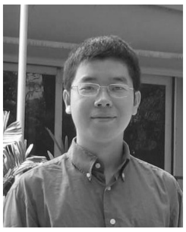
Deployable Tension-Strut Structures: Design Guidelines



K.K. Vu, T.C. Tran, J.Y.R. Liew, A. Krishnapillai
Department of Civil Engineering, National University of Singapore, BLK E1A, #02-18, 1 Engineering Drive 2, Singapore 117576
g0306014@nus.edu.sg

KEYWORDS

Deployable structures, space frame, tension-strut structures, pre-tensioning.

Abstract

This paper introduces a unique solution for rapid deploy requirement, Deployable Tension-Strut Structure (DTSS), which is proposed to be as rigid as conventional lattice structures and can be built as quickly as constructing deployable space frame due to its deployability. Four types of DTSS with different span lengths are proposed as the bases. They are analyzed and found comparable to equivalent lattice structures in terms of structural efficiency. In addition, these non-linear analyses show that the optimum design parameters such as Span/Depth ratio are similar to that of conventional space frame. Prototypes are built in various materials such as plastic, aluminium, and steel to assure that the concept of deployability actually works. Although prototypes may not provide analitical assessment but they provides good information about manufacturability and constructability, which cannot be found from numerical modelling. The physical models offer good experience for building DTSS in industrial practice.

1. Introduction

Various designs of space frame have been proposed to accommodate social demand for structural integrity, lightweight, aesthetics and creativity, or rapid construction and removable. The most dominant concept must be named as the double-layer space frame, tensegrity described by Motro [2003], and deployable space frame introduced by Gantes [2001]. However, these structural concepts are not to cover combination of demands which are listed above.

This paper introduces Deployable Tension-Strut Structures (DTSS), which can be as structurally effective as conventional double layer space frame and can be deployed as fast as previously proposed deployable structures.

This structural concept can be implemented with many different structural forms. However, within the limited space of this paper, the key structural forms are studied and compared to conventional space frame.

2. Design concept

Four systems of DTSS are introduced in this paper: Pyramid-On-Pyramid, Pyramid-In-Pyramid, Pyramid-Pantograph-Cable, and Pyramid-Pantograph-Pyramid.

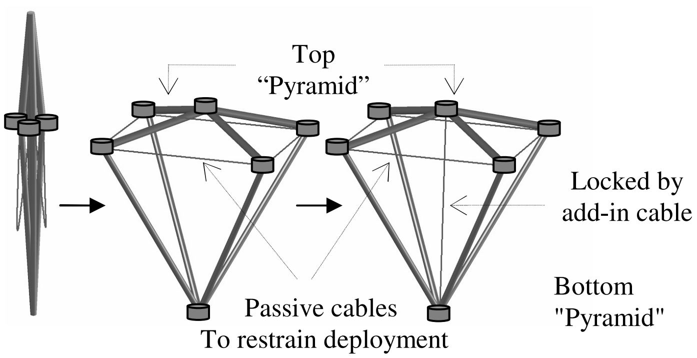


Figure 1. Deployment of Pyramid-On-Pyramid structure

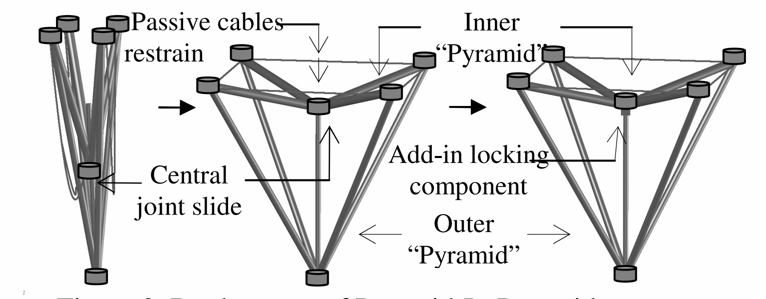


Figure 2. Deployment of Pyramid-In-Pyramid structure.

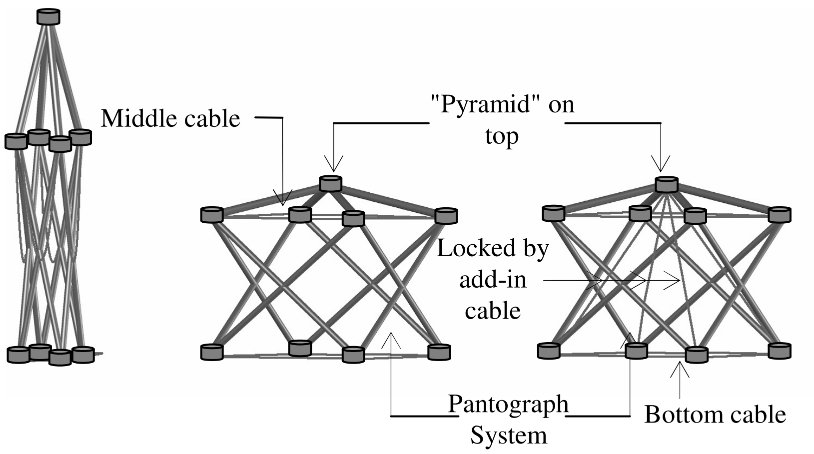


Figure 3. Deployment of Pyramid-Pantograph-Cable structure.

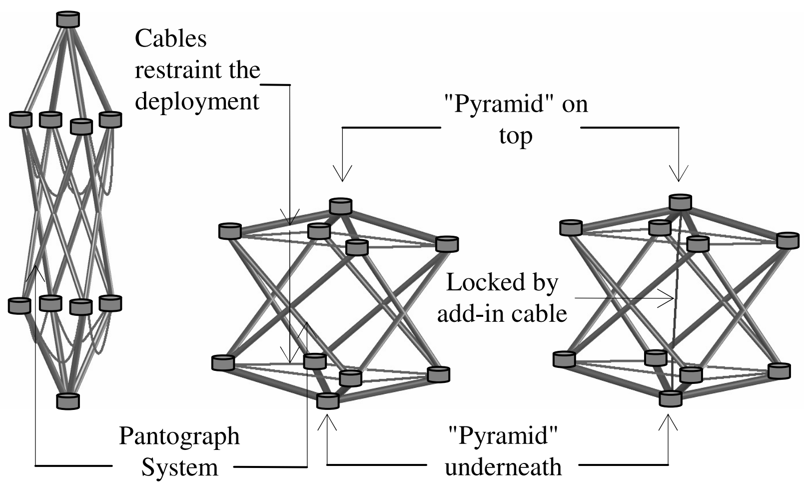


Figure 4. Deployment of Pyramid-Pantograph-Pyramid structure.

Pyramid-On-Pyramid structure is composed of two pyramids attached to each other at their base as shown in Fig. 1. The "Pyramid" consists of four struts, connected in the center by a pinned joint, to which a detachable strut is attached.

Pyramid-In-Pyramid structure is composed of two pyramids attached at the base but within each other. The "Pyramids" are formed by four pinned connected struts as in the POP structure. The deployment of PIP is achieved by sliding the central joint along the central rod and locking in its final configuration as shown in Fig. 2.

A new class of structures combing in scissor-like elements (SLE) and pyramidal elements is proposed. These interlinked SLE forms a kinetic chain which increases the depth and facilitates deployment of the structure. Pyramid-Pantograph-Cable is stabilized into the deployed state by attaching the locking cables to the top pivot as shown in Fig. 3.

Pyramid-Pantograph-Pyramid structure (PPP) is another SLE-based system. A "Pyramid" is placed under the SLE system as shown in Fig. 4. The structure is deployed and stabilized by attaching and pre-stressing the central locking cable.

3. Optimum Design Parameters

Parametric study is performed to find out the optimum design parameters, Span/Depth ratio and the Span/Module Width ratio and to compare the structural performance of different DTSS. Non-linear analysis is used to analyze the DTSS.

The studying structures are designed and analyzed by an iterative process where the optimal sections are chosen from Handbook of structural steelwork, 2002 to satisfy the codes limit state criterion (BS 5950. Part 1: Structural use of steel works in building, 2000). One section size is chosen for each type of structural member e.g. diagonals, top struts. The struts are made of circular hollow sections with yield strength of 275 N/mm^2 and the high-tensile cables are made of steel with breaking stress of 1089 N/mm^2. The Young modulus of the steel is taken to be $210x10^3$ N/mm^2 and the Young modulus of the high strength steel cable is $145x10^3$ N/mm^2.

The imposed live load of 0.75 kN/m^2 is applied on all structures, which is common for heavily loaded roof. The load is assumed to be distributed at the bottom nodes of the structures. Spans ranging 24 m, 36 m, 48 m and 60m made of 8x8, 10x10 and 12x12 modules with span to gross height ratio of 8, 10 and 12 is considered. All boundary nodes are restrained against displacements. The serviceability deflection limit is taken as 1/200 the span of the structure as prescribed by BS 5950:2000, Part 1.

Structural efficiency of structures is evaluated by structural efficiency index SEI as defined in Vu *et al* (2006).

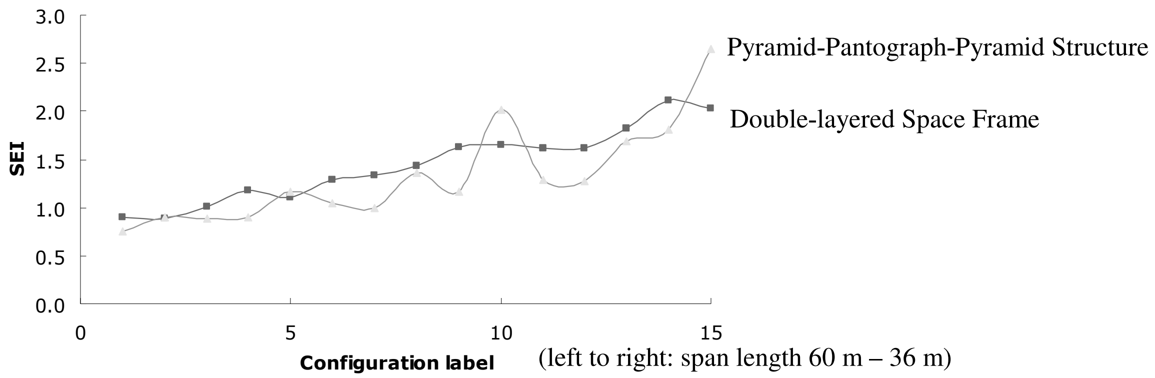


Figure 5. Structural Efficiency of Pyramid-Pantograph-Pyramid and Space Frame

It was found out that the structural efficiency of the proposed Pyramid-Pantograph-Pyramid structure is comparable to that of conventional double-layer space frame as shown in Fig. 5.

High SEI can be observed with the number of modules of 6x6 to 10x10 for any DTSS with any span length. Higher number of modules will cause higher self-weight while lower number of modules may reduce stiffness of the structure and both cases would lead to reduction in SEI.

The optimum Span/Height ratio is 8 to 10. The optimum configuration is corresponding to the highest SEI. When the Span/Height ratio is higher than the optimum range, the stiffness of the structure is much lower and the structural behaviour is closer to membrane. When the Span/Height ratio is lower than the optimum range, the diagonals are long and slender, and the self-weight of structures is higher. The structural behaviour in this case is closer to short beams. The word "Height" is used in stead of conventional word "Structural Depth" because the structural depth of DTSS is different from its height due to the inclination of top struts.

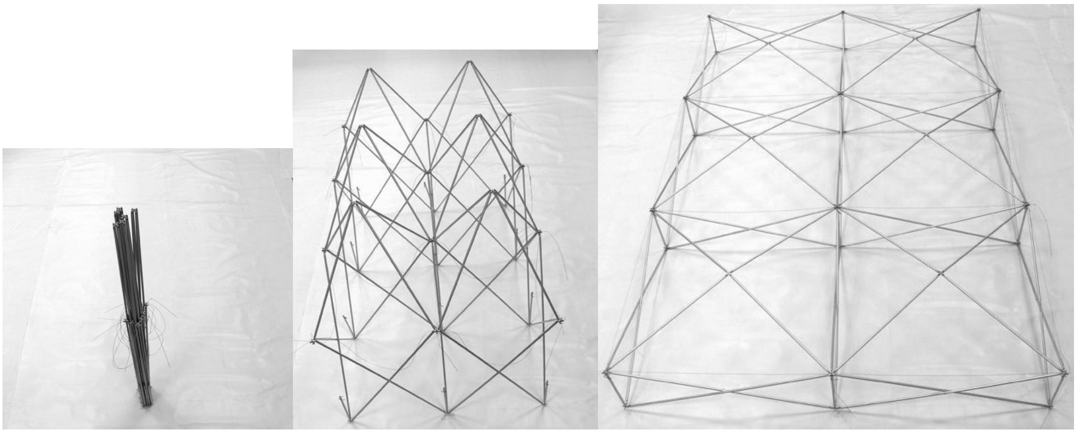
Combining the optimum parameters Number of modules (6 to 10), Span/Height (8 to 10), the optimum shape of a structural module can be determined as follows: Span/Module Width = 6 – 10, Span/Module Height = 8 – 10,

→ *Module Height/Module Width = 0.6 – 1.2.*

4. Prototypes and Testing

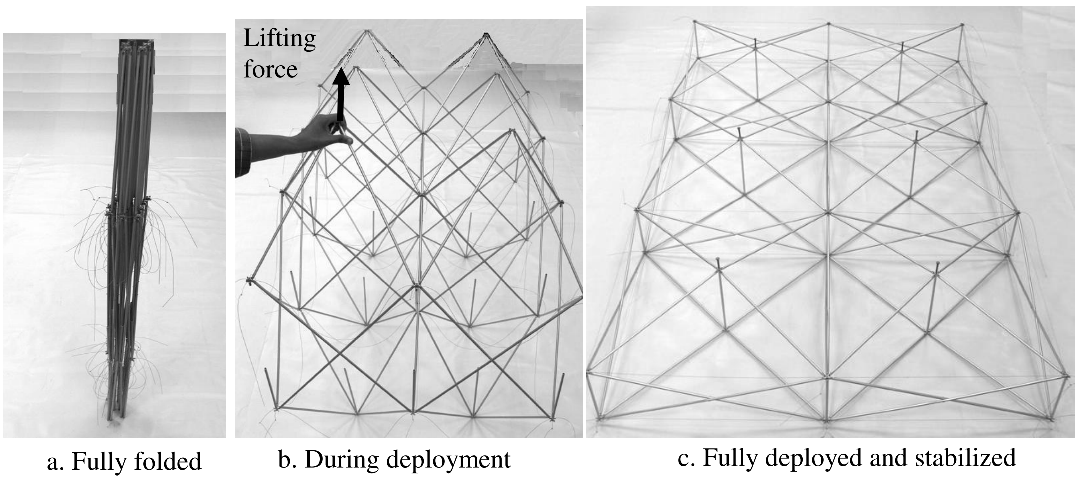
Prototypes are built to verify the concept of deployment and structural stiffness. Figs. 6 to 8 shows the deployment of prototypes of Pyramid-On-Pyramid structure, Pyramid-Pantograph-Cable structure, and Pyramid-Pantograph-Pyramid structure.

Figure 6. Prototype Deployment of Pyramid-On-Pyramid structure.



a. Fully folded b. During deployment c. Fully deployed and stabilised

Figure 7. Prototype Deployment of Pyramid-Pantograph-Cable structure.

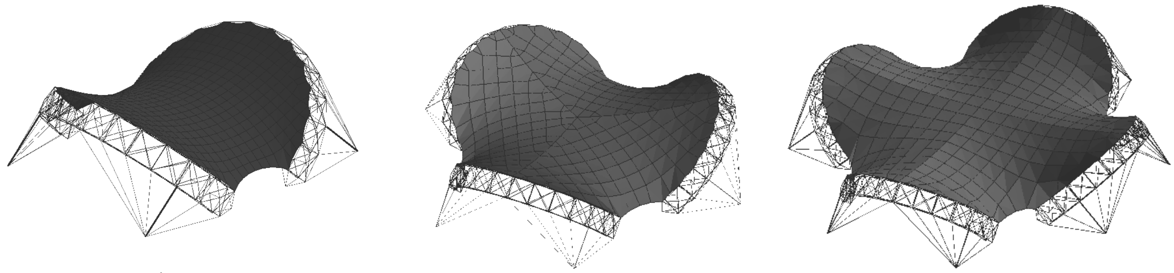


a. Fully folded b. During deployment c. Fully deployed and stabilized

Figure 8. Prototype Deployment of Pyramid-Pantograph-Pyramid structure.

5. Applications

Deployable strut-tensioned structures are potential to be the supports for membrane structures, resulting in a system of light-weight and rapidly erected enclosures. Figure 9 shows the use of Pyramid-Pantograph-Pyramid structure as a rigid supporting arch for a novel membrane structure named as Butterfly-wing structure proposed by Tran and Liew [2005].



a. Two-wing b. Three-wing c. Four-wing

Fig. 9. Butterfly-wing structures

The arches are allowed to be rotateable about the hinge support and kept in inclination position by membrane and fans of anchor cables. Various striking butterfly-wing forms with anticlastic membrane surface are created as shown in Fig. 9. Membrane tensioning is attributed a part to the self-weight of the arches, reducing erection time and cost. Innovative DSTS supporting make Butterfly structure able to enclose large clear space very rapidly. However, the inefficiency of the deployable strut-tensioned system lies in the cable layers along the arches which subject to compression under applied loads. Table 1 shows that about half amount of along-arch cables of a three-wing butterfly structure are slackened under wind uplift of $0.45kN/m^2$. Structural efficiency of the system can be improved by using struts to replace those along-arch cables, resulting in about 20% total weight reduced (Fig. 10), at the expense of more time consumed for strut assembling. However, the strut assemblage can be done very simply and rapidly (bolt connection) when the arches are in fully deployed configuration.

Table 1. Amount of slackened cables for 3 three-wing butterfly structure, 12 modules arch

L/h	Total along-arch cables	Slack along-arch cables	$\frac{\text{Slack}}{\text{Total}}$
15	144	66	0.46
20	144	60	0.42
25	144	60	0.42

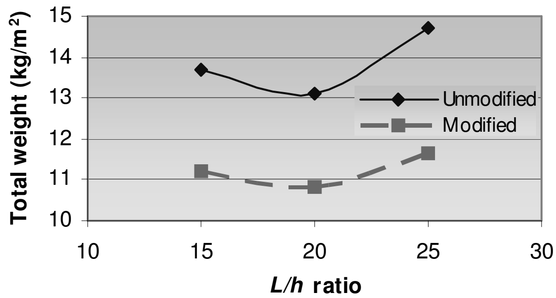


Fig. 10. Total weight improved by modified arch

6. Conclusions

Four forms of Deployable Tension-Strut Structures are introduced to be structurally effective and can be deployed rapidly as verified by prototyping. Numerical studies show that the optimum shape of module should satisfy the condition Module Height/Module Width = 0.6 – 1.2. A potential application of the proposed system for Butterfly-wing structure is discussed.

References

British Standard Institute, 2000, "*BS 5950. Part 1: Structural use of steel works in building*", UK.

Gantes C. 2001, *Deployable Structures: Application and Design*, WIT Press, USA.

Motro, R. 2003, *Tensegrity, Structural systems for the future*, Kogan Page Science, London, UK.

Vu K.K., Liew J.Y.R., and Anandasivam K. 2006, *Deployable Tension-Strut Structures: from concept to implementation*, Journal of Constructional Steel Research, pp. 195-209.

Tran C. T., Liew J.Y.R, *Butterfly structure: A conceptual design*, Proceeding of KKCNN18th Symposium, Taiwan, pp. 695-882.