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Shading for the Inner Courtyard of the Holy Mosque of Makkah

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Abstract: The inner courtyard *(Sahan)* of the Grand Holy Mosque of Makkah can be provided with a shading structure to control the climate as well as to further enhance the quality of the enclosed space without compromising or hindering the regular and continuous functioning of the mosque. Obviously, any structural solution has to be lightweight and long span structure, which can be erected with in a short period of time with minimum of disturbance to the existing structure and ground. There are five different major structural systems that can accomplish these criteria: they are (1) Rigid reticular dome structure, (2) Pyramidal space frame Structure, (3) Low-rise pneumatic structure which can provide climate control to the entire mosque, (4) Tensile membrane structure, which will provide shading from solar radiation and (5) Open cable-net Structure. Tensile membrane structure can have a range of morphological variation with different effects on forms, space, lighting, cooling and ventilation.

The paper discusses the feasibility and architectural effect of all the five types of structural systems for shading the Grand Mosque *Sahan*. The paper also presents computer-generated models of all the structures with an additional view of the recommended Tensile Membrane structure as the optimum design solution.

Introduction

The Grand Mosque of Makkah is the most sacred site in Islam. Millions of Muslims come here to visit, pray and perform pilgrimage from all over the world. The Government of Saudi Arabia has successively remodelled and enormously expanded the Mosque to a grand and magnificent work of Islamic Architecture. To be comfortable, enjoy ease of movement, and for security of the visitors and pilgrims, the Saudi Government also has provided numerous services and various aspects of care to the users of the Mosque.

Because of the unique religious function, enormous number of moving users and unique configuration and size of the building, the Grand Mosque does not yet have air-conditioning and the inner court *(Sahan)* is not shaded against the hot sun. In Makkah, summer temperature reaches up to 50 degrees Celsius. To provide thermal comfort to the visitors and pilgrims, the inner court can be provided with shading with several types of structural systems. Each of these structural systems will bring about different character to the space, image of form and level of comfort. Choice of these systems has implication of cost, construction time and other technical considerations.

The design of any shading structure for this Holy Precinct must address following criteria:

1. Long Span: To maintain the regular and continuing tawaf (circum-ambulation) most part of the *Sahan* must be kept free from obstacles like columns, pylons, cables and other support systems;
2. Fast Construction: The construction time should be minimum;

3. Image: The structure should be achieved with minimum modification to the existing Mosque structure and the ground;
4. Moderate Cost: It should be realised and maintained within reasonable expenditure;
5. Natural Light: A good level of natural lighting should be available. It will be desirable to enjoy some sunshine and view to sky from the Precinct in the cooler times of the year;
6. Appearance: Shading structure should enhance the quality of the Mosque, when viewed from within and from outside.
7. Safety: Safety and security of the visitors and pilgrims is very important.

According to the above design criteria and the size and shape of building form, it is obvious that shading structure will be of wide span and lightweight structural system. Ale objective of this paper is to present several different practical and modem structural concepts, which is to satisfy the above mentioned criteria. Several kinds of such structural systems are discussed and analysed here in terms of their suitability for the Holy Precinct.

The five major structural systems are presented here, (1) Rigid Skeletal Dome Structure, (2) Pyramidal Space Frame Structure, (3) Air Supported Membrane Structure, (4) Tent Structure and (5) The Open Cable-net Structure. The structures shown here graphically represent a generic form and a range of morphological variation can easily be achieved with different formal expression and spatial character.

To decrease the enormous volume a dome encloses, the rise should be shallow, and for greater stiffness the dome may be built of double layers of struts. Roof cladding may be of heat reflective glass or have stretched fabric material. Dome forms require a circular base for its support (Fig. 1).

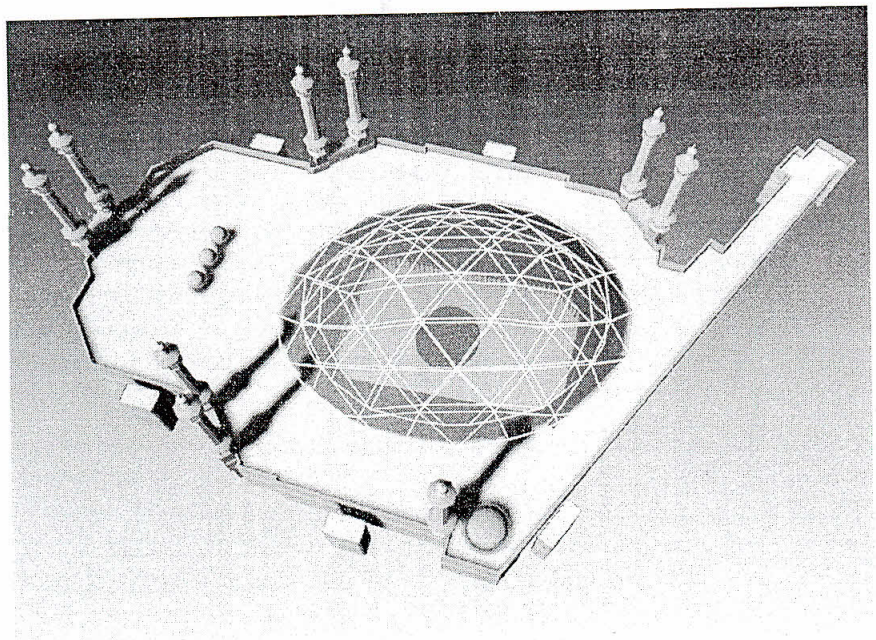


Fig. 1: Rigid Reticular Dome.

The 26,600 sq. meter court is oblong in shape. To solve this particular problem the dome either has to be large enough (about 240 m diameter) to sit on the roof of the Mosque, which will restrict much of roof level prayer space and specially *Tawaf* passage over *Sea* area. Also in all likelihood the Mosque structure is not designed to withstand the weight of the dome and other loads. Alternative could be the dome being small enough (about 120 M Diameter) to sit with in the court itself. To save all the prayer space and to keep free flow of people to the central space for *Tawaf*, the dome has to be elevated

above one story height (9m). Geodesic dome is simpler to construct with minimal scaffoldings. Geodesic geometry based on frequency subdivision of half of an octahedron will provide a flat circular base. Lattice or lainella dome will allow the structure to have a circular opening at the top, which will allow sunshine or daylight to illuminate the Holy Kabah. In this system about half of the *Sahan* space can be provided with shading. Air-conditioning will not be possible. Dome form goes well with mosque architecture. A glazed dome will enhance the quality of the court. Connections of the dome to the supporting columns are to be designed to permit a considerable amount of horizontal movement due to temperature change, drag and uplift due to wind load. The big drawback of domed interior is its acoustic problem. Elevated dome with applied sound absorbent material will have less acoustical problems but this will compromise transmission of light.

Unlike a dome, pyramidal (or polyhedral) form can have an irregular octagonal base. The whole of *Sahan* can be free of any column supports. The tubular strut members will have the same length and the same outer diameter. It will **fit** very closely to the irregular octagonal shape of the courtyard. The base of the pyramid is to sit on the surrounding Ottoman Portico, and the pyramid's weight will be supported by ten (eight on corners and two at the mid points of opposite long sides) strong steel pylons, which will go through the roof and floor of this masonry domed portico area. Apart from shading the *Sahan*, it will be possible to air-condition the entire space. The approximate height of the pyramid pick will be 50 meters above the *Sahan* level; the depth of the space frame will be about 4 meters (Fig. 2). The structure will provide very monumental effect when viewed from inside as well as from the outside.

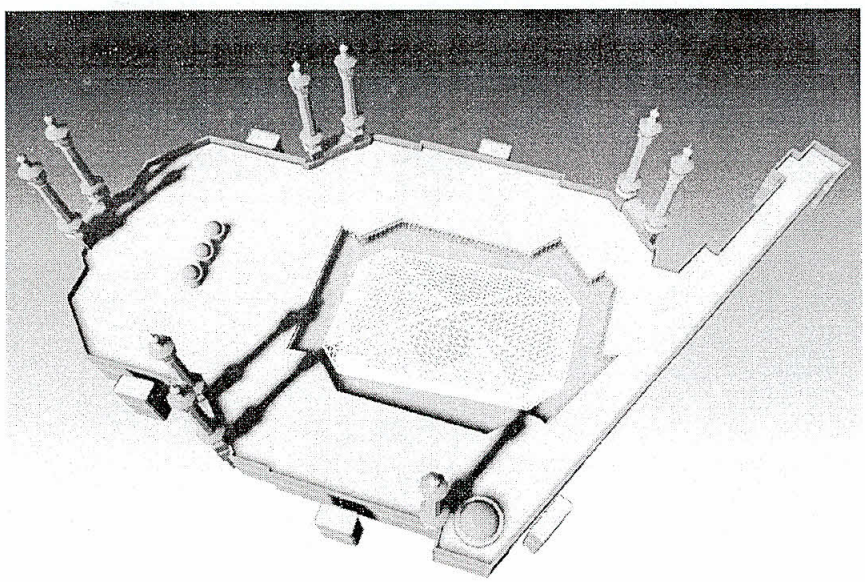


Fig. 2: Pyramidal Space Frame.

If the structure is to be made of stainless steel and anodised heat insulated glass, the internal spatial quality will be overwhelming. It will also allow the pilgrims and visitors to experience the surrounding Mosque building and sky. From the upper levels, through the transparent cladding and metal space frame, pilgrims and visitors will be able to glance the Holy Kabah and the *Sahan*. Connections of the structure to the supporting piers are to be designed to permit a considerable amount of horizontal movement due to temperature changes, drag and uplift due to wind load. The enormous headroom space will produce very large air-conditioning load. The ambient July temperature of Makkah reaches up to 50 degree Celsius and in January temperature goes down to 15 degree Celsius.

Diurnal variation is up to 20 degree Celsius in the summer. Opening will be required at the crest of the pyramid to ventilate the stratified hot air. A large rain water drainage system is to be incorporated along the base of the structure. Air-conditioning is the decisive consideration. Chilled water plants and cooling towers require separate buildings on ground away from the Mosque, since they give off heat noise and vibrations. Availability of site space is very limited. The location of air handling rooms and air distribution system will have to be designed with great care so that they do not consume the quality and quantity of the space. This will be an expensive and time taking construction process and may disrupt the regular and continuing religious activities.

This is the simplest and least expensive way to cover and shade the Courtyard space. The form of the pneumatic structure is the result of the force system acting upon it (Fig. 3). If the structure is built of lightweight, thin and flexible material, the membrane of the structure will be under pure tension. Form can be designed to take the shape of the *Sahan* area and entire area will be free from columns and cables. The air pressure differential between outside and inside of the structure is only of the order of 115000 atmospheric pressure. It is hence not noticeable to the occupant but it is sufficient to hold up the covering membrane. Air locks have to be provided to contain the air pressure and continuously operating fans or blowers are necessary to maintain it. Doors and windows are to be air sealed, but because the air pressure deference is so small, the actual loss of air through opening is also small, and can easily be compensated by fans. To keep the ground level free for circulation the membrane can not be anchored to the ground, a suitable position would be the roof level of the Ottoman Portico.

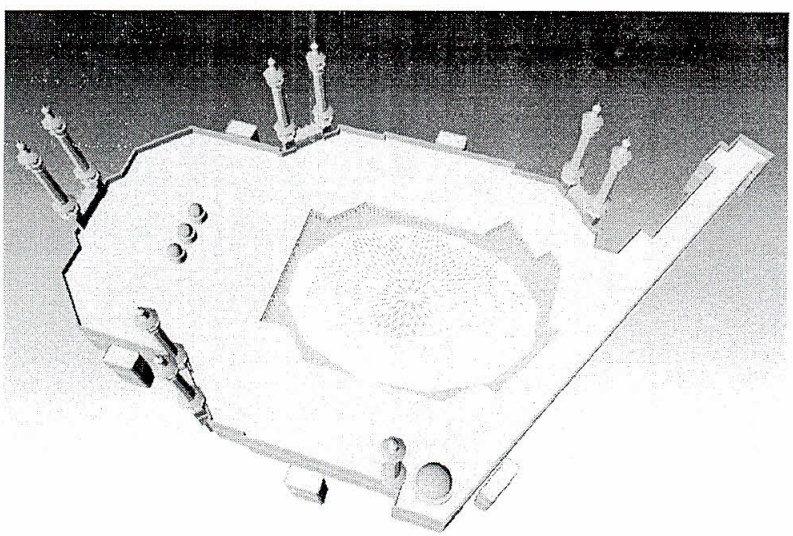


Fig. 3: Low-rise Pneumatic Structure.

However the Portico itself is rather a delicate old stone masonry structure, and it can not withstand the inward pull of membrane and the uplift of the wind load. To anchor the membrane an independent structural system has to be introduced on to the Portico area. Depending on the transparency or opaqueness of membrane, availability of natural light inside will vary greatly and artificial supplementary lighting may be required even in the daytime. With a smooth membrane to cover such large space will result at an enormous tensile stress per unit length of membrane, To overcome this disadvantage it is possible to use an air inflated steel cable net in combination with the outer membrane, This way when the membrane is inflated, it lifts the cable net with it. When the final shape, depending on the length of the cables, is reached, the pressure forces the cable in to tension,

thereby holding the inflated membrane down. The membrane is puffed out between the cables. This will reduce the head room under the shading structure and thereby reduce the air-condition load. Another advantage is that with much greater curvature on the subdivided membrane surface, its membrane tension will be greatly reduced. which will add to the life of the structure. It would be also easier to replace the subdivided membrane panels.

The pressurisation system is an integral part of the structural system and should be provided with maximum reliability. In order to prevent loss of air when entering of leaving the Mosque, revolving doors for users are to be provided, provision must be made for emergency power, in the event of loss of primary electric power. The added cost of inflation and special access equipment will be more than the savings in the basic membrane structure. Since the building is pressured with conditioned air, the *Sahan* along with the surround buildings should better be air-conditioned. Several large compressors, chillers and cooling towers will be required around the Mosque building.

The membrane can be wire reinforced for additional strength and durability in the unlikely event of accidental rupture, Protective cables are to be provided in case the membrane does deflate. In this system the view from the upper levels of the Mosque to the Holy Kabah will be permanently lost, people will see only the top of the membrane which is rather an unpleasant view. View to the sky from the *Sahan* will be permanently lost. Since Air supported Structure is a permanent structure it cannot be de-mounted in the good weather months. The natural lighting inside the structure will be always defused and non-directional.

A tent structure system can also give large unobstructed span. Beautiful examples of this system exists in the Kingdom. Tent has also historic and cultural connection with the Mosque. The rigidity and strength of tent membrane derives from the pre-stressing force of the membrane through the ridge cable, valley cable and edge cables (Figs. 4 & 6).

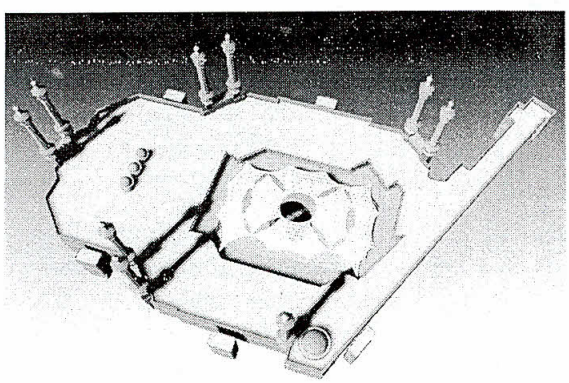


Fig. 4: Tensile Membrane Structure.

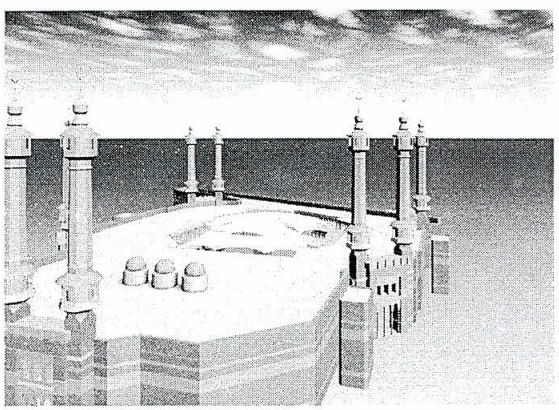


Fig. 6: Tent Structure.

Though a large span flat tent is possible, the greater the surface curvature (principal curvatures) of the membrane, the lower the resultant membrane stress. The flatter the angle at the base the greater masts the lateral load on the mast or anchorage system. The quality of cutting pattern of the membrane is also very important for the usefulness, economy and appearance of all tensile structures. Double curved surface must be made of strips of fabrics and these strips should follow the detection of principal curvatures. Minimal surface tent with zero mean curvature, can be made to cover space of any configuration. If the tent is designed on minimal surface geometry, following soap film geometry, the stress will be uniform at all points and in all surface directions and the strips can be laid out in any direction. It is the uniformity of stress that adds life and aesthetic quality to the tent structure.

A ring of eight masts will be required to be installed in the central *Sahan* area. lie space can not be air-conditioned since there will be openings at the periphery and at the middle around the Holy Kabah. Good shade will be provided and solar heat absorption be the marble floor and glare will be eliminated. Air can circulate through the openings in the tent. Further ventilation can be provided by electric fans.

Modern tents are relatively permanent structures. They are low in maintenance and create sculptural form and space. This project lends itself more realistically to tent structure. Tent will provide free and open access from the side buildings in to the *Sahan,* The tent will create more architectural drama, being high above the ground, the structure can be largely not monitored and there is historical tradition to have awning structure in front of the portico around *the Sahan* space.

Horizontally stretched cable net structure with lightly stretched fabric covering will provide good shading in the *Sahan* area and will cut down heat gain on the marble flooring. Cable-net system may not require any mast supports in the interior of the courtyard. Cable-net can be fabricated on many different patterns (Fig. 5).

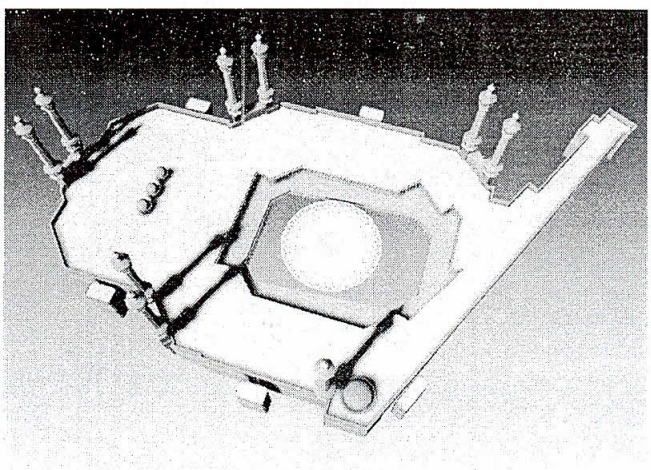


Fig. 5: The Open Cable-Net Structure.

In the radial system, prestressing force is to be applied by jacking at the outer anchoring pylons only Cable-net with lightly stretched fabrics will provide ventilation in the space and the fabrics can be easily replaced periodically and can be completely taken out in good weather time. A glare free and brilliantly lighted *Sahan* will be achieved. Air conditioning is not possible, but cooling can be accomplished by ceiling fans suspended from the cable net. In both the patterns the central part of the net can be left open so that sun light could shine on the Holy Kabah. The structure would need steel pylons, cable-net and restraining cables. To allow some sag and to protect the structure from accident, the cable-net can be installed at 9 meters high.

Conclusion

The Holy *Sahan* of the Grand Mosque can be shaded with several different lightweight structural systems that meet the original design criteria at different levels. Proposal one, the rigid skeletal dome structure has the inherent problem of acoustics. In proposal two, the construction of pyramidal space frame is the most expensive and it requires longer construction time. In proposal three, the air supported system, the views between outside and inside will be permanently lost. In proposal four, though the tent system requires installation of eight masts in the *Sahan* area, it is the most elegant structural system that satisfies the design criteria very satisfactorily and hence, it is the optimum

solution for shading the Holy *Sahan.* For a simpler, quicker and more economical solution, proposal five, the cable-net system discussed here will be a correct choice. lie designs presented in this paper represent preliminary conceptual stage approaches. The selected prototype needs further design development.

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مظلة لساحة الكعبة في المسجد الحرام بمكة المكرمة

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ملخص البحث: يمكن تغطية صحن المسجد الحرام بمظلة للتحكم البيئي ولزيادة فاعلية فراغ الكعبة الشريفة وبدون تجريح لوظائفه الدائمة والمنتظمة. ومن الواضح أن أي حل إنشائي لهذه المظلة يجب أن يكون خفيف الوزن مشكل من جوائز طويلة المسافة، كما يجب أن يكون وقت الإنشاء قصيرا بشكل لا يكدر المصلين ولا يعرضهم أو البناء لأي أذى. وهنالك خمس منظومات إنشائية رئيسية لتحقيق هذا الهدف وهي : ١- منشأة ذات قبة شبكية صلبة، ٢- إنشاء فراغي هيكلي هرمي، ٣- منشأة مليئة بالهواء المضغوط ذات التقعر الخفيف، ٤- إنشاء نسيج من الأغشية الرقيقة والتي يمكن لها حماية المصلين من الشمس، كما تعطي تكويناتها المتنوعة تأثيرات معينة في أشكالها ، فراغ الصحن ، الإضاءة والتبريد والتهوية، ٥- إنشاء من الحبال (الكوابل) المشدودة .

ويناقش هذا البحث مدى تحقيق الاحتمالات ومدى تأثيرها المعماري مع ترجيح الاقتراح (٤) المذكور أعلاه كخيار مفضل .