STRUCTURAL EFFICIENCY OF DEPLOYABLE STRUT-TENSIONED MEMBRANE STRUCTURES

T.C. Tran[1] and J.Y.R. Liew[2]

[1]*Department of Civil Engineering, National University of Singapore, #02-18, BLK E1A, 1 Engineering Drive 2, Singapore, 117576*
Tel: +65 6874 6498; Fax: +65 6779 1635, Email: tranchitrung@nus.edu.sg

[2]*Department of Civil Engineering, National University of Singapore, #05-13, BLK E1A, 1 Engineering Drive 2, Singapore, 117576*
Tel: +65 6874 2154; Fax: +65 6779 1635, Email: cveljy@nus.edu.sg

ABSTRACT: A novel system of deployable strut-tensioned membrane structures (DSTMS) has been proposed recently for the purpose of fast-track construction of large span enclosures. The objective of this paper is to determine the most optimum design parameters for the proposed DSTMS. Efficiency studies are carried out on 48m x 48m square grid of two DSTMS groups which are the Cone-shaped and the Umbrella DSTMS. Geometrical non-linear analysis is performed to evaluate the weight efficiency of different configurations of DSTMS. The minimum weight of the structures required to support predetermined load combinations is used as an optimization algorithm. DSTMS are proved to be capable of enclosing large span with weight efficiency as of double-layer space truss. The deployment efficiency of DSTMS is verified by building prototype models.

Keywords: Deployable strut-tensioned membrane structures, geometrical non-linear analysis, efficiency studies

1. INTRODUCTION

The concept of deployable strut-tensioned membrane lies on the idea of combining a system of deployable skeleton with high strength membrane to span over large space in one shot. This combination makes use of high strength membrane as a tension component to stabilize the deployable skeleton. On the other hand, membrane can be pre-tensioned by the deployment of the deployable skeleton, thus reducing the tensioning work.

This design concept was first proposed by Liew and Tran [1], followed by two classes of deployable strut-tensioned membrane structures (DSTMS) which are the Umbrella DSTMS and the Cone-shaped DSTMS. On one hand, the structures benefit the capability of rapid erection, easy transportation of deployable structures [2]. On the other hand, they inherit the appealing shape and light weight of tensioned membrane structures [3]. They are also proved to be capable of enclosing large span space with weight efficiency as of double-layer space trusses, thus overcoming the inherit weakness of deployable structures.

In this paper, the conceptual design of the Umbrella DSTMS and the Cone-shaped DSTMS is briefly reviewed. After that, the efficiency studies are conducted to determine the most optimum geometry of the two proposed DSTMS.

2. CONCEPTUAL DESIGN OF DSTMS

Deployable strut-tensioned membrane structures (DSMTS) are constructed from modules formed by interconnected struts, continuous membrane and cables to achieve self-stress equilibrium in the fully deployed configuration, thus removing the need of anchoring system.

Based on this concept, two novel DSTMS groups and their versatility are generated. Figure 1 shows the geometry of an Umbrella DSTMS module. This configuration is inspired by the umbrella mechanism, in which the cloth on top is opened and tensioned by the opening of the rods attached to it.

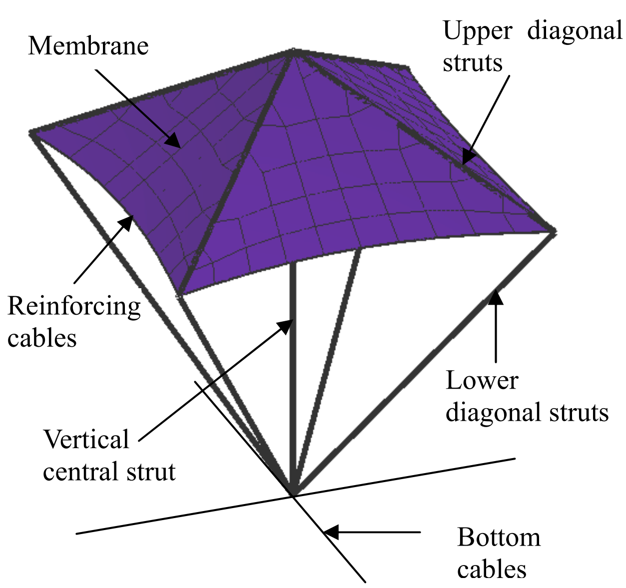

Figure 1. Geometry of an Umbrella DSTMS in Deployed Configuration

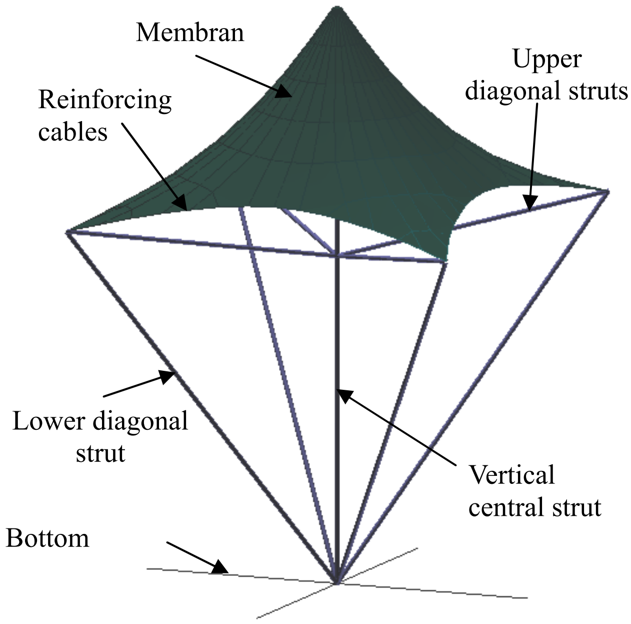

Figure 2. Geometry of a Cone-shaped DSTMS in Deployed Configuration

Each Umbrella DSTMS module consists of four upper diagonal struts which form a top pyramid, four lower diagonal struts which form a bottom up-side down pyramid, a vertical strut and membrane. The deployment process of the Umbrella DSTMS module is illustrated in Figure 3. Membrane attached on the top pyramid is opened and tensioned as of an umbrella. The deployment is locked by the vertical strut, which is in tension due to the self-stress equilibrium of the module.

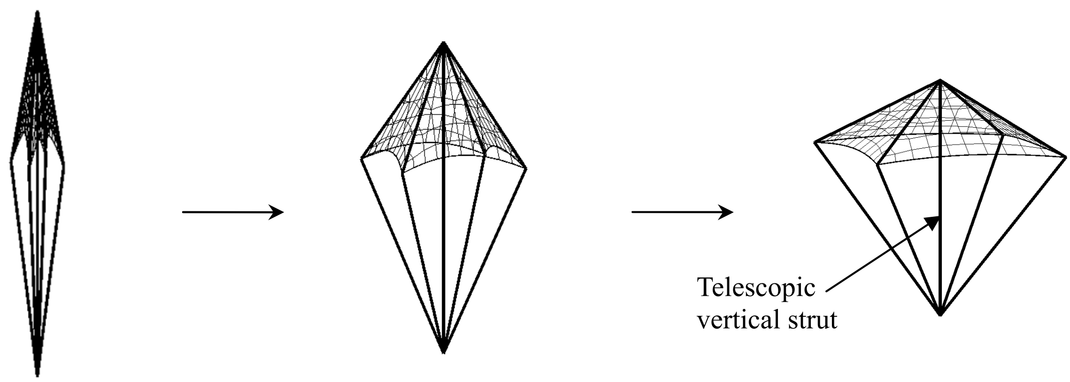

Figure 3. Deployment Process of Umbrella DSTMS Module

The geometry of a Cone-shaped DSTMS module is as shown in Figure 2. Basically, each module consists of four upper diagonal struts which form an up-side down inner pyramid, four lower diagonal struts which form an up-side down outer pyramid, a vertical strut and membrane. When the module is deployed, the membrane is propped at the center by the vertical strut and pulled down at four corners by diagonal struts. Therefore, the membrane forms a cone shape at the deployed configuration. The deployment process of Cone-shaped DSTMS module is illustrated in Figure 4. Unlike the Umbrella DSTMS, the vertical strut of Cone-shape DSTMS module is acting as a mast, and thus it is in compression. However, there are four upper diagonal struts connected to the vertical strut, providing an effective restraint point at its intermediate length. Hence, the effective buckling length of the vertical strut is reduced significantly.

Versatility of the DSTMS can be achieved by assembling identical modules in different ways to suit the shape and size of the applications. DSTMS modules are interconnected at their middle nodes while their bottom nodes are linked together by a layer grid of bottom cables. Typically, there are two general types of DSTMS which can be formed: flat structure and curved structures. By adjusting the grid size of the bottom cable layer to be equal to or smaller than the module width, a flat or a curved DSTMS is generated accordingly as shown in Figures. 5 & 6.

When DSTMS modules are interconnected together, the membrane is laid and tensioned continuously from module to module. Therefore, there is an interaction between adjacent connected modules due to the tension action in membrane. Hence, in the deployed configuration, the whole structure is in self-stress equilibrium state. The bottom cables are thus self-pretensioned to balance the tensile stress in the membrane. In addition, these bottom cables are pre-tensioned further due to the self-weight of structure. These prestressed cables also help the structure resist reversal load when subjecting to uplift wind force. The uplift wind force may be partly resisted by the top tensioned membrane.

Under gravity load, the top bars are in compression and the bottom cables are in tension forming a couple to resist bending action. The diagonal and vertical struts are the web elements to resist shear force.

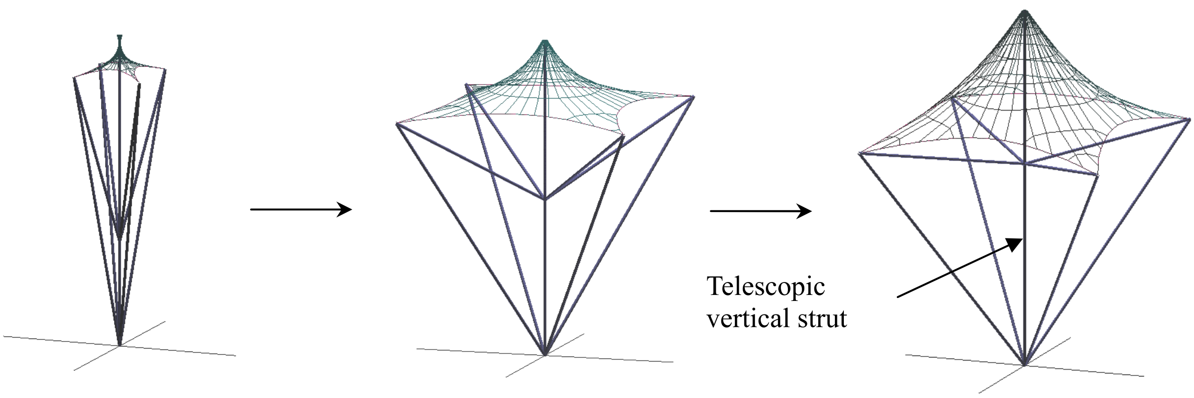

Figure 4. Deployment Process of Cone-shaped DSTMS Module

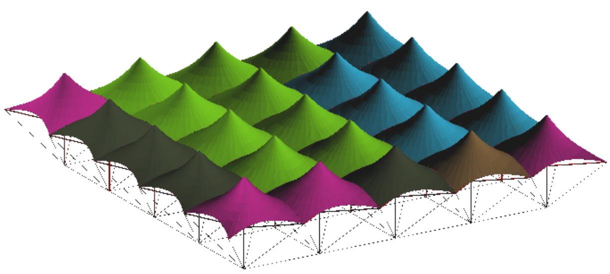

Figure 5. Flat Cone-shaped DSTMS

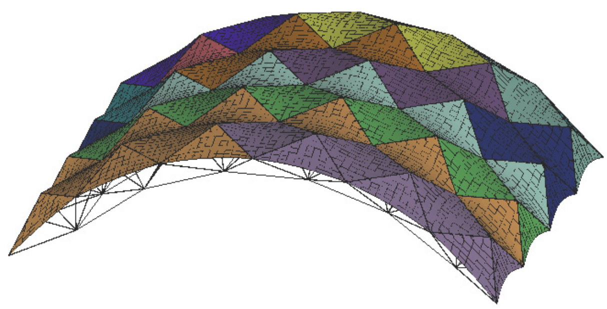

Figure 6. Curved Umbrella DSTMS

A reduced scale model of the Umbrella DSTMS was built to verify the deployment efficiency of the proposed structures. The model is a curved structure comprising of two bays. Each bay consists of seven identical modules crossing a span of 3.1m. The structure covers an area of 1.3m by 3.1m and has a total weight of approximately 4kg. The prototype model is shown in Figure 7.

Figure 7. Ultra-lightweight Scale Model of Umbrella DSMTS

The deployment process of the Umbrella DSMTS model is shown in Figure 8. The structure was deployed from two ends within a minute. This structure can also be deployed easily from one end with the other end fixed on the ground. Experimentation with this small scale model has demonstrated the capability of the proposed DSTMS for rapid deployment on site. It was observed that the membrane could be tensioned efficiently by the deployment of the strut system. On the other hand, the strut system became more stable due to the tensioning effect from the tensioned membrane.

Figure 8. Deployment Process of Umbrella DSMTS Prototype

3. EFFICIENCY STUDIES

There are three important design parameters which define the geometry of DSTMS: the span/depth ratio (*L/H*), the span/modular width ratio (*L/W*) and the inclination height/modular width ratio (*h/W*). The inclination height *h*, the depth *H*, the modular width *W* and the span *L* are defined as shown in Figure 14 and Figure 15.

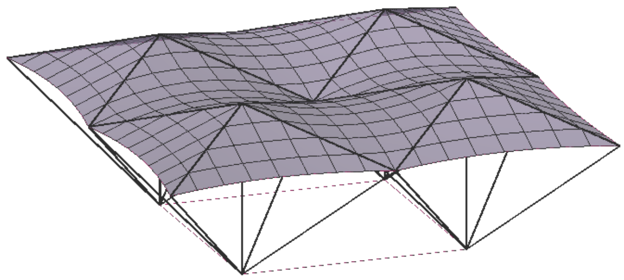

Figure 9. Saddle form of Membrane Surface between Umbrella DSTMS Modules

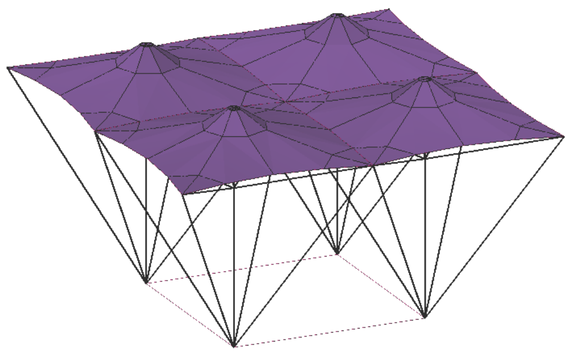

Figure 10. Conic form of Umbrella DSTMS Modules

The *h/W* ratio determines the effective membrane shape of DSTMS. A good membrane surface will result in smaller resultant forces induced by applied loads. Smaller forces results in lighter structures [5]. DSTMS possess the two basic anticlastic shapes of membrane structure which are the saddle form between those modules of Umbrella DSTMS (except the triangular membrane shape along the boundary) and the conic form of series connected modules of Cone-shaped DSTMS as shown in Figures. 9 & 10. In order to tension the membrane of DSTMS more effectively, it is possible to adjust the inclination height/modular width (*h/W*) ratio. Considering the case in which the two proposed DSTMS are subjected to wind uplift pressure of $0.45 kN/m^2$. Table 1 show the maximum membrane stress, maximum membrane displacement and the membrane usefulness (which is the ratio of membrane area/plan area). The results are plotted in Figures. 11, 12 & 13 respectively.

It can be seen that the maximum membrane stress and maximum membrane displacement decrease when the *h/W* ratio increases. The reason is that the higher *h/W* ratio will provide more curvature for the saddle and conic shape of DSTMS. The more curvature the smaller the forces that will develop as the result of applied loads. When the *h/W* ratio is larger than 0.2, the maximum membrane stress and displacement do not reduce much or start increasing due to significant increase in the membrane area exposed to wind force. In addition, higher *h/W* ratio means larger membrane area is required for a given plan area, resulting in higher cost. It can be observed that optimum *h/W* ratio is about 0.2. In the subsequent parametric studies of span/depth and span/modular width ratios, the *h/W* ratio of 0.2 is selected for both DSTMS.

Table 1. Maximum Membrane Stress and Displacement of Umbrella and Cone-shaped DSMTS

h/W	Umbrella DSTMS			Cone-shaped DSTMS		
	Max stress (kN/m)	Max displacement (cm)	Membrane usefulness	Max stress (kN/m)	Max displacement (cm)	Membrane usefulness
0.1	6.34	27.5	1.013	19.23	51.7	1.013
0.2	5.48	20.7	1.051	5.59	20.2	1.05
0.3	4.43	21.9	1.11	4.5	17.5	1.107
0.4	4.38	23.3	1.187	4.51	15.2	1.179

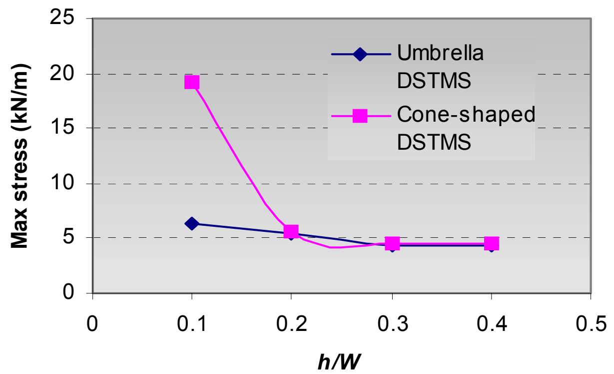

Figure 11. Maximum Membrane Stress vs. *h/W* Ratio

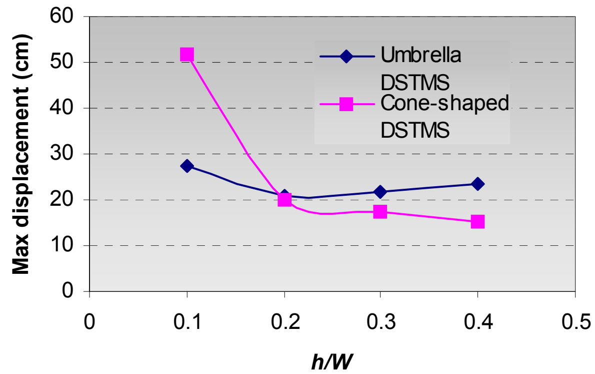

Figure 12. Maximum Membrane Displacement vs. *h/W* Ratio

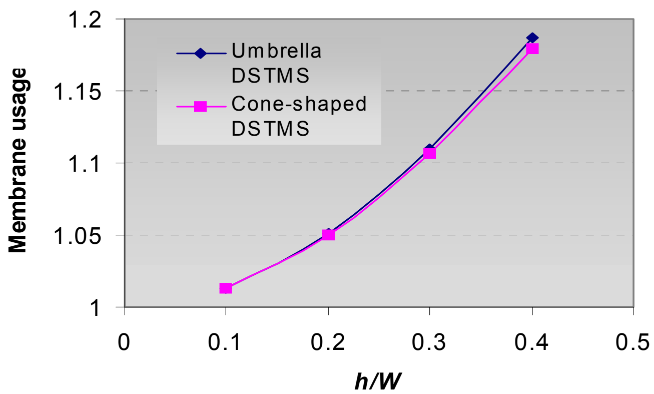

Figure 13. Membrane Usefulness vs. *h/W* Ratio

The optimum span/depth (*L/H*) and span/modular width (*L/W*) ratios of DSTMS are determined from efficiency studies of weight-to-strength ratio of the structures. In this paper, the minimum weight of structural elements that is designed to resist predetermined load combinations is used as a basis for comparing different span/depth and span/modular width ratios. Geometrical nonlinear analysis is carried out on 48m x 48m square grids of the Cone-shaped DSTMS and the Umbrella DSTMS with pinned supports at four sides. The span/depth ratios studied are 6, 8, 10 and 12 while the span/modular width ratios are chosen to be 6, 8 and 10 (Figures. 14 & 15).

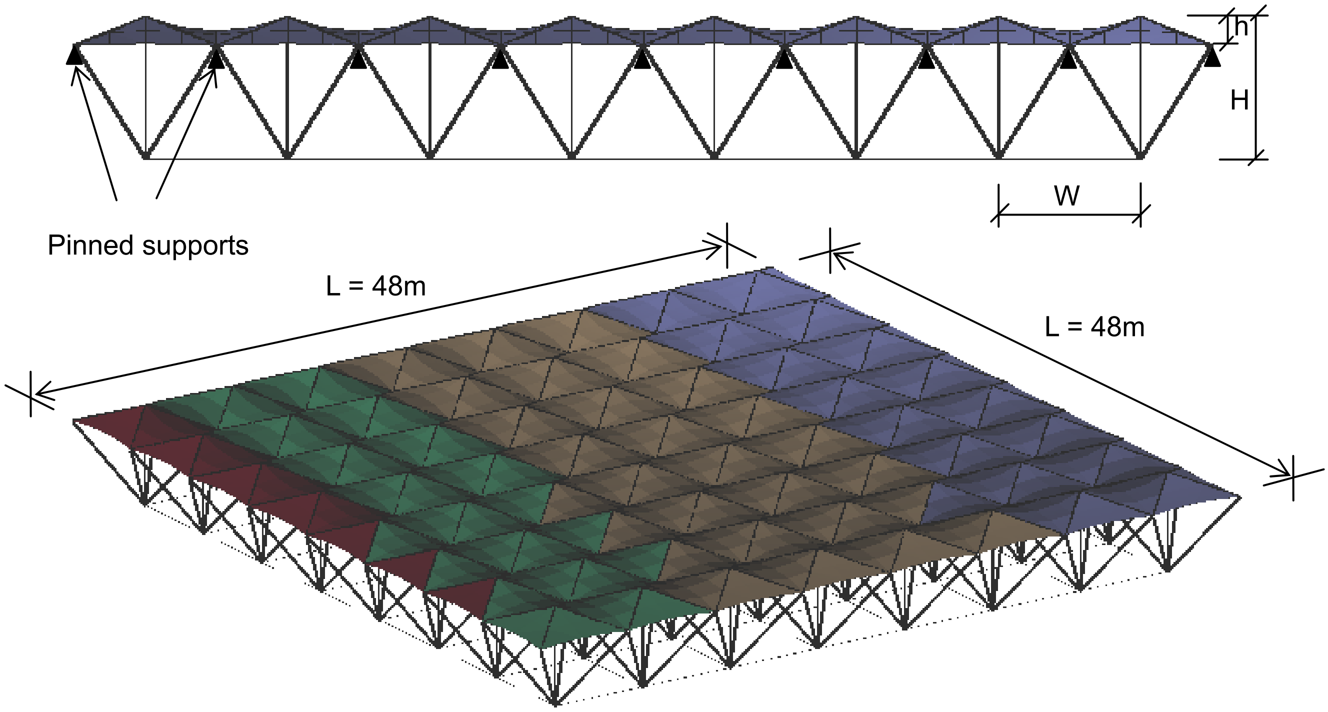

Figure 14. Configuration of Umbrella DSMTS, Span of 48m x 48m, 8x8 Modules

In this study, two major load combinations are used for designing DSTMS. The first load combination includes gravity loadings which are the self-weight of the structure and an imposed live load of 0.75kN/m^2. The load is distributed at the bottom nodes of the structures. The factored gravity load combination is 1.4 x self-weight of structure + 1.6 x imposed load in accordance with BS 5950, Part 1 (2000) [4]. The second load combination includes wind uplift loading. Wind is often the predominant loading on membrane fabric roof. A typical wind speed of Singapore of 35m/s which is equivalent with a design wind suction load of 0.45 kN/m^2 is assumed. The wind uplift force is applied uniformly and normal to the membrane surface. The factored uplift load combination is 1.0 x self-weight of structure + 1.4 x wind uplift load in accordance with BS5950, Part 1 (2000) [4].

The following procedure has been adopted for the design of DSTMS.

a. The structure is modelled with one section for struts and one for cables.
b. Form-finding process is performed using Force density method to find the initial equilibrium shape of structure.
c. Geometric nonlinear analysis is performed with load combination 1: (1.4 x self-weight of structure + 1.6 x imposed load) and load combination 2: (1.0 x self-weight + 1.4 x wind uplift load) to determine member forces.
d. Section capacity and member buckling of struts and cables are checked against ultimate limit state. Membrane stress is checked to ensure no membrane part is under compression or exceeds allowable stress. Maximum deflection of supporting structure is recorded to check against serviceability limit state as specified in BS 5950, Part 1 (2000) [4]. In this study, the deflection limit of L/200 for steel beam [4] is used.
e. The members are resized if necessary and the design procedure is repeated from step 2.

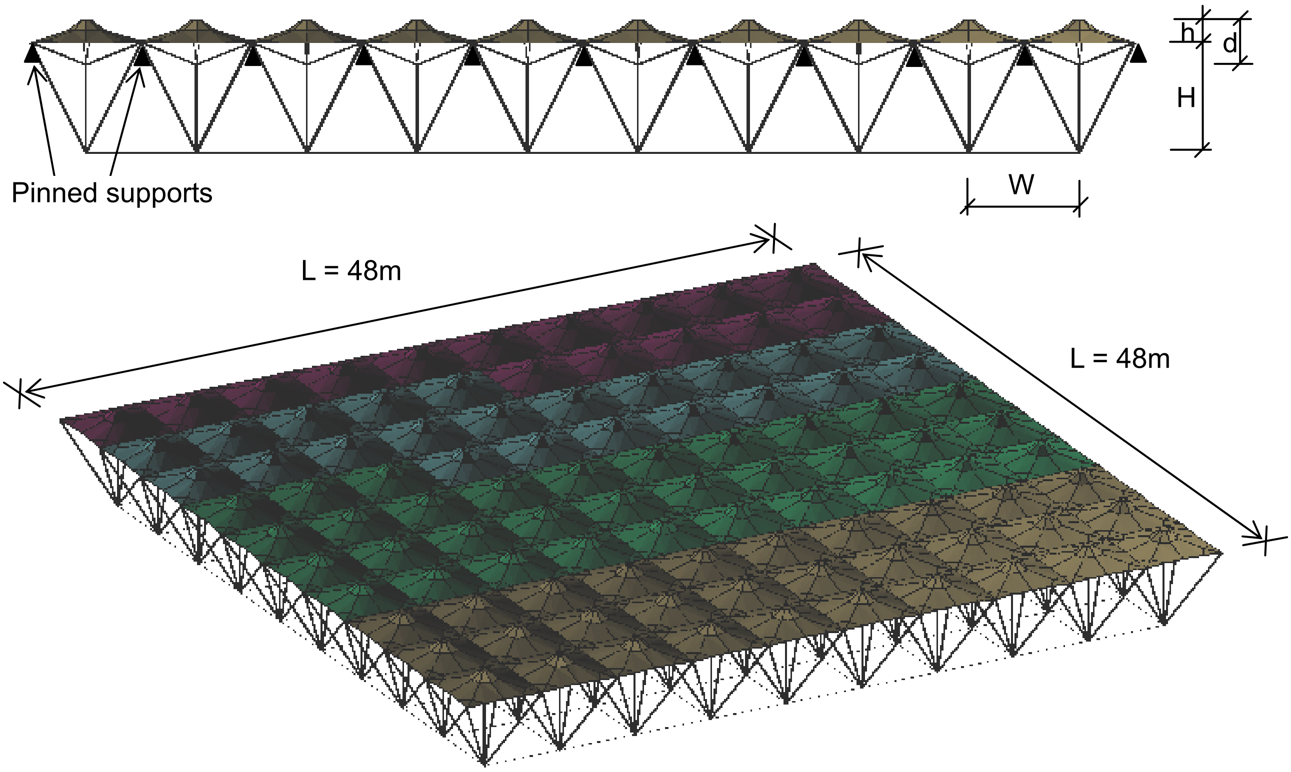

Figure 15. Configuration of Cone-shaped DSMTS, span of 48m x 48m, 10x10 Modules

Parametric studies show that the optimum span/depth ratio falls in between 9 and 10 and the optimum span/modular width ratio occurs from 6 to 8 as illustrated in Figures. 16 & 17.

For structures with the same span/modular width ratio, the change in span/depth ratio will affect the length of the struts. If the span/depth ratio is small, the forces induced in upper diagonal struts (chord) are small but the lower diagonal struts and the vertical struts are very long. The strength reduction due to buckling is significant, thus the required member sizes of diagonal struts and vertical struts are large resulting in high self-weight. When the span/depth ratio increases, the forces induced in both the upper and lower diagonal struts increase while the lengths of the lower diagonal struts and vertical struts are reduced. As a result, the member size of the upper diagonal struts is increased as their length is unchanged. On the other hand, a decrease in buckling length of the lower diagonal struts will be accommodated with the increase of forces induced, thus the member size of lower diagonal struts is not influenced much. Therefore, the weight of diagonal vertical struts is reduced considerably due to the decrease in length. In addition, the forces induced in the vertical strut is kept unchanged while the buckling length is reduced, requiring smaller section size (lighter weight). Thus, in overall, the self-weight of the structures decreases with the increase of span/depth ratio. However, at a very high span/depth ratio, the self-weight starts to increase if the span/depth ratio continues increasing. This is because the strength of lower diagonal struts increase due to the decrease in buckling length is not significant compared to the increase of force induced in them. Hence, the required size of the lower diagonal struts is larger, resulting in significant increase in self-weight of the structures. As can be observed in Figures. 16 & 17, the relationships between self-weight of structures and span/depth ratio for different span/modular width ratios follow the same trend. The minimum weight of each system occurs around a span/depth ratio of 10.

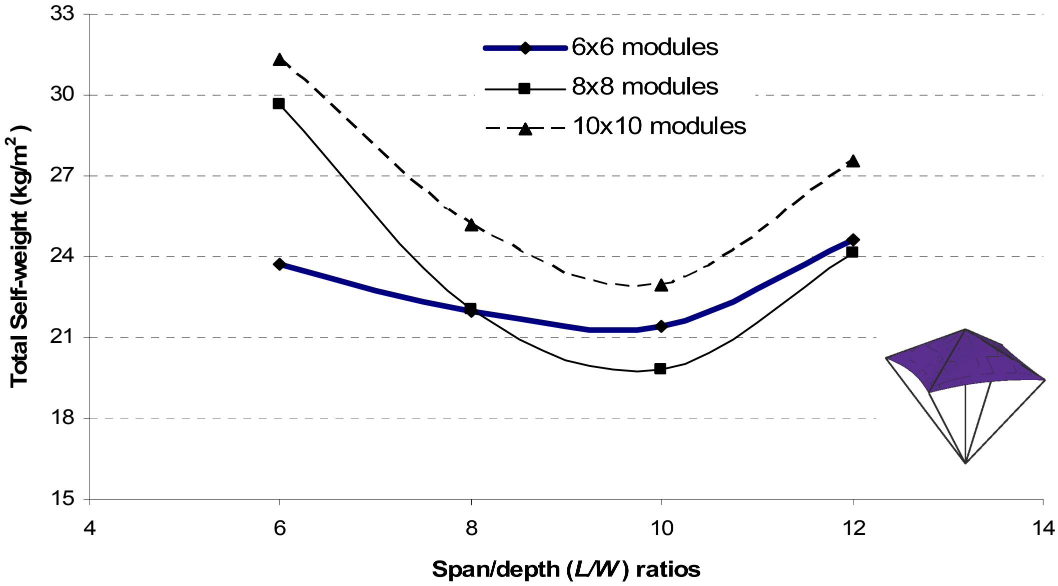

Figure 16. Self-weight of Umbrella DSTMS with Span of 48m

Different span/modular width ratios also affect the design weight of structures. The increase in span/modular width ratio results in higher grid density and lower forces induced in structural elements. At low span/depth ratio, although member forces induced in struts are smaller with higher grid density, significant strength reduction due to buckling length requires larger member sizes. Thus the structure with higher span/modular width ratio has larger section size and higher self-weight. However, at large span/depth ratio, the effect of buckling length is less pronounced with higher span/modular width ratio due to shorter element lengths. Therefore, the decrease in self-weight due to the increase in span/depth ratio of structures with higher span/modular width ratio is more significant. The minimum weight of each system occurs around a span/modular width ratio of 8.

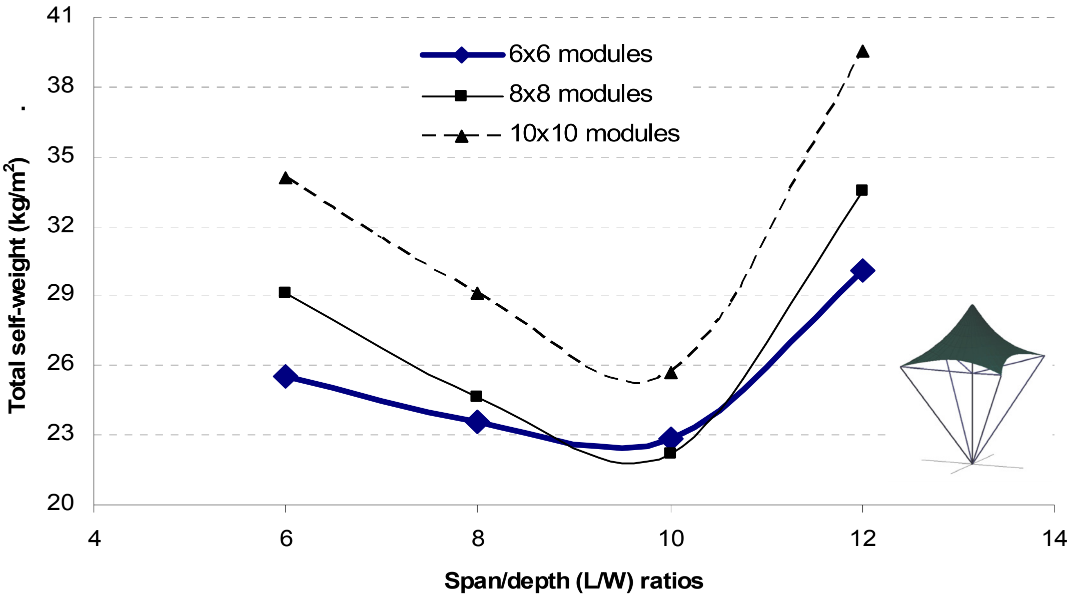

Figure17. Self-weight of Cone-shaped DSTMS with Span of 48m

In general, the span/depth ratio has more significant influence on the self-weight of DSTMS than the span/modular width ratio. It is found that the self-weight of Umbrella DSTMS is smaller than that of Cone-shaped DSTMS. The reason is that, for the same span/depth and span/modular width ratios, the length of lower diagonal struts of Cone-shaped DSTMS is larger than that of Umbrella DSTMS. Although Cone-shaped DSTMS has shorter vertical struts, the contribution of lower diagonal struts on self-weight is much greater.

Based on optimal range of span/depth and span/modular width ratios, the relationship between the depth and the modular width of DSTMS can be deduced as shown in Figure 18. It can be observed that optimum depth/modular width ratio is around 0.8. This ratio can be used as a reference to determine the optimum span/depth and span/modular width ratios for curved DSTMS.

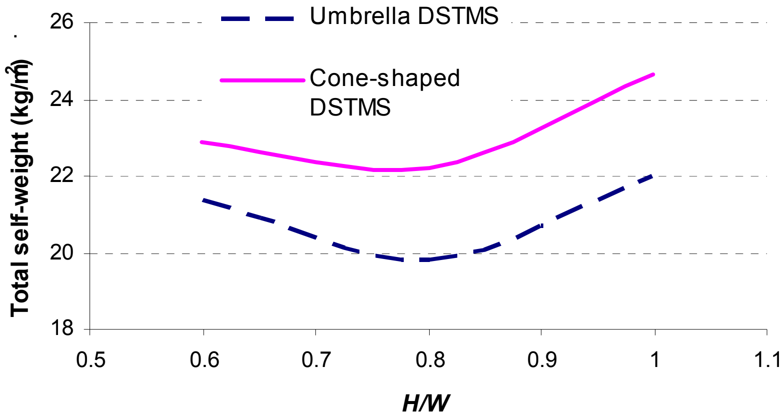

Figure 18. Total Self-weight vs. *H/W* ratio of Umbrella and Cone-shaped DSTMS

A summary of the optimum span/depth ratio and span/modular width ratio is given in Table 2. The lowest weight of Umbrella DSTMS is 19.8 kg/m^2 while the lightest weight of Cone-shaped DSTMS is 21.8 kg/m^2. They are comparable with the self-weight of similar layout double-layer space trusses excluding roofing material and fabric support framing (in case of using membrane roof) [6]. Therefore it can be concluded that DSTMS possess good structural efficiency as of double-layer space trusses.

Table 2. Optimum Design Parameters and Weight of DSTMS (Span 48m x 48m)

Type of DSTMS	Optimum *h/W* ratio	Optimum *L/H* ratio	Optimum *L/W* ratio	Optimum *H/W* ratio	Optimum total self-weight
Umbrella DSTMS	0.2	10	8	0.8	19.8
Cone-shaped DSTMS	0.2	10	8	0.8	21.8

4. CONCLUSIONS

Two novel groups of DSTMS have been introduced and developed. Those structures combine the advantages of both deployable structures and tensioned membrane structures, thus they have the capability of rapid erection on site incorporated with eye-catching membrane appearance. Series of parametric studies are carried out to determine the most efficient geometry of two proposed DSTMS. A summary of optimum design parameters for the two DSTMS is given as a design recommendation. It is proved that DSTMS are capable of enclosing large span space with equivalent structural efficiency as of double-layer space truss. Prototype model has demonstrated the deployment efficiency of the proposed DSTMS.

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