



DEVELOPING A NEW COMBINED STRUCTURAL ROOFING SYSTEM OF DOMES AND VAULTS SUPPORTED BY CEMENTITIOUS STRAW BRICKS

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ABSTRACT

The primary objective of this research was to develop a structural technique for roofing rice straw buildings by domes and vaults through encouraging the specification of innovative materials which may be more sustainable than their traditional counterparts. This paper examines the effectiveness of using rice straw cementitious posts and walls as an innovative natural construction method to support domes and vaults in straw bale buildings. Three proposed mix ratios for rice straw cementitious bricks were mechanically tested. A finite elements analysis of the proposed roofing system was performed, to check the safety of the roofing material, and their resultant reactions on the rice straw bricks support. Different cases of loading were applied including wind and settlement. Obtained results helped in the decision making of the most economical and environmental friendly brick mix. Besides, the results emphasized that all stresses were within acceptable limits of the Egyptian code of practice.

Keywords: domes, vaults, roofing system, rice straw bricks, building materials, finite element analysis.

1. INTRODUCTION

From adobe to straw bales, traditional building materials are being adapted to meet code-required standards for health and safety in contemporary buildings. These natural alternatives match the strength and durability of many mainstream construction materials, as well as being cost effective and environmentally friendly.

1.1 Straw bale structural systems

There are different ways of building with straw bales among which are the load bearing, light weight frame and load bearing, infill and timber frame and hybrid design.

1.1.1 Nebraska also called load bearing

This is the original method of building, pioneered by the Nebraskan settlers in the USA. In this method, the bales themselves take the weight of the roof - there is no other structural framework. One of the most important design features of a load bearing straw bale house is to distribute the loads as evenly as possible around the whole building. Never use point loads.

The bales are pinned to the foundations and to each other with coppiced hazel, and have a wooden roof plate on top. The roof plate is fastened to the foundations and the bales with coppiced hazel and strapping, and the roof is constructed in the usual manner on top of the roof plate. The main advantage of this style of building is its simplicity, ease of design, minimal use of timber, and the opportunity it affords for a modern day wall raising. While it is not favoured due to the constraints that limits the openings for windows and doors so as not to exceed 50% of the wall surface area in any wall. Also the maximum unsupported (un-braced) wall length is 6m (20 ft) [1].

1.1.2 Infill also called post and beam or timber frame

In this method, the weight of the roof is carried by a wood, steel, or concrete framework, and the bales are simply infill insulation blocks between the posts. This has often been the preferred option for architects, as the structural concepts are not innovative and rely on an already established method of construction; therefore the risk associated with an experimental technique is minimized. There is no need to satisfy oneself of the capacity of the bales to take the weight of the roof, since the framework does this. This method requires a high level of carpentry skill and uses substantially more timber than a load bearing design, which has significant cost and environmental implication [1].

1.1.3 Light weight frame and load bearing

This design has been pioneered by Barbara Jones of Amazon Nails as a way to retain the benefits of the load bearing style, yet enabling the roof to be constructed before the straw walls are built, thus giving protection against the weather throughout the wall-raising process. It uses a timber framework that is so light-weight that it cannot stand up alone. It requires temporary bracing to give it stability until the straw is in place. The straw is an essential part of the structural integrity of the building, more so than the timber, and it works together with the timber to carry the load of floors and roof. Timber posts are located at corners and either side of window and door openings only, and are designed such that the timber wall plate at first floor and/or roof level can be slotted down into them once the straw is in place allowing for compression on the bales. Compression of the straw bale infill walls is essential for stability [1].

1.1.4 Hybrid method

Here the bales are used much more like conventional brick walls, with cement mortar holding



them all together. The bales are stacked in vertical columns so the cement, in effect, forms posts between each stack. The whole building is cement rendered inside and out. It is rarely used now because of the knowledge of simpler methods. It is still an experimental method, and being so simple, allows for invention during practice. It is very effective and has passed all building regulation tests in Canada [1].

1.2 Building codes and the straw bale structural systems

Austin city code and California building codes establishes minimum prescriptive standards of safety for the construction of structures that use baled straw as a load-bearing or non-load-bearing material. The codes indicates that buildings with load bearing bale walls shall not exceed one story in height, and the bale portion of the load bearing walls shall not exceed a height-to-width ratio of 5.6:1. The ratio of unsupported wall length to thickness, for bale walls, may not exceed 15.7:1. The allowable vertical load (live and dead load) on the top of load bearing bale walls may not exceed 400 pounds per square foot (psf) (1.95t/m^2) and the resultant load shall bear at the centre of the wall. Straw-bale structures must be designed to withstand all vertical and horizontal loads as specified in the Building Code. Load-bearing bale walls must have a roof bearing assembly at the top of the wall to bear the roof load and to provide a means of connecting the roof structure to the foundation. The roof bearing assembly must be continuous along the tops of structural walls.

Bale walls and roof bearing assemblies may be anchored to the foundation by means of other methods which are adequate to resist uplift forces resulting from the design wind load. There shall be a minimum of two points of anchorage per wall, spaced not more than 6 feet apart, with one located within 36 inches of each end of each wall. With load bearing bale walls, the dead load of the roof and ceiling systems will produce vertical compression of the walls. Regardless of the anchoring system used to attach the roof bearing assembly to the foundation, prior to installation of wall finish materials, the nuts, straps, or cables shall be retightened to compensate for this compression [2, 3].

2. BACKGROUND OF DOMES AND VAULTS

2.1 Historical background

Shell structures have been constructed since ancient times. The Pantheon in Rome and the Hagia Sophia in Istanbul are well-known examples. After the Roman times the traditions of domes continued up to the 17th century. Since then they seemed forgotten. Stimulated by the newly developed reinforced concrete and the demand to cover long-spans economically and column free the shell made a comeback in the early 20th century [4].

2.1.1 The Nubian vault traditional Egyptian roofing technique

The Nubian Vault is an environmentally sound, comfortable, and aesthetic roofing technique that requires neither expensive steel reinforcement bars for its construction, nor great amount of timber beams. The old-aged Nubian vault technique was notably revived by the Egyptian architect Hassan Fathy in the 1940s with the building of a new village at Gournah, near Luxor [5].

Since the year 2000, the Nubian Vault (Figure-1) has been recently used by a French Association La Voûte Nubiennne, by simplifying and codifying the technique, and has promoted the construction of over 200 vaulted buildings in Burkina Faso. One of the key advantages of the Nubian vault is that it can be built without any support or shuttering. The bricks are laid leaning at a slight slope against the gable walls in a length-wise vault [6].



Figure-1. Nubian vault building process in Burkina Faso [6].

2.1.2 The burned clay brick dome

The dome is an ancient architectural form which developed as a roofing system for circular mud-brick huts in ancient Mesopotamia about 6000 years ago. Throughout history, the dome has been the architectural form of choice wherever the efficiency and strength are required of a structure. From the simple igloo that shelters the Arctic hunter through the ravages of a blinding storm, the dome has been used in every culture, on every continent, as one of man's most versatile constructions [11]. Also, the dome is a traditional way for roofing buildings in Egypt. Most of the Egyptian masonry builders are accustomed to build domes for mosques and churches. In addition to the benefits that the dome is a good environmental way for roofing in hot arid zones, it has an external appealing look.

In the 14th century B.C, the Mycenaean Greeks built tombs roofed with steep corbelled domes in the shape of pointed bee hives. The Romans developed the masonry dome in its purest form, culminating in the Pantheon (Figure-2), a temple built (ad 118-128) by the emperor Hadrian. Set on a massive circular drum 6 m (20 ft) thick



that conceals eight interlocked masonry piers, the coffered dome rises 43 m (142 ft) to admit light [7].

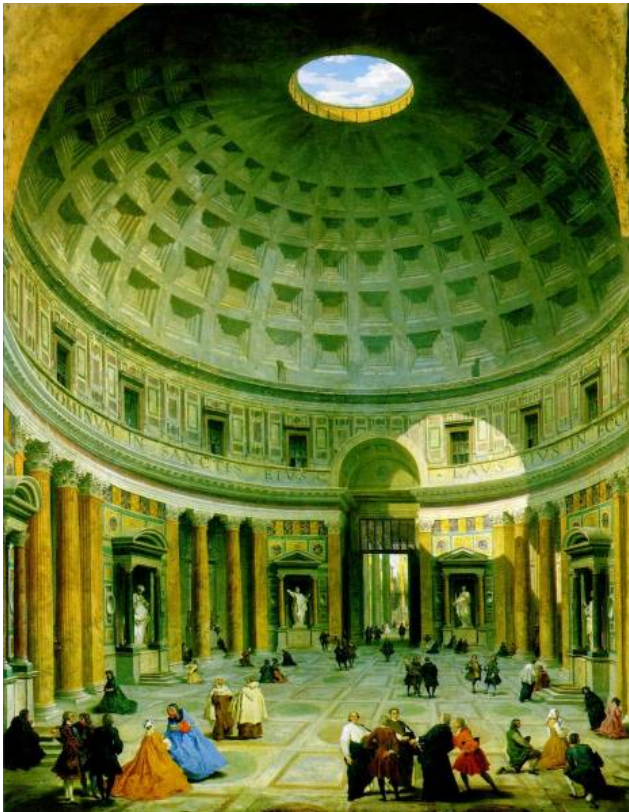


Figure-2. Interior of the pantheon showing the light opening [7].

2.2 Technical background

To design an efficient shell structure, it is thus important to provide an extensive study of the geometrical and structural interaction, which results in a prevalent membrane stress field. A prevalent membrane stress field forms an efficient load-carrying system without the need for bending moments. Bending moments normally arise when the line of thrust, determined by the loading and supporting conditions, does not coincide with the system line of the structure. In shells, however, circumferential stresses are able to 'correct' the deviating line of thrust back into the system line. By this principle, the surface of a properly designed shell can give rise to quite large shape deviations from the line of thrust, while staying in a membrane stress state. Ancient engineers were well aware of the force flow in shell structures as can be seen in the construction of old domes and churches, for example the famous Pantheon in Rome. The Pantheon in Rome can practically be seen as a combination between an arch and a shell. The upper part of the Pantheon is in compression and acts like a real shell structure. In the lower part, however, tensile stresses arise in circumferential direction. Because their low quality concrete was unable to absorb these tension forces, the lower part of the pantheon acts like an arch. The ancient engineers must have been aware of the tension forces and even must have known the

location where the circumferential stresses transform from compression into tension, providing the increase in cross-sectional thickness at the turning point. The larger cross-section makes sure the line of thrust stays inside the system line. In other ancient structures tension is absorbed by the wooden ties placed along the parallel circles of the dome or prevented by constructing domes confined to the compression zone.

Up to the present day the theory of shells and the physical models are extended by computational design and analysis methods. Numerical analyses facilitate determining stresses and techniques as form-finding and shape optimization are automatized. These new techniques offer innovative design possibilities to determine membrane supporting shapes.

The membrane behavior of shell structures refers to the general state of stress in a shell element that consists of in-plane normal and shear stress resultants which transfer loads to the supports. The initial curvature of the shell surface enables the shell to carry even load perpendicular to the surface by in-plane stresses only. The carrying of load only by in-plane extensional stresses is closely related to the way in which membranes carry their load [10].

3. PROBLEM STATEMENT AND RESEARCH OBJECTIVE

This research is part of an ongoing National project aiming to examine the feasibility of using rice straw bales in constructing economic buildings in arid desert areas of Egypt. The main objective was to use the greatest amount of rice straw, this agricultural residue, which is considered an environmental pollutant to the Egyptian population due to its illegal burning. The amount of rice straw produced after harvesting exceeds 4 million tons annually according to the Ministry of Agriculture in Egypt. This objective coincided with the great insulation benefits achieved from using rice straw in desert areas.

This paper aims to investigate the effect of using domes and vaults in roofing a full scale prototype, including shells forces on rice straw bale load bearing walls.

However, due to the membrane behaviour of shell structures that consists of in-plane normal and shear stress resultants which transfer loads to the supports, the straw bale walls were built in the whole perimeter of the building to serve as external thermal and sound insulator carrying its own weight under the vaults and domes roofing areas. The rice straw bale load bearing walls were not suitable to resist the resultant horizontal forces from the shell structures. As a structural supporting alternative, another rice straw recycling technique was used to support the domes and vaults. In this technique a cementitious straw brick was examined to undertake the resultant forces.



4. RESEARCH METHODOLOGY

4.1 Case study: full scale Egyptian straw bale building in an arid desert area

A 100 m² house unit (Figure-3) was constructed using rice straw bales of dimensions 1.00 x 0.50 x 0.50 m that met all the minimum requirements of the California Codes for density, shape, moisture content, and ties of bales.

The house was designed and allocated to provide the thermal comfort required for an occupant resident in an arid desert area. The walls were constructed as load bearing in the outer perimeter to make advantage of the high insulation performance of the straw bales in such an arid desert area. Vertical reinforcing bars with a diameter of 16 mm were embedded in the foundation to a minimum depth of 30 cm, and extended above the foundation by a minimum of 50 cm. These vertical bars were located along the centre line of the bale wall, spaced not more than 50 cm as recommended by the codes.

Three different kinds of roofing techniques were examined in sheltering this prototype: burned clay bricks domes, burned clay bricks Nubian vaults and wood roof made of wooden joists and beams. Both the vaults and the domes were aimed to offer high ceilings and help in collecting the hot air volume during the summer period at a higher level than the occupant usable area. The Nubian vault roofing was used to cover the kitchen and bathroom area, while the domes were used to cover the reception area. The building material used for the vault and domes construction was light weight burned clay brick with holes. The voids in the construction brick offered two advantages: first was the light weight of the brick, second the thermal insulating effect of the proposed roofing system. Vaults and domes offered an easier low cost construction technique than the traditional reinforced concrete slab for building in such arid area.

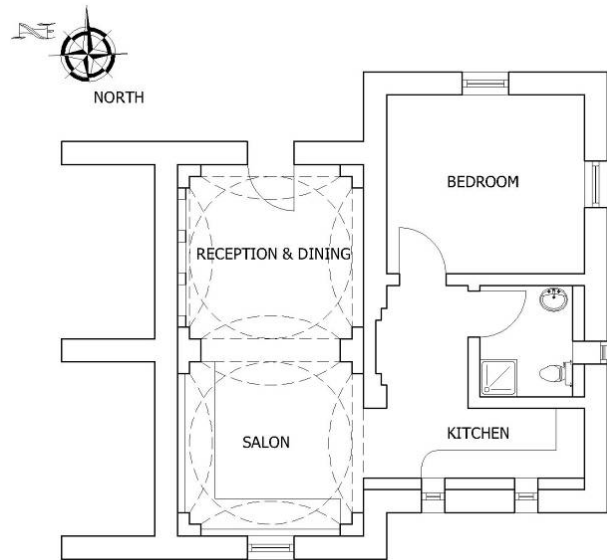


Figure-3. Plan of full scale Egyptian straw bale building in an arid desert area.

4.2 Adopted rice straw recycling technique used to support the domes and vaults

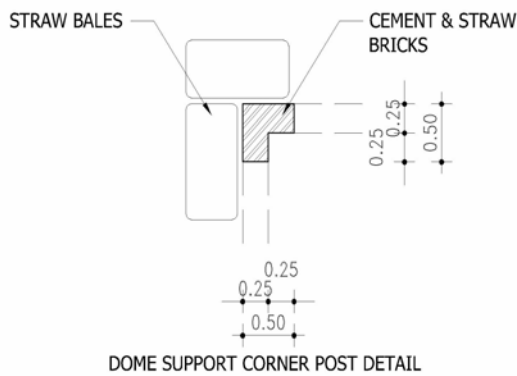
At the interior of the straw bale walls, 6 corner pendants made of cementitious straw bricks (Figure-4) were designed to support the 2 domes roofing the reception area. A similar technique was adopted to lift the line load resulting from the vaults (Figure-5) used for roofing the kitchen and the bathroom. The loads were carried by continuous walls built in parallel to the exterior straw bale walls, using the same cementitious straw brick. In this technique the straw bale walls acted as insulators without carrying any vertical loads except its own weight.



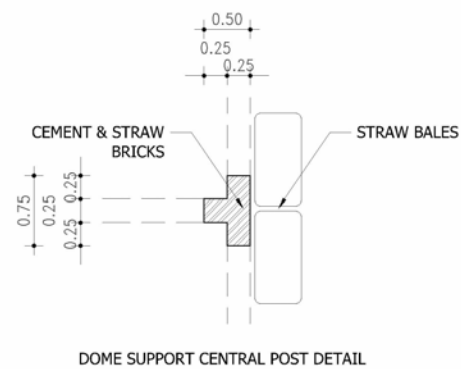
Figure-4a.



Figure-4b.



DOME SUPPORT CORNER POST DETAIL

Figure-4c.

DOME SUPPORT CENTRAL POST DETAIL

Figure-4d.**Figure-4.** Cementitious straw bricks pendants for lifting the domes.**Figure-5.** Cementations straw bricks wall supporting the vaults.

4.3 Physical properties of the cementitious straw building unit

Samples of three mixes were examined with various proportions of straw, aggregate, and cement.

Table-1 presents the physical properties of the 3 mixes of bricks which were examined under compression to determine the critical crushing load of each sample [12].



Table-1. Materials needed to produce 1000 cementitious straw bricks of dimensions (25 x12 x 6) cm.

Mix No.	Straw (kg)	Fine aggregate (m ³)	Coarse aggregate (m ³)	Cement (kg)	Density
1	40	0.9	0.9	400	1800
2	70	0.85	0.4	400	1330
3	90	0.85	0.2	400	1114

4.4 Mechanical properties of the building unit

A 1000 KN universal tension- compression machine (Figure-6) was used in testing the bricks for compression. The Shumadsu machine is equipped with a data analyzing output unit for output data recording. From visual inspection, it was clear that mix 3 with the highest straw content 90 kg was non consistent. Accordingly, bricks of mix 3 were excluded.



Figure-6. The Shumadsu machine used for testing the cementitious straw bricks.

Bricks of mix (1) and (2) reached the critical crushing point under compressive stresses of 36.6, and 26.6 kg/cm² respectively (Table-2).

In order to be able to evaluate the expected stresses from the roofing system, thus choose which type of bricks of mix 1 or 2 would be the most suitable brick to support the proposed roofing system, a finite elements analysis was performed on the intended roofing domes and vaults using SAP program.

Table-2. Maximum compressive stresses of tested bricks.

Mix No.	Force (ton)	Stress (kg/cm ²)
1	11	36.6
2	8	26.6

5. FINITE ELEMENT ANALYSIS (FEM) AND DISCUSSION OF RESULTS

5.1 Dimensions and geometry of domes and vaults

The roofing system consisted of two domes of rises 60, 68 cm and of the same diameter (3.40 m), and two cylindrical vaults of 1.4*0.8*3.4 m, and 2.6*1.1*3.60 m (width * height * length) respectively. FEM analysis results will be discussed for the dome and vault of larger dimensions.

5.2 Finite elements models (FEM)

4-Nodes shell elements were used to model both domes, and vaults. Finesse of the finite element mesh for the dome had obvious impact on the local stresses that were acting on the irregular mesh areas. Analysis started with a rather coarse mesh (157 shell elements), and ended up with a 1324 elements with 7944 degrees of freedom (D.O.F) (Figure-7).

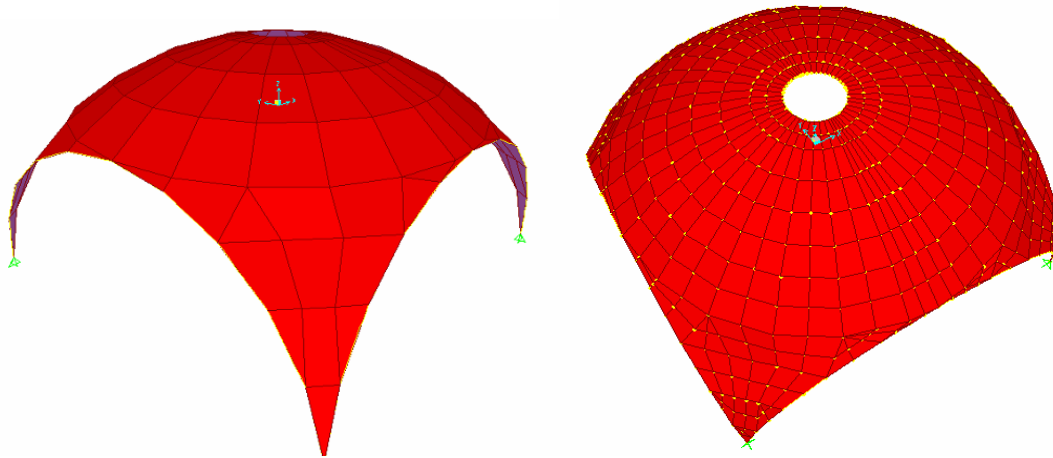


Figure-7. Finite elements mesh finesse of dome roof.

Vaults were regularly meshed using 64 shell elements with 384 D.O.F (Figure-8). The aspect ratio does not exceed 1: 1.5 for all used elements in either domes, or vaults.

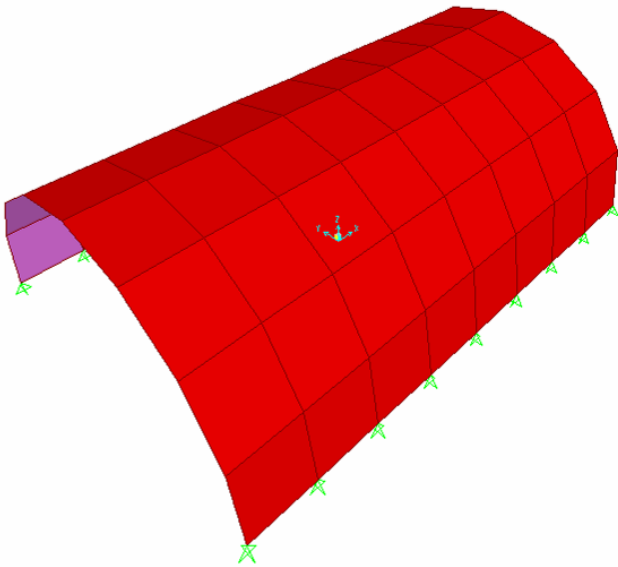


Figure-8. Finite elements mesh of vault roof.

5.3 Finite element analysis results of dome roof

5.3.1. Stresses under main loads

5.3.1.1 Dead load + super imposed dead loads

The own weight of the roof, in addition to a super imposed static load of 100 kg/cm^2 were applied on the dome.

Figure-9, presents a finite element, showing the indicated directions for skin forces F11 and F22, where F11 acts in local axis 1 direction (ring direction), and F22 acts in local axis 2 direction (tangential direction).

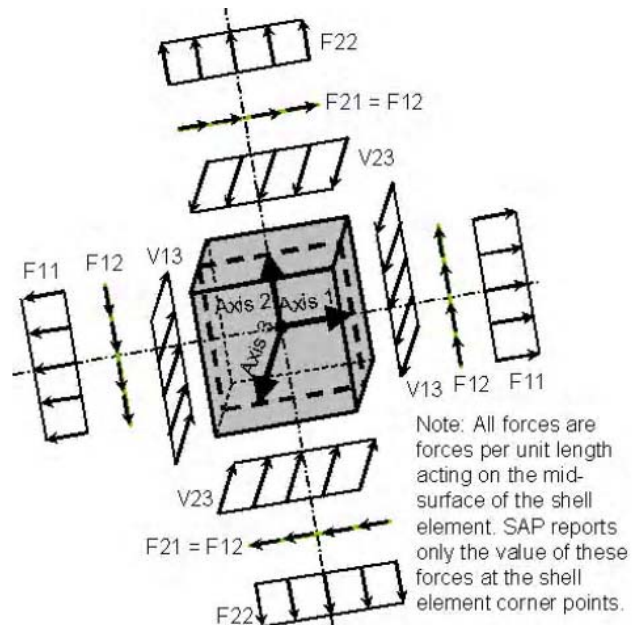


Figure-9. Directions of shell element output forces [8].

In order to derive the skin stresses in the two perpendicular directions S11 and S22, the induced forces in both directions were divided by the width of the element they cover. The maximum skin forces - in both perpendicular directions F11 and F22 were presented in Figures 10 and 11 respectively. The maximum compressive skin stress did not exceed 5 kg/cm^2 for S11, and 10 kg/cm^2 for S22 direction for the dome. The observed local tensile forces in F22 direction at the centre of the dome side spans, and in an intermediate strip in F11 direction resulted in tensile stresses that did not exceed 0.6 kg/cm^2 .

These values comply to the Egyptian Code of Practice ECOP 204-2005 [9], which states that the compressive stresses should not exceed one fifth the maximum value reported in the Egyptian Code of Practice ECOP 204-2005 for this kind of bricks which is 80 kg/cm^2 .

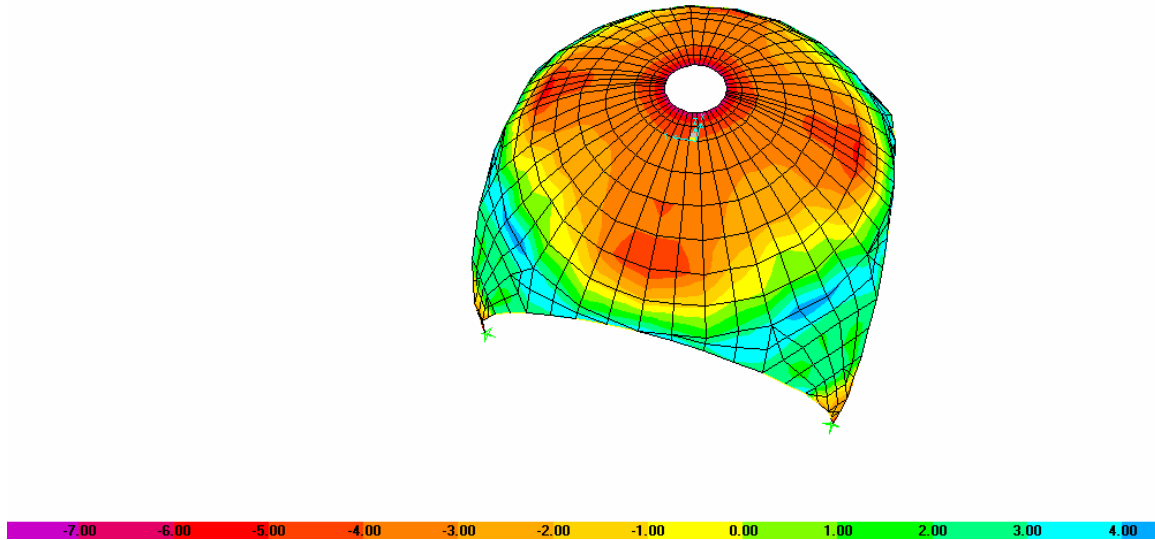


Figure-10. Force in F11 direction for dome 68 cm rise.

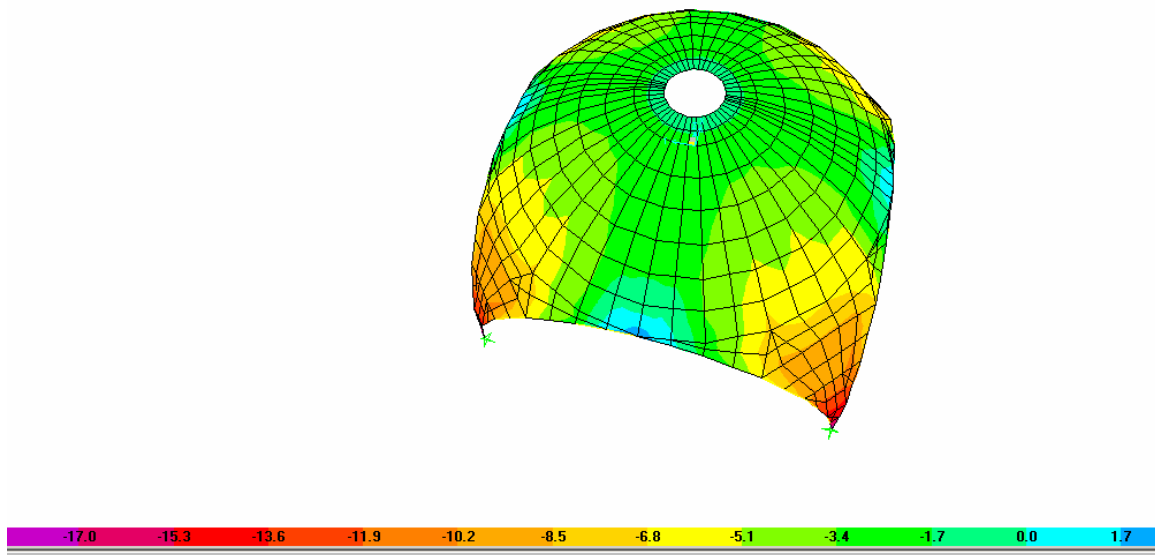


Figure-11. Force in F22 direction for dome 68 cm rise.

5.3.1.2 Settlement

Masonry systems are known for their high sensitivity to differential settlements, due to:

- The light weight of these structures.
- The poor tensile resistance of the binding mortar (around 1.0 kg/cm^2).

Most of the codes do not allow any tensile stresses in the cement mortar including the Egyptian Code of Masonry structures. Accordingly, the differential settlements under the supports of the proposed roofing system (domes and vaults) were investigated.

One of the external pendentives supporting the analyzed roofing system was exposed to a differential settlement of 1.0 cm. Tension zones over the displaced support were observed in Figures 12 and 13. The tensile stresses reached 1 kg/cm^2 in some locations-close to the displaced support- which can be sustained by the binding mortar of the dome skin. While the reaction in (Table-2) resulting from dead loads and super imposed loads did not exceed 2 tons on the external pendentive (including its own weight), the 1.0 cm differential settlement induced tensile reaction of 12 tons. This draw back is recommended to be treated either by a strong foundation system (raft, strip footing, etc.), or excellent soil conditions below the foundations.

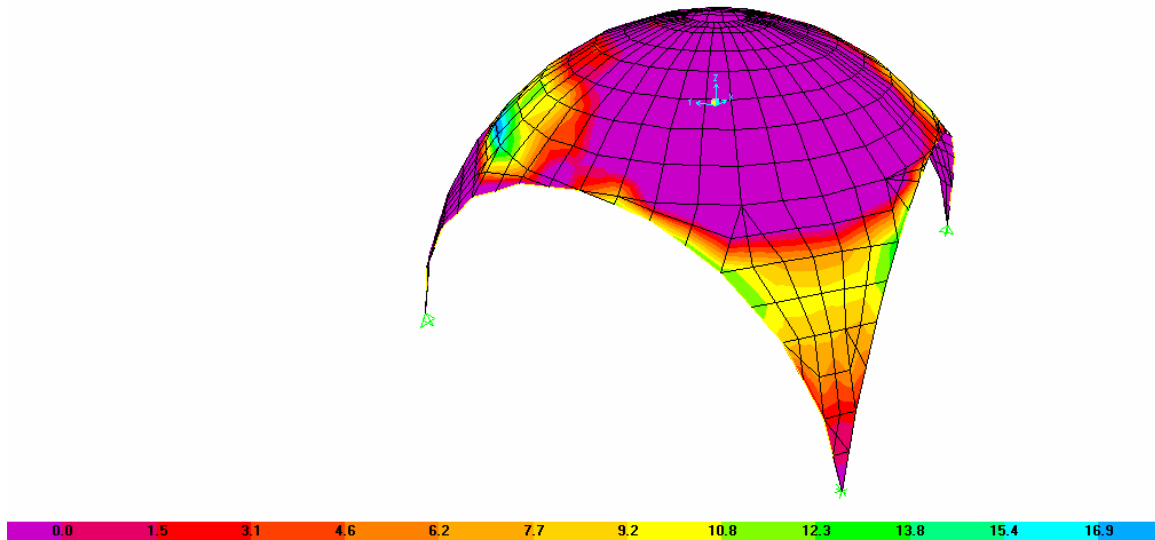


Figure-12. Tension zones in F11 direction - under 1.0 cm settlement.

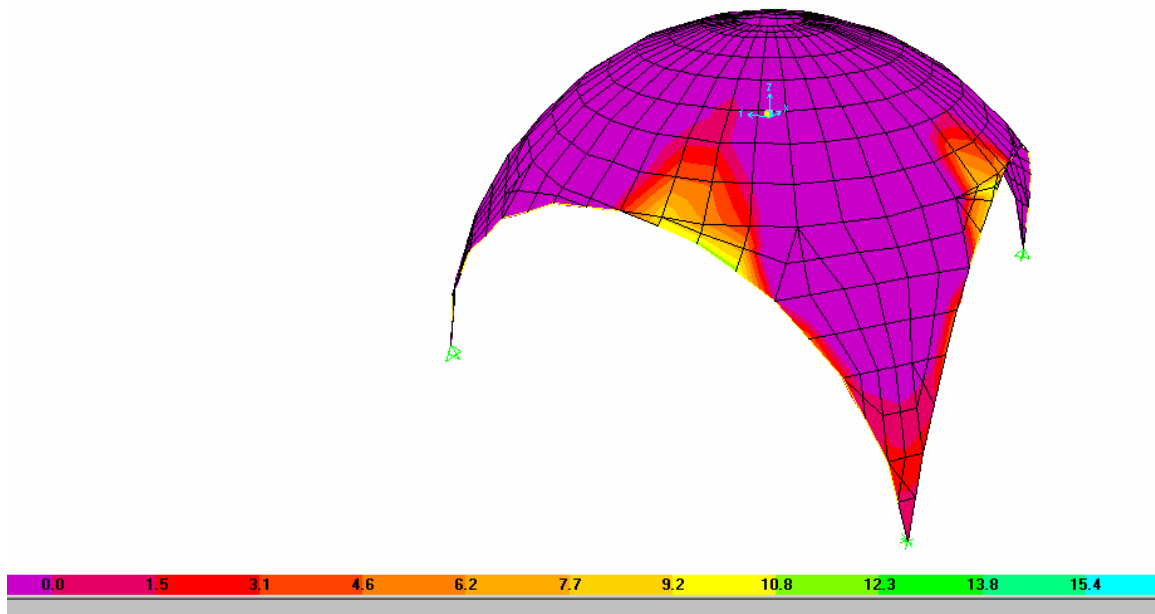


Figure-13. Tension zones in F22 direction due to settlement 1.0 cm.

Accordingly, to confirm with the Egyptian code regulations, the straw bale building under study was not allowed to be exposed to differential settlement. The soil was replaced with clean sand compacted in layers of 25cm each as specified in the Egyptian Building codes. Besides, a concrete raft foundation was adopted - that served as a flooring at the same time.

5.3.2. Induced stresses from wind loads

The building under study was also analyzed under wind load, as instructed by ECOP. It was conservatively assumed that the wind pressure acts only from one direction and positively. In actual fact, the external pressure profile of a spherical structure is partly

negative (i.e. suction) for angles between 45 and 135 degrees - relative to wind direction [13], this would act to reduce the load (Figure-14).

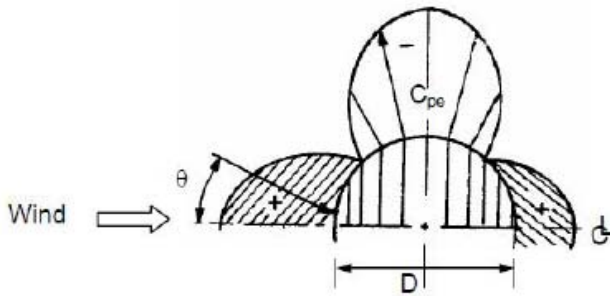


Figure-14. External wind pressure coefficients for a spherical structure.

In order to get the total wind load acting on the building, the force coefficient C_f and the effective area A_e , along with design wind pressure P_d were calculated. Hence, wind load F_w was derived from the equation:

$$F_w = C_f A_e P_d$$

Accordingly, wind stress of 56 kg/m^2 was applied on the dome.

The following cases of loading were investigated:

$$W = 1.3 \text{ D.L} + 0.9 \text{ wind pressure.}$$

$$W = 1.3 \text{ D.L} - 0.9 \text{ wind pressure.}$$

The maximum resulting stresses from the above load combinations were 4.7 kg/cm^2 for S11, and 10.6 kg/cm^2 for S22. Thus, the increase in stresses due to different cases of wind loading did not exceed 7% of the main loads case.

5.3.3. Reactions on rice straw cementitious brick columns

The resultant reactions in different directions are displayed in Table-3, which shows the values of the generated horizontal forces F_1 , and F_2 . The resulting vertical reactions F_3 were 1.63, and 3.2 tons - for external and intermediate supports respectively- which performs a stress of 1.51 kg/cm^2 on the external straw brick pendative of area 1056 cm^2 , and 2.25 kg/cm^2 on the intermediate straw brick pendative of area 1512 cm^2 . These values are less than one fifth the maximum stress reported from the above experiments of compressive stresses of 36.6, and 26.6 kg/cm^2 on the rice straw cementitious bricks of mix 1 and 2 respectively.

These results complies with the Egyptian Code of Practice ECOP 204-2005 [9]. Accordingly, brick of mix 2 was selected to build supporting systems for the proposed roofs as it complies with the Codes, and uses more amount of rice straw meeting the aim of the project as well as being more economic.

Table-3. Reactions induced on brick columns supporting the domes under main loads.

Support Location	Horizontal F1 (ton)	Horizontal F2 (ton)	Vertical F3 (ton)
External 1	0.45	0.45	1.63
External 2	0.45	-0.45	1.63
Intermediate 1	-0.9	0	3.2
Intermediate 2	-0.9	0	3.2

5.4 Finite element analysis results of roofing vaults

5.4.1 Stresses under main loads

The vault roof was analyzed under its own weight, in addition to a super imposed dead load of 100 kg/cm^2 . From Figures 15 and 16, the maximum forces in F11 and F22 direction were 2.5 and 8.5 ton respectively, resulting in an average skin compressive stress of 6 kg/cm^2 for S11, and 19.5 kg/cm^2 for S22 direction while the

tensile stresses in S11 direction did not exceed 0.5 kg/cm^2 . The vault was supported by a straw brick cementitious wall; consequently, differential settlement was not in the scope of study.

These values comply with the Egyptian Code of Practice ECOP 204-2005, which indicates one fifth the maximum value reported in the Egyptian Code of Practice ECOP 204-2005 for this kind of bricks (80 kg/cm^2).

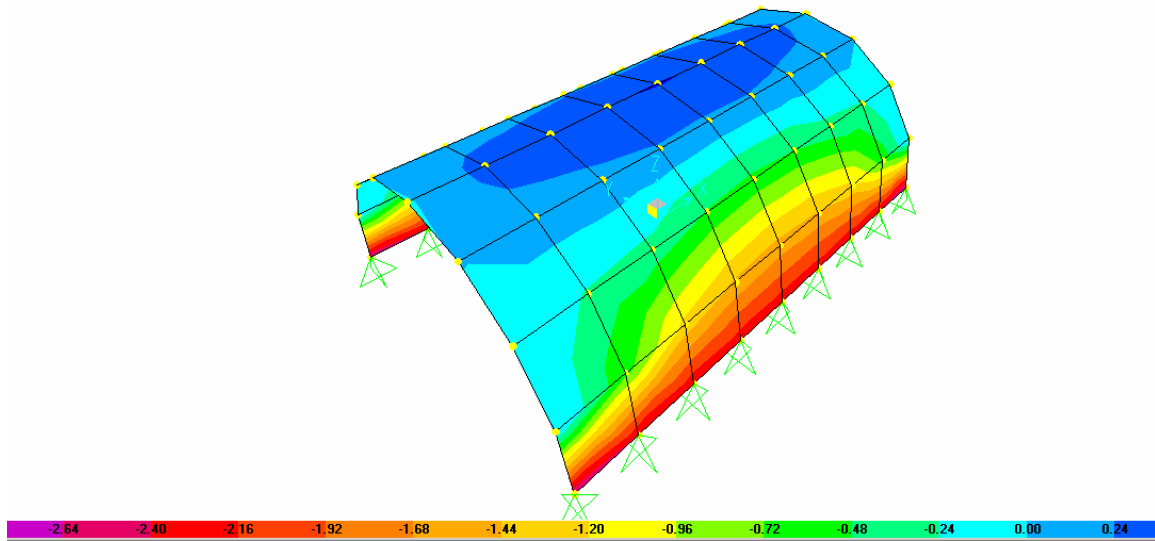


Figure-15. Induced forces in F11 direction of the vault roof under main loads.

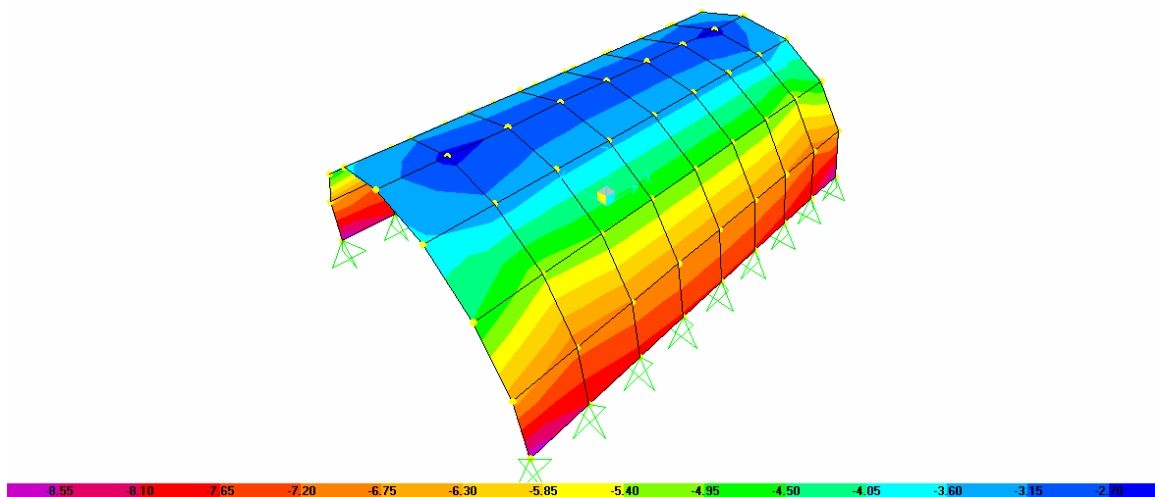


Figure-16. Induced forces in F22 direction of the vault roof under main loads.

5.4.2. Induced stresses from wind loads

The vault roof was analyzed under wind load, as instructed by ECOP. In order to get the total wind load acting on the building, the force coefficient C_f and the effective area A_e , along with design wind pressure p_d were calculated. Hence, wind load F_w was derived from the equation:

$$F_w = C_f A_e p_d$$

Accordingly, wind pressure of 56 kg/m^2 was applied on the vault.

The following cases of loading were investigated:

$$W = 1.3 \text{ D.L.} + 0.9 \text{ wind pressure.}$$

$$W = 1.3 \text{ D.L.} - 0.9 \text{ wind pressure.}$$

The maximum resulting stresses from the above load combinations were 6.5 kg/cm^2 for S11, and 20.8 kg/cm^2 for S22. Thus, the increase in stresses due to different cases of wind loading did not exceed 7% of the main loads case.

5.4.3 Reactions on rice straw cementitious brick wall

The reactions on the rice straw cementitious brick wall supporting the vault are displayed in Table-4. The values presented indicate that the maximum vertical reaction on the rice straw cementitious brick walls is 380 kg. Dividing the load on the element width 50 cm, and depth 12 cm, the stress on the straw brick wall is 0.6 kg/cm^2 . These comparatively low values emphasized the previous selection of brick mix 2.



Table-4. Reactions of the vault roof on the rice straw cementitious brick wall.

Support No.	F1 (ton)	F2 (ton)	F3 (ton)
1	0.0652	0.0739	0.2239
2	0.04	0.1143	0.3803
3	0.0193	0.1183	0.3762
4	0.0081	0.1181	0.3727
5	0	0.1176	0.3722
6	-0.0081	0.1181	0.3727
7	-0.0193	0.1183	0.3762
8	-0.04	0.1143	0.3803
9	-0.0652	0.0739	0.2239

6. CONCLUSIONS

This paper presents a structural roofing system of domes and vaults applied on a rice straw bale building supported by a new technique of recycled rice straw. The proposed technique of supports was rice straw cementitious brick pendants of areas 1056 cm² and 1512 cm² for the domes, and a strip of 12 cm width wall of the same brick for supporting the vaults. In order to test the proposed supporting technique under the domes and vaults a finite elements analysis of the proposed roofing system was performed, to check the safety of the roofing material, and their resultant reactions on the rice straw bricks support.

SAP program was used to analyze the different cases of loading under study including wind and settlement.

Findings are summarized as follows:

- Induced skin stresses in the proposed shell roofs lay within the acceptable limits for the used type of bricks (according to ECOP for commercial red brick);
- The reactions of the roofing system on the proposed supports were less than one fifth the maximum compressive stresses reached through the experimental tests for the rice straw cementitious bricks of mix 1 and 2;
- Wind pressure effect led to an increase in the internal forces that did not exceed 7% of those induced from main loads for both roofing systems;
- No differential settlement is allowed in this proposed system, so it is recommended to avoid such settlements by using stiff foundations and /or improving the soil conditions under this type of buildings. It is also recommended to avoid local settlement sources - as excessive irrigation and water leakage; and
- This case study emphasized the feasibility of using rice straw cementitious bricks as an innovative building technique to support the roofing systems recommended by the great architecture Hassan Fathy.

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