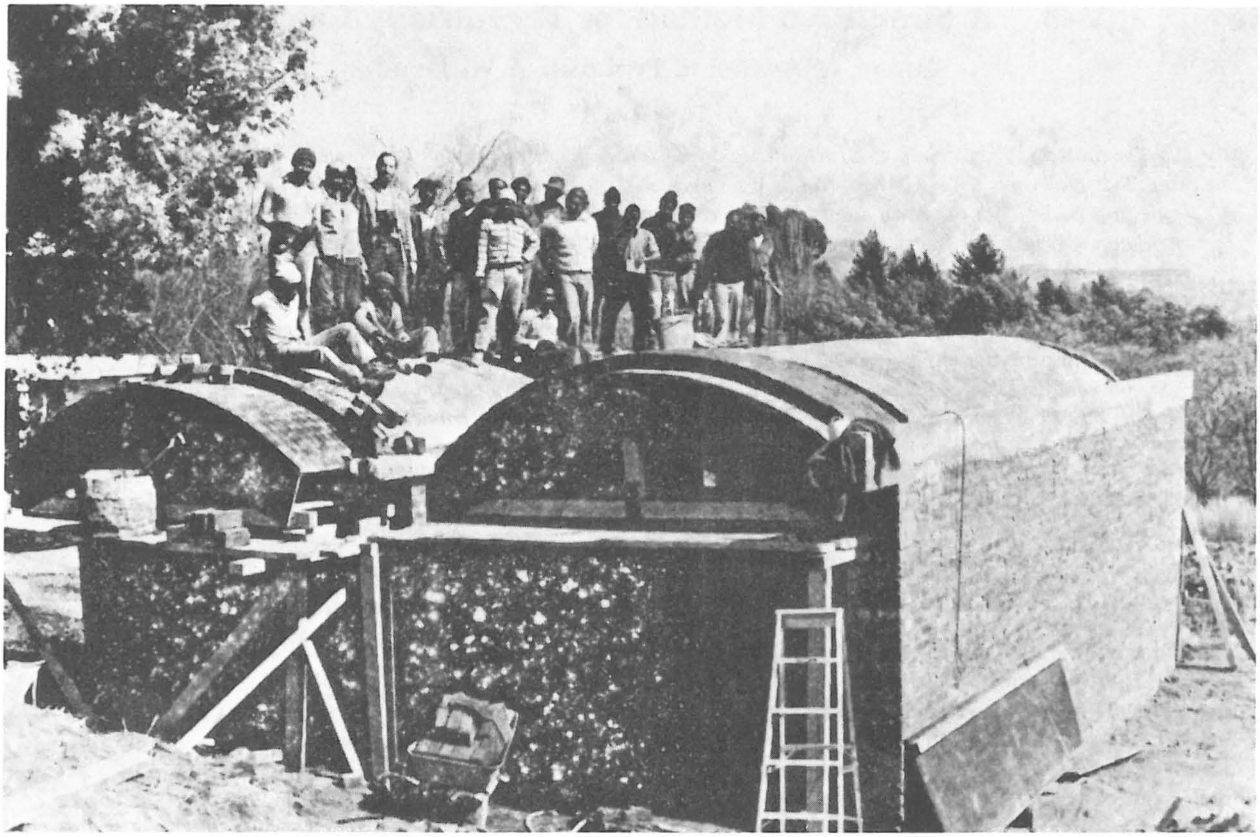

Photo 1

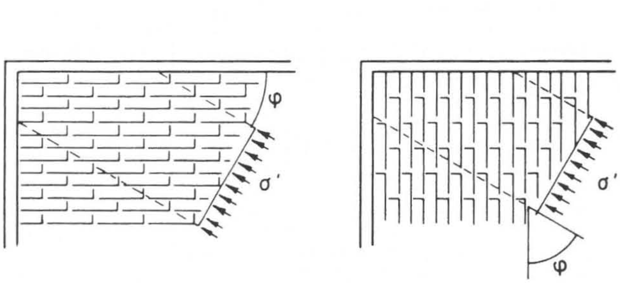

Figure 4.

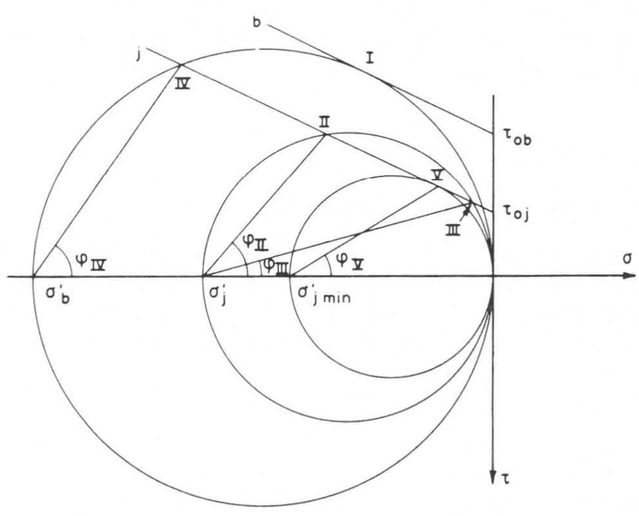

Figure 5.