Design and construction aspects of an earth brick dome used for low-cost housing

TECHNICAL PAPER
Journal of the South African Institution of Civil Engineering, 46(2) 2004, Pages 9–14, Paper 567

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A dearth of low-cost housing in South Africa is a current and widespread problem. Although spherical dome structures are not a common form of housing, the shape has many favourable characteristics, which enables a significant reduction in material and construction costs. However, dome structures have several challenging aspects – the analysis is complex and the construction difficult. This paper deals with both issues. The design adapts membrane equations from classical theory, but boundary conditions, which introduce complexities in the analysis, are dealt with in a simplified manner. A method of construction is also proposed to ensure quality control of materials and to ensure that the walls are constructed within acceptable tolerances. A new type of composite wall is also presented – cement-stabilised soil brick and a fibre-impregnated structural plaster. To verify the proposals, a prototype dome was constructed in Mozambique.

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Keywords: domes, shells, masonry, earth bricks, fibre reinforcement

INTRODUCTION

In South Africa, the shortage of housing is in the order of 2,2 million homes. In addition, the number of new households increases by 200 000 per year, which adds to the backlog. This shortage is primarily amongst the low-income group, who cannot afford the cost of a home. The government, in response, has initiated several programmes in an effort to alleviate this almost insurmountable problem. A current programme administered by the Department of Housing (Department of Housing 2002) is a subsidy-based programme designed to reduce the cost of a home. The maximum subsidy is around R23 000, which is granted to those who fall into an income group not exceeding R18 000 per annum. Those who qualify are eligible for a home with 30 m^2 of living space.

It is evident, considering the income levels of subsidy recipients, that the cost of the home should be reduced as much as possible. This will require inventive schemes to make the house more affordable. An alternative housing design is presented here with the objective of reducing the cost of the home, but at the same time maintaining a reasonable amount of living space and ensuring a durable and sound structure.

The traditional western style of home in South Africa is made of bricks, a concrete ground slab, timber trusses and tiles or steel sheeting are used as roofing cladding. The roof comprises the majority of the cost of the structure. This type of house has been around for many years and optimised to such an extent that any further advancements are usually of marginal benefit. In order for a significant savings to be achieved, the traditional home must be scrapped and new types of housing developed. This paper describes a new type of home shaped in the form of a spherical dome. The walls are constructed from a composite material composed of stabilised soil bricks (Bolton 1998) and plastered with a fibre-impregnated mixture.

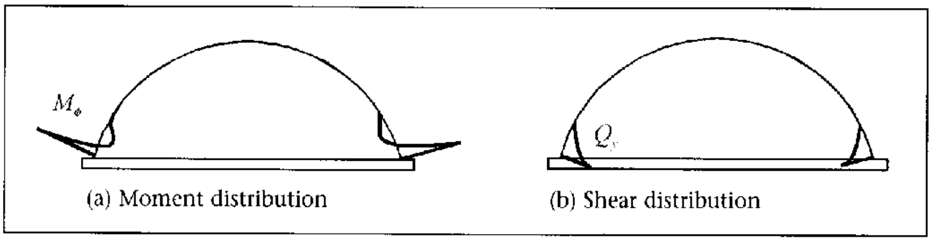
Although domes are extremely efficient, this structure has lost popularity over the years because of two main reasons: First, the analysis is complex and requires specialised engineering skills to either apply classical mathematical solutions or a finite element analysis. These specialised skills are usually not prevalent amongst practising engineers – therefore a safe but simplified approach is desirable. Second, construction is difficult and tends to be expensive when forming double curvature structures. Furthermore, the walls of the domes must be constructed to close tolerances to prevent buckling and asymmetric gravity loading.

Design and construction aspects are examined and various solutions are presented to overcome the inherent difficulties stated above. To verify the proposal, a prototype dome was constructed in Mozambique. This structure is also described.

ANALYSIS USING CLASSICAL MATHEMATICAL METHODS OF DESIGN

Membrane forces and boundary effects

Prior to the advent of computerised analysis, shells were designed according to classical mathematical methods. These classical methods of design are, by nature, complex. The difficulty lies in assessing the effects of boundary conditions. If the edge is fixed or pinned, moments and shears may occur at the base. Solving these edge forces are possible by formulating a set of compatibility equations These compatibility equations are composed of deformations, which are referred to as errors and corrections. The deformation



(a) Moment distribution

(b) Shear distribution

Figure 1 Moment and shear distribution in a shell due to boundary effects

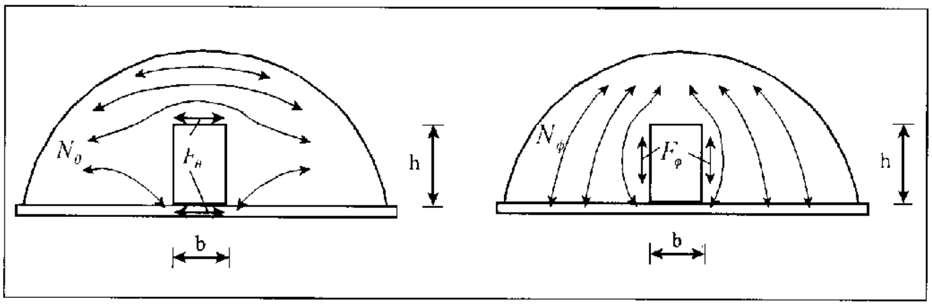


Figure 2 Flow of circumferential forces in a dome with openings

errors are those which occur if the shell is assumed to be unrestrained at the boundary (membrane theory). These deformation errors are corrected by applying edge forces to model a pinned or fixed edge. The solution of the compatibility equations yields the edge forces, or the reaction at the boundary.

Boundary effects are a primary cause of bending moments and shears in the shell. Bending and shear forces are expensive forces. If the shell is very stiff, the influence is greater. Dome shells, however, are usually thin and sufficiently flexible to minimise this effect. In addition, moments and shears are usually confined to the lower quarter of the shell and are relatively small in magnitude. A typical moment and shear distribution is illustrated in figure 1 for a fixed edge. As illustrated, peak moments and shears occur at the base and rapidly dissipate a short distance up the shell. If the shell is able to rotate in the meridional direction as well as translate normal to the shell mid-surface, boundary moments and shears would not exist, assuming smoothness conditions are satisfied (Zingoni 1997). This, however, is not a real condition since most shells are either fixed or pinned. For this reason, efforts to diminish, rather than eliminate boundary effects are a more realistic endeavour.

If the shell is subjected purely to membrane forces (no boundary effects), the analysis is significantly simpler. Membrane equations are formulated by constructing equilibrium equations in the circumferential and meridional directions

$$N_\phi = -\frac{R}{2\pi r_0 \sin\phi} \tag{1}$$

$$N_\theta = \frac{R}{2\pi r \sin^2\phi} - p_z \frac{r_0}{\sin\phi} \tag{2}$$

where N_ϕ is the meridian force, N_θ is the circumferential force, R is the total vertical load, p_z is a load per unit area applied normal to the surface, r_0 is the horizontal radius, r is the radius of the sphere and ϕ is the meridional angle measured from the vertical axis.

Equations 1 and 2 are fundamental equations and are adapted to various load configurations to solve membrane forces in a shell closed over the apex. The most common equations are those applicable to a uniformly distributed gravity load, given below. Similar equations for other types of loads are extensively published (Billington 1982; Gould 1999):

$$N_\phi = \frac{-rq}{1+\cos\phi} \tag{3}$$

$$N_\theta = rq\left(\frac{1}{1+\cos\phi} - \cos\phi\right) \tag{4}$$

where q is the uniformly distributed load.

Since the influence of boundary effects is confined to the lower extremities of the shell and relatively small in magnitude, designs based solely on membrane forces are safe if the structure makes an allowance for boundary forces. This is usually in the form of a localised thickening, which gradually tapers out within the region of boundary influence (approximately one quarter of the height of the shell). Alternatively, the boundary effects could be resisted by strengthening the shell walls locally. Vertical starter bars projecting from the foundation into the shell walls are one way to strengthen this region.

Bending and shear forces at the base may be minimised by using form-finding techniques (Isler 1994). The most common method is to hang a flexible material (eg fabric), allowing the shape of the dome to form naturally under a uniformly distributed load. In this state, the fabric is in tension and the boundary free of bending forces. To maintain the shape, the fabric is moistened and frozen or a resin is applied. In a hardened state, the model is flipped over causing a reversal in stress – from tension to compression. The coordinates (defining the shape of the shell) are then recorded. By simply scaling the coordinates, the form of the shell is defined

A grillage model could be formed out of pin-ended bar elements arranged to resemble a circular flat 'spider-web'. Normal loads are applied to the nodal points and the magnitude of these loads should be in proportion to the tributary areas to resemble a gravity load. Under loading, the plate will deform creating a natural shape in tension and free of bending at the base. These deformations can then be scaled to define the shape of a full-size dome. This part of the analysis is simply a form-finding technique to determine a natural shape under gravity loads. To complete the analysis, the shape should be entered into a finite element analysis package and analysed with shell elements under an assortment of load combinations (gravity, wind, earthquake, etc). By doing so, the shape is confirmed for gravity loads and the magnitude of the boundary effects are determined for other load configurations.

The analysis of point loads or non-symmetric loads

Resistance against point loads is an inherent weakness of shells. If the load-carrying capacity of point and uniformly distributed loads are compared, there is a vast difference in strengths. Distributed loads are carried in the shell primarily by in-plane membrane action. Point loads, on the other hand, are carried locally by bending and shears. As previously mentioned, bending and shear forces are expensive forces and require a substantial amount of material to provide resistance. Despite the disparity, designing for point loads is essential, simply because they exist and it is probable that the shell will be subjected to such loading during the life of the structure.

Design procedures for point loads may be similar to those used to assess the capacity of slabs or flat plates (ie, punching shear analysis, etc). After all, a shell is a plate with a curve, either in one or two directions. An understanding of classical theory would reveal that thin shell theory adapts plate equations. The use of Johansen's yield-line analysis (1962) is an alternative and a simple means to determine the effects of point loads in slabs using plastic theory. Current research at the University of the Witwatersrand is investigating the application of this method to shell theory, which would simplify the analysis considerably and enable economy of design. However, the majority of point load designs are based on a finite element analysis or buckling theory (Billington 1982; Gould 1999). Non-symmetric loads, such as wind, are almost exclusively assessed by finite elements.

Openings in the shell

Openings in shell walls introduce an assortment of mathematical complexities. Classical methods are restricted to standard shapes and simplistic loads. Closed formed solutions are not available to analyse shells with openings with the exception of a circular skylight located at the apex of a spherical dome. Several methods, however, have been devised to assess the effects of openings.

A less common method is a photoelastic analysis. A scaled model is made of a plastic material referred to as CR-39, or alternatively Bakelite (Davis 1964). Polarised light is passed through the loaded model creating colour patterns, which represent the state of stress in the shell. Concentrations of stress are identified by concentrations in colour contours.

A finite element analysis is one of the most effective ways of determining the effects of openings in a shell. The only requirement is to ensure that a sufficient number of elements exist in regions of concentrated stress – typically at the corners and along the edges. The resulting stress patterns not only illustrate the area of influence, but also the magnitude of stress.

A simple, yet effective technique used commonly in the US is to consider the irregular flow of hoop (circumferential) and meridian forces around openings in a shell. The stress tends to flow around the opening as illustrated in figure 2, similar to water flowing around a pier. This flow of force causes a concentration of stress around the corners and sides of the opening The force due to a concentration of hoop stress (F_φ), located at the top and bottom of the opening, is approximately equal to the stress times the height of the opening divided by two. Equation 5 was formulated assuming that half of the force will flow around the top and bottom of the opening.

$$F_\theta = \frac{N_\theta h}{2} \tag{5}$$

where h is the height of the opening and N_ϕ is the hoop stress in units of force per unit length.

Membrane stresses do not dissipate by introducing openings, but are diverted along the boundaries. As a general rule, strengthening around an opening should not be less than the required strength of the materials displaced. For example, if the dome is constructed of reinforced concrete, the amount of steel concentrated around the openings should not be less than the amount of steel displaced by the opening.

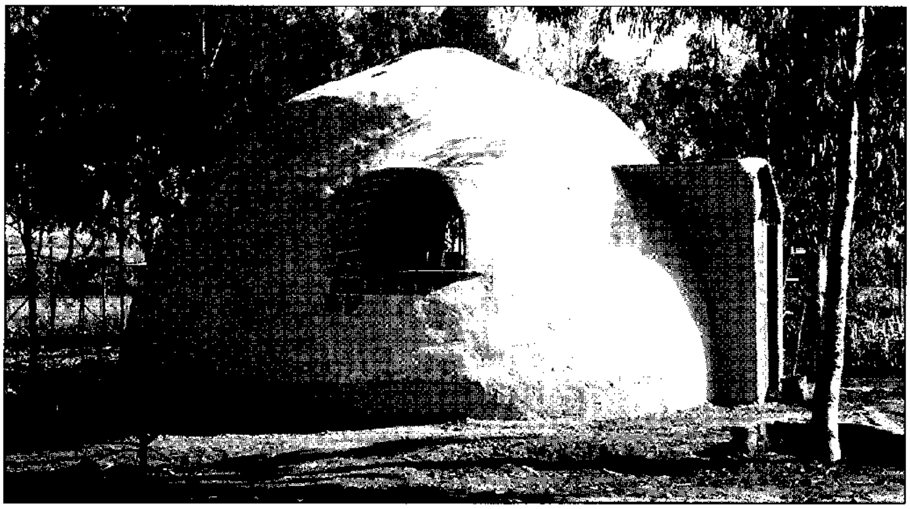


Figure 3 Prototype dome constructed in Mozambique

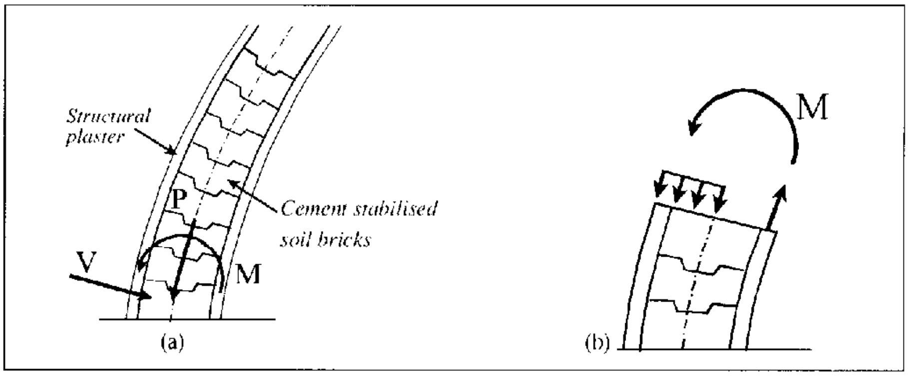


Figure 4 Boundary forces in the dome walls

It should be noted that this approach is highly simplified and leads to a conservative solution. Finite elements should be employed where a more exact solution is required.

Along the height of the opening, the concentrated force due to the meridian stress is determined using a similar equation:

$$F_\phi = \frac{N_\varphi h}{2} \tag{6}$$

It is prudent to further strengthen the corners where the highest concentration of stress exists. If the dome is constructed of reinforced concrete, additional diagonal bars are usually placed in the corners of the opening. Other strengthening methods include the use of a structural fibre, reinforced plaster or localised stitching. The stitching technique is not a common method, but may be used to repair cracks in brick walls as well as localised reinforcing. This technique has been the subject of research at the University of the Witwatersrand as well as other institutions (Fung 1974).

PROTOTYPE DOME

A prototype dome was constructed in Mozambique (fig 3) implementing the various design principles discussed in this paper. The shape of the dome is a sphere, measuring 2,5 m high by 6 m in diameter. To economise, the walls were formed of compressed cement-stabilised bricks (measuring 400 mm x 200 mm x 120 mm) with a structural plaster applied to the inner and outer faces of the wall, forming a composite. A section of wall is illustrated in figure 4a. Also included in this diagram are the moments, shears and axial load, which must be resisted by the shell wall. The 'sandwich-like' walls are unique in application to dome structures. The purpose of the configuration is to provide moment and shear resistance as well as limited ductility.

The shape of the bricks serves two purposes – they resist the compressive forces as well as the shears (Magaia 2004). Each brick is moulded with a shear key on one face and an indentation on the other side. The indentation receives a shear key from an adjacent brick. As the name implies, the shear key assists in transferring the shear across mortared joints.

The bending moment, on the other hand, is resisted by the composite action of the materials (ie, brick and plaster). The mechanism is illustrated in figure 4b. As drawn, the compressive stress is resisted by the brick and the tension stress is resisted by a fibre-reinforced structural plaster. The properties of each of these materials are described below. A summary of the analysis and design is also given. Furthermore, various techniques are presented to improve the construction and material quality.

Compressed stabilised soil bricks

The bricks used in constructing the shell walls are composed of a compressed cement-stabilised soil (Magaia in prep; Houben 1998; Carroll 1992). The soil is stabilised and bound by the addition of cement and the material is densified by applying a compacting pressure. The result is a high-quality brick with 28-day compressive strengths ranging from 3 MPa to 10 MPa – depending on the mix proportions and the compacting pressure. To economise, local soil is used to produce the bricks.

A sieve analysis is performed to determine the gradation of the soil used to construct the prototype dome. This information is given in table 1. Not all soils are suitable for brick making; any soils containing organic material should be avoided. The correct proportions of clay for plasticity and sand for workability are needed to minimise the effects of shrinkage during curing and to optimise the compressive strength. The amount of clay in the soil is critical to prevent excessive shrinkage and loss in durability. If the clay content is less than 5 % or greater than 30 %, more cement, clay or sand must be added to balance the mixture. The percentage of fines (clay + silt), the liquid limit, the plasticity index and the per cent shrinkage are parameters considered in the design of the mix.

Table 1 Particle size distribution of soil used in the prototype dome

Material	Particle size (mm)	%
Clay	0–0,002	22
Silt	0,002–0,06	24
Sand	0,06–2	44
Gravel	2–60	10

If fibres are added, the compressive strength may increase as much as 10 %. Fibres also control shrinkage cracking; this is particularly useful with soil types which contain a high percentage of clay.

The amount of cement added to the mix will vary depending on the compressive strength required and the proportion of clay in the soil. Typically, the cement content will vary between 3 % and 12 %. However, 6 % to 10 % cement content is commonly used to obtain satisfactory compressive strengths. A cement content of 10 % was used in the tests listed in table 2. The amount of compressive force applied to form the bricks contribute significantly to the compressive strength of the bricks. Three different categories of compression were applied – uncompressed, manually compressed, and mechanically compressed.

The compressive strengths of table 2 are statistically interpreted (BS 1975) to determine the design compressive strength of the bricks, based on a 95 % confidence interval.

Table 2 Compressive strength of cement stabilised soil bricks

Test no	Compressive strength (MPa)	Moisture content	Type of compression* to form the bricks
1	3,82	>20 %	Uncompressed
2	3,14	(ϑ 1 795 *kg*/m^3)	
3	6,86	10 %	Compressed manually
4	5,26	(ϑ 1 800 *kg*/m^3)	
5	6,38		
6	7,96		
7	9,40	10 %	Compressed mechanically
8	9,13	(ϑ 1795 *kg*/m^3)	
9	3,44		
10	9,86		

* Soil compressed to the given density

Fibre-reinforced structural plaster

The structural plaster used in the prototype dome is not a plaster in the conventional sense (ie sand, cement and water). The plaster is composed of the same materials as the bricks, but with a higher percentage of cement and the inclusion of fibres. Sisal fibres, between 40 and 60 mm in length, were used in the mix. The thickness of the plaster averaged about 20 mm.

The purpose of the plaster is to provide a durable membrane with ductile properties, bind the structure together and resist tension forces in the wall. The plaster is applied in the same manner as other plasters (hand trowelled). The mix, however, is not compressed like the bricks and therefore has a lower compressive strength. The primary role of the fibre is to provide tensile strength, that is, to resist bending moments. Table 3 contains the results of nine specimens tested in tension.

The shape of the specimens is given in figure 5, which has a cross-sectional area of 4 000 mm² (40 x 100 mm). A ramping tensile force was applied until failure occurred.

The experimental data was statistically interpreted to solve for the characteristic strength of the materials (BS 1975).

Table 3 Results of tensile tests of the fibre reinforced structural plaster

Specimen no	Quantity of fibre *kg*/m^3	Tensile strength (MPa)
1	20	1,10
2	20	1,20
3	20	1,25
4	20	1,68
5	20	1,45
6	20	1,58
7	20	1,55
8	20	1,70
9	20	1,45

Analysis and design

The dome was analysed by a finite element analysis as well as applying various simplified design techniques. The masonry code (SABS 1980) was utilised to determine the material resistance to load. The results of the analysis are given in table 4. The values stated are maximum or minimum values.

The tensile capacity of the plaster is relatively small, but sufficient to resist the hoop forces in the dome. At the base of the dome, a plaster thickness of 50 mm is required to resist the boundary moments. As a precaution, ordinary reinforcing bars (Y10) extended 1 m from the ring beam foundation and into the structural plaster of the walls. These bars not only help resist the bending moment, but assist in resisting the shear force in this region.

To simplify the analysis, equations 5 and 6 were used to estimate the concentration of force around the openings. As seen from the table, the estimated tension force is significantly higher than the values obtained from a finite element

Table 4 Analysis of forces and the resistance of the composite walls

	Finite element analysis	Simplified approach	Resistance
N_T (hoop forces)	7,36 kN/m	6,49 kN/m	13,20 kN/m
N_M (meridian forces)	-10,60 kN/m	-14,2 kN/m	-106,20 kN/m
M_l (meridian moments)	2,27 kN.m/m	Membrane solution only	3,38 kN.m/
F_T (force around opening)	0,80 kN	4,75 kN	17,28 kN

analysis. However, both values are lower than the tension capacity of the shell. In the prototype dome, the openings are reinforced with an increased thickness of structural plaster around the windows. Reinforcement and a double layer of brickwork forming an arch are used to strengthen the door opening.

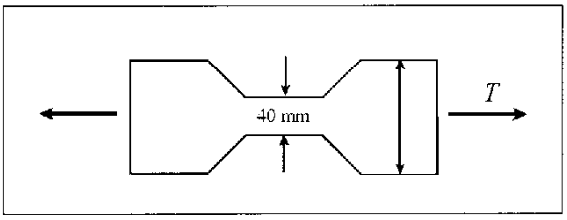


Figure 5 Shape of tensile specimens

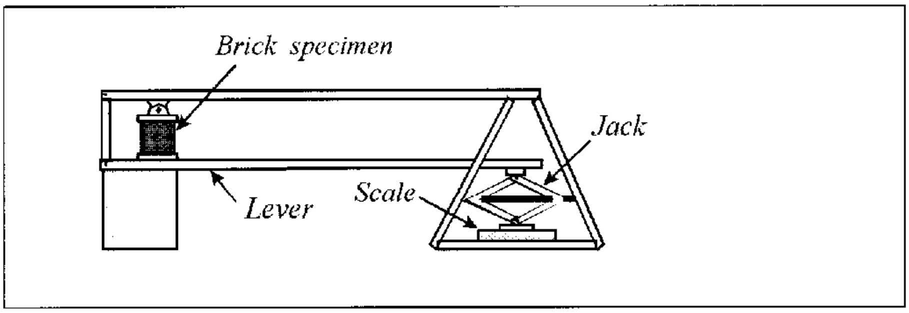


Figure 6 Compression testing apparatus

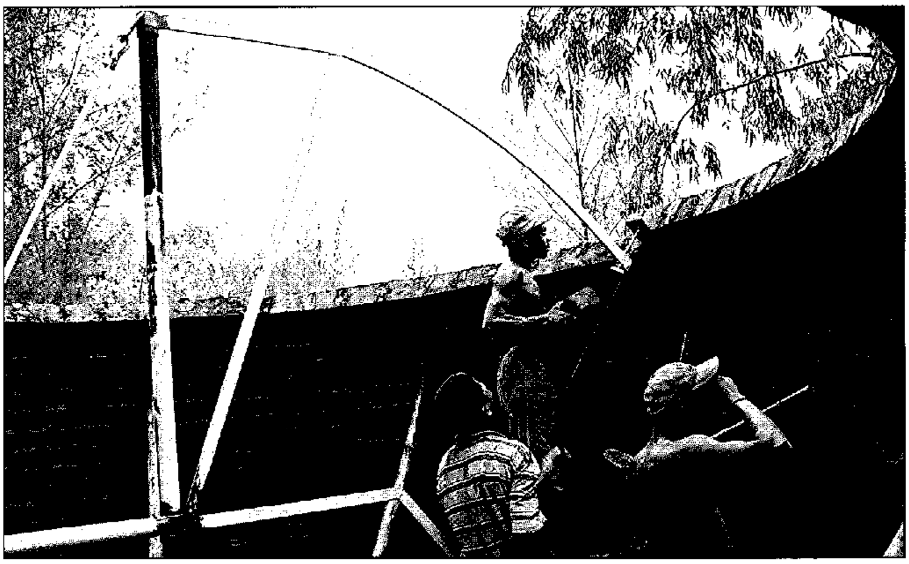


Figure 7 Guiding template to construct wall

Method of construction

The strength and stability of the dome is related to the quality of construction and the strength of the materials. An 'out-of-plumb' shell can result in buckling or over-stressing. It is imperative that the structure is constructed to the intended form with close tolerances. Therefore, inventive schemes are required to ensure quality construction

On-site testing of the compressive strength of the bricks

Luker (1999) identified problems determining the compressive strength of masonry at construction sites located in rural areas. More often than not, the strength of bricks produced in rural areas is not checked simply because testing equipment and laboratories are not available. Luker devised a simple testing apparatus, which is cheap to construct and easy to transport. A schematic of the apparatus is given in figure 6.

As illustrated, a brick specimen is placed between two pressing plates. On the face of one plate, a bar is welded which is in contact with the specimen, and precipitates a splitting failure. The apparatus works on a similar basis to a 'nut cracker'. A load is applied by gradually jacking the lever until splitting failure occurs. The splitting force is related to the compressive strength of the specimen by Poisson's ratio.

Ground slab and ring beam construction

The ring beam and ground slab are the only components of the dome that are constructed of concrete. Depending on the soil condition, loads and size of dome, the ring beam may or may not be reinforced. The ring beam serves two purposes: first, it acts as a foundation to support the dome at ground level. Second, depending on the stiffness, the ring beam attracts tension forces that otherwise would be distributed in the shell. Without a ring beam, the shell acts like a free-sliding dome on vertical supports and the hoop tension near the edge tends to be very large.

Construction begins by clearing the site of vegetation. The first 300 mm is usually stripped to rid the site of organic matter. A spike is then driven into the ground at the location of the centre of the dome. A rope is attached to the spike and two rudimentary circles are drawn inscribing the extents of the ring beam foundation. A trench, usually about 500 mm deep, is dug and the soil compacted (and possibly stabilised). The concrete is then poured to form the ring beam and ground floor slab, which are typically monolithic in small domes. The foundation steel depends on the magnitude of ring tension. However, it is advisable that the ring beam contains at least minimum steel.

Shell wall construction

It is vital that the wall is constructed according to the intended shape of the shell, within an acceptable tolerance. In this case, the shell takes the form of a sphere. To achieve this, a guiding template is used, as shown in figure 7.

The base of the template is fixed to the centre of the concrete floor and the template arm swivels horizontally 360 degrees. The bricks are placed along the edge of the template arm to ensure that the shell has the correct curvature along the meridian and circumferential directions.

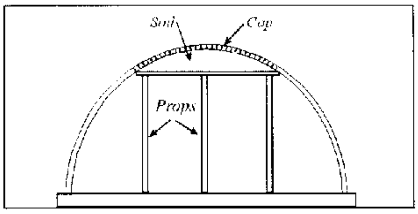


Figure 8 Construction of the dome cap

Construction of the apex

As the brick wall is laid, the slope of the wall will reach a critical stage in which the bricks tend to slide off while the mortar is wet. The top of the dome is therefore constructed by placing horizontal formwork at the apex of the shell (see fig 8). A hip is formed of soil and the remaining bricks are placed into position forming a cap. Once the mortar has cured sufficiently, the formwork is removed. Care should be taken to prevent the soil cap from subsiding during construction. Some subsidence occurred near the apex of the prototype dome.

Other considerations

The prototype dome is spherical in shape with sloping walls. For practical reasons, the walls near the base should be vertical to make the structure more serviceable (ie, to accommodate pictures, cupboards, furniture, etc). Larger hemispherical domes usually satisfy this requirement, but for smaller domes, cylindrical shaped walls with a dome roof is a more serviceable option.

Shell structures are noted for their favourable thermal properties. In an open plan dome, convection occurs, which enables a more constant and even room temperature. The thermal properties can further be enhanced by insulating the shell walls to produce a cool environment during the summer and a warm environment during winter.

The greatest challenge facing the concept of using a dome as low-cost housing is social and cultural acceptance. Although indigenous housing in South Africa took on many shell shapes in the past, present forms are traditional western-style rectangular homes. Clearly, acceptance will hinge on the cost, aesthetics and other cultural perceptions.

CONCLUSIONS

The objective is to devise a low-cost home that is structurally sound and affordable. A dome structure, presented here, was found to be a viable alternative. To minimise cost, the walls of the shell are constructed of local materials. The shape of the shell inherently eliminates the need for a conventional roof, which typically is the most expensive part of the structure. The prototype dome was constructed at a cost of $55 per m^2. The cost of other similar low-cost housing projects in Senegal ranged from $110 to $195 per m^2 (Guillaud 1995). These figures indicate the potential economy of earth domes.

As indicated, analytical methods are complex and require a certain degree of understanding of shell theory. However, various methods of design have been devised to simplify the analysis and produce a structure that is robust and structurally acceptable. Boundary effects may be dealt with by utilising form-finding techniques to minimise moments and shears at the base. Alternatively, the walls of the dome are strengthened locally to resist any residual stresses – this method was used in the prototype dome. Openings in the dome (such as doors and windows) also introduce analytical complexities. This problem is resolved by considering the flow of stress around the opening and calculating the resultant forces which act parallel to the edges of the opening. These areas of concentrated stress are reinforced. Equations 5 and 6 were found to be conservative estimates. Where higher accuracy is required, a finite element analysis is employed.

The structural integrity of shells is compromised by poor construction. 'Out-of-plumb' walls could lead to structural failures due to buckling or asymmetric loads. To ensure conformity to the original design, prefabricated guiding templates are utilised to ensure that the walls are constructed to the correct curvatures. At the apex, however, a soil hip is formed to construct a cap.

Other methods have been devised to ensure control over construction quality. For example, the brick compressive strength may be monitored by using Luker's (1999) masonry testing apparatus.

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