Shaded Dome: a hybrid air-supported – tensile membrane structure

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1 Abstract

The Shaded Dome[patented] is a semi-permanent facility, comprised of an air-supported **dome** covered by a tensile membrane **shade**. The two layers are separated by a grid of spacers, through which forces are transferred. In the space between the two layers a constant natural air flow is present, which enables a pleasant internal microclimate. This passive design element provides protection from extreme climatological conditions like solar radiation, wind, high air temperature, humidity and precipitation. The concept provides a design challenge concerning the force balance between the air-supported dome, as the primary stability structure, and the tensile membrane shade which must remain in shape. The Shaded dome provides a solution for example for temporary events, such as World Cups or the Olympics, to replace the large and expensive venues, which often are abandoned once the event is over.

Shaded Dome Technologies explored the basic principles of an air-supported dome covered by a shade through rigorous experimenting. Parallel to empirical testing in scaled handmade models, a design model was scripted and its behaviour simulated. These two “methods” were not sequential but informed each other. The concept is cast in a computational design model. This computational model is used to simulate the inflation of the air-supported dome, generate the tensile membrane shade on top, study and vary each aspect of the design and optimise and prepare the geometry for manufacturing. The results produced within this computational framework were further explored and validated using finite element method software. This all lead to the construction of a successful prototype.

Keywords: The Shaded Dome, air-supported structures; tensile membrane structures; hybrid structures; light-weight structures; computational design; finite element method.

2 Introduction

Almost any usage of public space, be it sports, exhibits, entertainment, etc., requires comfortable environmental conditions such as cool temperatures, medium humidity levels, satisfactory lighting and ventilation performance.

Mainly focusing on areas suffering from high temperatures and irradiation levels, a consortium of three Dutch companies (ZJA Zwarts & Jansma Architects, Royal HaskoningDHV and Poly-Ned) developed a new concept: The Shaded Dome[patented]. This hybrid concept is an eco-friendly, semi-permanent building facility, initially designed to deliver high-tech solutions and boom the sports industry of desert-covered countries. Key to that challenge is controlling the indoor environment through the development of new design principles and low-tech building materials [1].

In 2010 the FIFA awarded the World Cup of 2022 to Qatar. This created a strong need for developing indoor training facilities that could protect athletes from exposure to excessive heat. This is where the idea for the Shaded Dome originated from. Because of the temporary nature of the World Cup and the requirement of a large open space to host sport events, the idea started with an air-supported dome. However, these structures provide little protection against direct solar radiation [1]. Therefore, a shade was added in the form of a tensile membrane structure. A multitude of small spacers keep the shade separated from the dome, creating a cavity between the dome and the shade. The cavity functions as a buffer zone between the outer climate and the inner microclimate. When direct solar radiation hits the shade, the heat conducts through the membrane and heats up the air in the cavity. The warm air rises to the top of the cavity where openings are present, releasing the warm air. Due to the chimney effect, cooler air is automatically drawn into the cavity from ground level, letting the cavity retain its buffering function (Figure 1).

In Section 3 of this article, the structural concept of the Shaded Dome is discussed in detail. In Section 4, the Shaded Dome design model is briefly highlighted, while Section 5 elaborates on the validation of the structural concept with a prototype. Section 5 discusses the validation of the prototype and the design tool, with some concluding remarks in Section 7.

3 Hybrid Structure

Although air-supported structures and tensile membrane structures are common structures, their combination into a hybrid structure like the Shaded Dome is new, and therefore, the design has been granted a patent [2].

3.1 Air-supported dome

The air-supported dome is the core of a Shaded Dome. It serves as the primary loadbearing structure and it assures the overall stability. The air-supported dome consists of a single membrane covered by a custom-made steel cable net [1]. This cable net dictates the overall shape of the dome and carries the majority of the loads, by which it significantly reduces the forces in the membrane.

The air-supported dome is stable due to the internal overpressure. Under moderate weather conditions the internal overpressure is set to 2.5 mbar, whereas under extreme climatological conditions, such as sand storms, snow or even hurricanes, the stability is assured by increasing the internal overpressure to a comfort-based limit of 5.0 mbar.

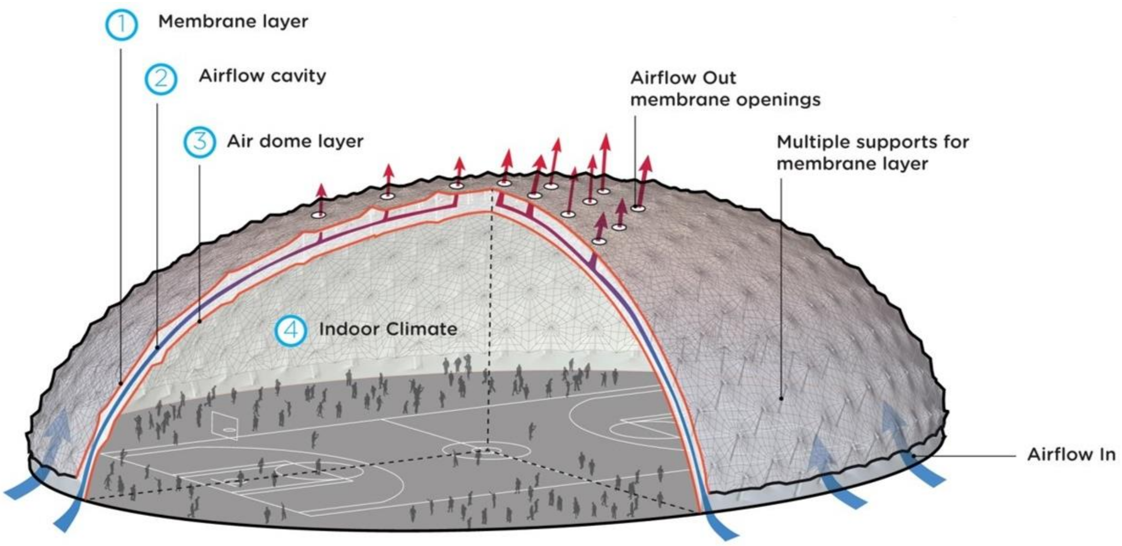

Figure 1. Functional Diagram of the Shaded Dome showing the buffering effect and the airflow in the cavity.

3.2 Spacers

Inside the cavity, a multitude of spacers form the link between the air-supported dome and the shade. A spacer is a circular hollow section capped with a convex plate to prevent puncturing of the shade. At the bottom it is connected to the steel cable net and at the top it supports the shade.

The function of the spacers is to maintain the cavity spacing and transfer forces between the two layers. They transfer the overpressure from the air-supported dome to the shade, while external loads, such as wind forces, are transferred in the opposite direction.

3.3 Tensile Membrane Structure

The shade shields the dome from excessive solar radiation, wind and precipitation loads [1]. This membrane is composed of patches which span between the spacers, as shown in Figure 2. Because the spacers are positioned on top of the nodes of the cable net, the patches follow the pattern of the cable net.

Figure 2: View of the shade, showing a few patches (on the right-hand side) and the complete membrane (on the left-hand side)

As is common for tensile membranes, the stability comes from their anticlastic shape [3]. The convex curvature is provided by the global shape of the dome, which is a result of the internal overpressure, and the concave curvature is provided by the curvature of the patches, which is a result of the relation between the size of the patches and the tension caused by the outward force in the spacers. At the periphery, the membrane is fixed to the foundation by either anchors or suspension cables.

3.4 Dome – Shade Interaction

The air pressure is the primary load bearing system in a Shaded Dome. Both the air-supported dome and the tensile membrane shade rely on the internal overpressure for their stability. The overpressure acts on the air-supported dome, which enables the cable net to transfer forces to the spacers holding the shade, as shown in Figure 3. The equilibrium between the forces in the dome and the shade is the most critical and delicate design aspect of the Shaded Dome.

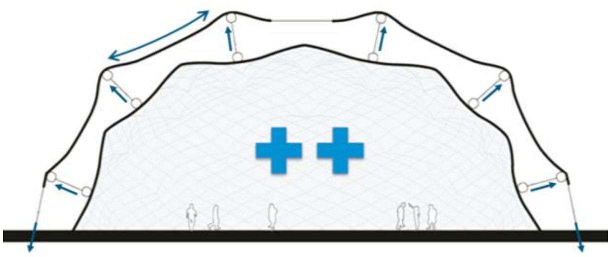

Figure 3. Section of the Shade Dome, showing the overpressure in the air-supported dome (blue plusses) and the forces (blue arrows) being transferred via the spacers to the shade.

There are ways to influence this force balance. First of all, the balance can be shifted in favour of the shade by applying stress compensation. This means, shrinking the shade patches to account for the required stress. However, the spacers act as spring supports, which makes determining the exact stress compensation an iterative process. Secondly, the force balance can be shifted both ways by changing the stiffness ratio between the cable net and the shade. For example, a reduction of the stiffness of the cable net will result in higher cable net strains. Hence, more forces will flow to the shade. Conversely, by increasing the stiffness of the cable net, the amount of forces flowing to the shade will be reduced. A third way to influence the force balance is by applying adjustment options to the edge of the shade, such as turnbuckles. However, the influence of this option is rather limited, especially when the structure becomes larger.

4 Parametric Design and Automated Engineering

As one can imagine, the Shaded Dome concept has many possible applications. From covering small tennis courts to accommodating large exhibition areas. However, the structure consists always of the same parts and order but with different dimensions. This provides the perfect opportunity for parametric design and automated engineering.

Shaded Dome Technologies created a computational design tool which generates a Shaded Dome down to its fabrication specifications. The design tool consists of a parametric model for designing, generating geometry and providing required output for verification software for structural engineering and building physics.

4.1 Parametric Design

The parametric model is the principle tool with which a Shaded Dome is created and in which the design requirements, the design process and the technological process and products are captured [4], using Grasshopper [5] and VBA. The design requirements are the input for the parametric model, and through generative computational algorithms, such as an inflation simulation, optimizations in the sizes of the patches, positioning the entrances, etc., a Shaded Dome is generated.

This output is later explored and validated in terms of structural engineering and building physics using finite element method software. After this verification, the latest adjustments are made and the parametric model generates the outputs necessary for manufacturing and assembly [6].

4.2 Automated Engineering

Once the initial Shaded Dome is generated, its structural integrity is verified using Finite Element Method (FEM) software. Each element coming out of the computational model is assigned to an element group and a self-defined Python [7] class.

Since a Shaded Dome consists of three types of structural elements, that is, trusses, cables and membranes, also three Python classes are defined; the truss, the cable and the membrane class. Depending on the group and/or class to which an element belongs different geometric and material properties and loads are assigned. The geometry, including all structural information, is parsed using Python into ready-to-use FEM software files for structural analysis (for instancing in Oasys GSA [8]).

5 Concept Development

The Shaded Dome originates from the idea of a passively ventilated air gap around a dome. While the focus of this concept has been on providing a comfortable micro-climate for the user, the structural aspect of it has never been undermined throughout its development.

As merging a tensile membrane on top of an air-supported dome is a new concept, it soon became essential for the design team to test the principle. Several models have been made with the aim of empirically verifying the rising and stability of the spacers when overpressure is applied in the dome (Figure 4). The models scaled up and became more elaborated each time to test involvement of more structural elements, such as the spacers, cable net, anchors and the shade.

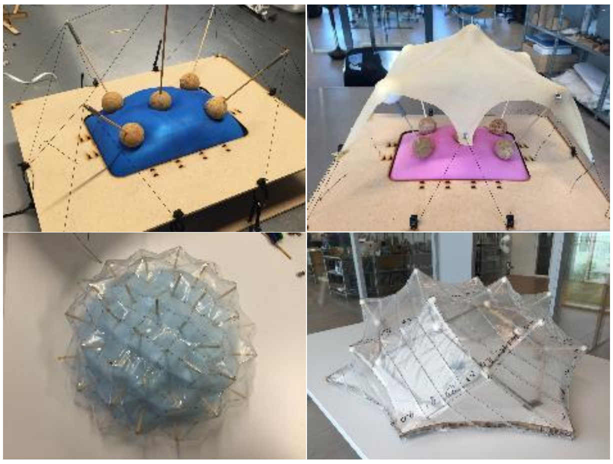

Figure 4: Scaled models to test the hybrid concept

5.1 Structural Development

After verifying the validity of the behaviour of the spacers, the lessons learnt from earlier studies and models were incorporated into a prototype. A structural analysis has been conducted to guarantee a stable shade and come to a deeper understanding of the structural aspects of this hybrid structure.

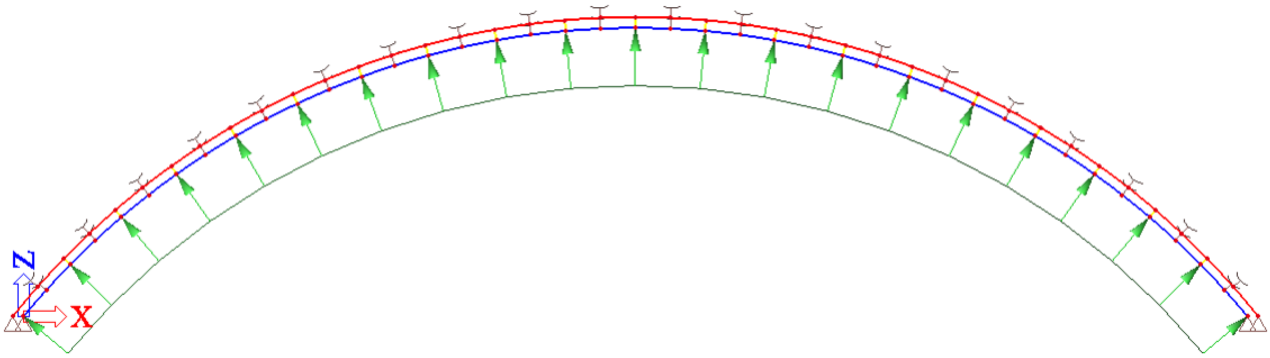

Figure 5: Two-dimensional FEM model to study the interaction the hybrid structure, with the blue cable representing the air-supported dome and the red cable representing the shade

The analysis of the hybrid interaction started with a basic two-dimensional FEM model, consisting of two cables and a few trusses (Figure 5). This model can be considered as a cross-section of the three-dimensional structure at half its length. The analysis provided a lot of insight in the force balance between the air-supported dome and the tensile membrane shade. It showed that a part of the forces is automatically transferred from the air-supported dome to the shade, with the exact amount depending on the dimensions of the structure. It also showed that the force balance can be influenced by changing the stiffness ratio between the air-supported dome and the shade, or by applying stress compensation to the shade. But most importantly, it showed the sensitivity of this force balance, because a minor change in the stiffness of one of the elements or in the stress compensation for the shade can significantly shift the force balance.

In the next phase, a three-dimensional FEM model was developed and optimized, which resulted in three design criteria. Firstly, the prestress in the tensile membrane shade should not be less than 1.3% of the average tensile capacity of the material [9]. This is required to prevent fluttering of the shade under wind loading. Secondly, the principle stresses in the shade should not differ by a factor of more than 10 [3]. This is required to prevent wrinkling of the shade. Finally, the anticlastic shape of the shade must be determined by means of form-finding.

5.2 Prototype

A prototype was develop using the computational model. All the parts and pieces were fabricated based on the output from this model and with respect to the results of the structural analysis. The prototype had a floor plan of 18.0 by 13.5 meters and a height of 6.0 meters. The floor plan corners are rounded with a radius of 5.0 meter. For this specific case, the FEM analysis showed that the shade should be shrunk with 2.0% to reach a prestress of at least 1.3% in the shade. The initial strain, in combination with form-finding of the shade resulted in the required cutting patterns. And finally, the shade was checked for wrinkling. The coloured areas in Figure 6 indicate the parts of the shade where wrinkles are expected. This will be around the rounded corners at the base and around the connection of the shade with the spacers.

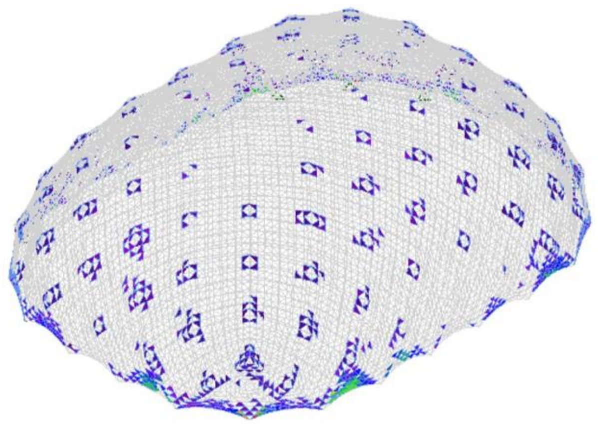

Figure 6: Three-dimensional FEM model of the prototype, with the coloured elements indicating a difference in principle stresses of more than a factor 10

Figure 7: Photos of the Prototype

The real Prototype is shown in Figure 7. In this real-life scale, it verified the successful role of the computational model and the parameters opted for the formation of the shade. However, it also showed room for improvements in terms of technical detailing.

6 Discussion

The prototype is a valuable source of information and offers a lot of insight in the behaviour of this hybrid structure. Its design principle is that the air-supported dome provides the global stability and the tensile membrane shade must assure only its local stability. Hence, the majority of forces should remain in the air-supported structure and, at least, a force of 1.3% of the material capacity should transfer to the shade. Finding this equilibrium is easier for Shaded Domes with a large radius, because a larger radius results in larger forces, given a constant overpressure. The required prestress in the shade on the other hand, is independent of the radius. Therefore, the larger the radius the smaller the fraction of forces required in the shade, which is beneficial for the global stability.

Despite the benefits of a larger radius, it also has its downside. For instance, a larger radius means a flatter structure, which is more vulnerable for water, snow and sand accumulation. Besides, a larger radius will result in a heavier structure because of the larger forces. Also, a larger radius might limit the usable floor space, depending on the intended use of the Shaded Dome.

7 Conclusion

In this paper the structural and bioclimatic concept of the Shaded Dome is described. Because of the extensive variety of applications for the Shaded Dome a computational model has been developed. The interaction of this hybrid structure was verified by means of numerous small physical models and a full-scale prototype. With the development of the prototype three design criteria were established. Firstly, the prestress in the shade should not be less than 1.3% of the average tensile capacity of the material. Secondly, the principle stress in the membrane should not differ by a factor of more than 10. Finally, the anticlastic shape of the shade must be determined by means of form-finding.

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