Development of a new deployable shelter

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Abstract

This paper presents an alternative deployable shelter system which is constituted of deployable space truss and an anticlastic stressed membrane. By employing an innovative deployable supporting system, the shelter has the capability of enclosing large span space while being able to be erected rapidly and transported easily. The use of lightweight stressed anticlastic membrane helps to reduce the secondary structural components. In addition, by replacing conventional vertical arches with inclination arches, the structure achieves lateral stability without bracing and the membrane achieves more advantageous curvature surface. Moreover, this inclination arrangement facilitates the entire structure to be deployable, resulting in further rapid and effective erection on site. Parametric studies are carried out to determine the effective geometrical properties for the deployable shelter. Large scale prototypes of the proposed shelter systems have been carried out. The deployable shelter system has been developed for military applications such as temporary aircraft hangars, or emergency shelters.

1. Introduction

Lightweight shelter systems are used in many industry and military applications. The shelter system normally has modular design and they are made of lightweight materials for the ease of transportation and erection. Various ranges of different scales and sizes of space enclosure using lightweight membrane have been developed [Hatton 1979]. In general, the shelter systems can be categorized into three generic types:

- Unstressed membrane shelter
- Stressed membrane shelter
- Anticlasic membrane shelter

Unstressed membrane shelter systems are tent-like. They comprise series of rigid supporting frames with an unstressed fabric membrane placed loosely over. The membrane thus needs to be heavy to prevent the fabric from fluttering. These shelter systems have the advantages of simple erection and low cost. However, the supporting frame is heavy and bulky due to secondary structural components and bracings. Therefore, they often take time for installation and removal, as well as more manpower involved. These shelter systems thus are not used for large span applications but often aimed at camping tents like the Modular general tent system [Eureka tent].
Stressed membrane shelter systems are characterized by the membrane fabric panel stretched between extruded/grooved rigid supporting frames (often using hydraulic jack [Drew 1979]). Unlike unstressed membrane which acts merely as roofing material, the prestressed membrane is acting as tensioned structural component to resist loads, resulting in lighter supporting frames. However, secondary members as purlins are required to maintain the membrane stress between rigid frames. Therefore, the system is lighter than unstressed membrane shelter but suffering the same problem of high erection and strike times due to bulky frames and complicated jacking works [Drew 1979].

Anticlastic membrane shelter systems consist of saddle form membrane hung and stressed between series of vertical supporting frames. The membrane is stressed in double curvatures by patterning into number of discrete sections. This allows a lighter fabric, partially eliminates secondary bracing. Furthermore, as the membrane is point-connected to the supporting frames, it is convenient to use space truss for large span frame with higher structural efficiency as frame members are placed in direct compression and tension without the requirement to resist bending forces.

Recently, deployable shelter systems have been developed to improve further their capability of rapid erection and easy transportation. The advantages of deployable structures are the compact configuration in transportation and rapid erection on site. Shipping and construction cost therefore can be reduced significantly. The strike time is also faster and simple due to their collapsibility, thus they are very suitable for temporary shelter systems. However, deployable structures often possess weak stiffness as mentioned by Gantes [2000], therefore their applications are limited.

This paper introduces a new deployable shelter system using anticlastic membrane supported by expandable space truss of high structural efficiency. Conceptual design and its versatility are discussed. Parametric studies are carried out to determine optimum geometrical parameters of the proposed shelter.

2. Design concept

Two key principles in the design of the shelter are:

- The use of a lightweight stressed anticlastic membrane
- A deployable supporting frame of large span capability

In order to accommodate these design principles, a deployable tension-strut system is proposed for the supporting frame. This innovative deployable structure which was first proposed by Vu et al. [2006] has the capability of rapid erection and transportation on site yet having equivalent weight and structural efficiency as of double-layer space truss. On the other hand, the membrane is patterned to form double curved panel stressed between vertical supporting frames. This stressed anticlastic membrane surface helps to partially eliminate secondary and bracing structures between supporting frames. Furthermore, the membrane fabric can be thinner and lighter as it will not have to resist degradation and stressing induced by fluttering.

Configurations of a deployable tension-strut module in folded and deployed states are

Figure 1. Module configuration - deployment (Vu et al. 2006) and prototype

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illustrated in Fig. 1. It is constructed from two pyramid struts and four scissor-like element struts which are all pin-connected. With this arrangement, the module can be folded and deployed efficiently. The deployment of each module is constrained by the length of two layers of cables. The final configuration of the module after deployment is stabilized by attaching and pre-stressing the central add-in cable as shown in Fig. 1. The supporting frame is constituted from series of identical modules connected together, forming a deployable space truss with an arch shape. Deployment of the truss arch is relied on deployment of modules. When the truss arch is deployed, all modules are deployed simultaneously due to joint constraint. The deployment process of the deployable truss arch is illustrated in Fig. 2.

Fabric membrane is connected to the arches once they are deployed and placed in position. With membrane attached, the arches are laterally braced along their length. The membrane is allocated in a single panel to be stretched in between each pair of arches. Pre-tension is applied on membrane by means of turnbuckle at connecting points. Anticlastic shape helps to tension the fabric evenly, prevents it from flapping and allows the use of lighter material.

The fabric membrane can be attached to the arches either at bottom joints to expose the supporting trusses (Fig. 3) or at top joints to cover the whole structure (Fig. 4). The point connection ensures that the truss members are subjected pure compression or tension. An alternative option is illustrated in Fig. 5 where the membrane is attached to the arches at lower middle joints. The void at each arch location can be enclosed by a curved transparent plastic attached underneath each arch. This can serve as both drainage gutter and skylight to provide daylight.

4. Deployable shelter

Based on the design concept of stressed anticlastic membrane and deployable supporting truss but with a different arrangement of the arches, the whole shelter can be made deployable to facilitate fast-track erection. Here the supporting truss arches are not arranged vertically as normal but in inclination position as shown in Fig 6.
Each arch is inclined to the adjacent arch so that their peaks meet at a tangent and are connected together. This design provides the lateral stability for the whole structure without the need of bracing. Furthermore, with the use of ground beam, the whole structure can be pulled and deployed easily so that the construction time and cost can be reduced.

Deployment of the shelter is performed in the manner as of an accordion as shown in Fig. 7. The joint at peaks of the two connecting arches are designed to allow them to rotate perpendicular to their plane. The arches are supported on the trolleys which can slide along the guide track during the deployment. When the trolleys of the two end arches are pulled outward, the whole structure will be deployed simultaneously. At the initial stage, the deployment of the shelter is facilitated by the self-weight of the arches. Temporary masts are required to control the gradually movement of the arches. The deployment also helps to open and tension the membrane efficiently without the need of turn-buckles or hydraulic jack. When the self-weight of the arches is in balance with the tension force in membrane, two fans of cables at each end arch are applied tension forces against the anchor points until achieving the final configuration of the shelter. Each cable fan has a safety strut designed to resist self-weight of the arch to prevent structure collapse due to accidental damage happens to membrane (Fig. 6). When the shelter is in deployed configuration, all arches are fixed to the ground beams.

5. Shape efficiency of deployable shelter

The membrane shape of the deployable shelter is characterized by the saddle surface between two inclined arches. There are two major parameters control the membrane shape of the deployable shelter which are the inclination angle $\alpha$ and the rise/span ($H/L$) ratio. The inclination angle $\alpha$, the rise $H$, the span $L$ and the radius $R$ of the arch are illustrated in Fig. 8. The relationship between $H$, $L$ and $R$ can be defined as:

$$R = \frac{4H^2 + L^2}{8H}$$

(1)

It is possible to adjust the inclination angle $\alpha$ and the rise/span ($H/L$) ratio of the arch in order for the saddle membrane to resist load more effectively. Assuming that the shelter is subjected to a wind pressure of 0.3kN/m$^2$ applied normal to the membrane surface (both uplift and downward directions) and supporting arches are rigid. Prestress in membrane is set at level of 4kN/m in both warp and weft directions. Table 1 shows the maximum membrane stresses subjected to downward and uplift wind pressure. The results are plotted accordingly in Fig. 9. It can be observed from Fig. 9 that the maximum membrane stress tends to decrease when the $H/L$ ratio increases. The reason is that an increasing $H/L$ ratio results in the increase of the altitude difference between the higher points and lower points of the saddle membrane,
thus providing more curvature surface. The more curvature the smaller the forces that will develop as the result of applied loads. Smaller forces results in lighter structures. When \( H/L \) ratio is smaller than 1/3, the maximum membrane stress increases suddenly as the membrane becomes too flat.

On the other hand, maximum membrane stress also increases significantly when inclination angle \( \alpha \) is increased up to 60\(^\circ\). This is because the angle between two the inclined arches become too small.

<table>
<thead>
<tr>
<th>H/L</th>
<th>Wind downward pressure</th>
<th>Wind uplift pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \alpha = 30^\circ )</td>
<td>( \alpha = 45^\circ )</td>
</tr>
<tr>
<td>0.5</td>
<td>12.73</td>
<td>13.69</td>
</tr>
<tr>
<td>0.375</td>
<td>11.33</td>
<td>13.4</td>
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<tr>
<td>0.167</td>
<td>22.94</td>
<td>29.36</td>
</tr>
</tbody>
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Table 1. Maximum membrane stresses (kN/m) subjected to wind pressure

Therefore, it can be concluded that the membrane shape of shelter is effective when \( H/L \) ratio is larger than 1/3 and the inclination angle \( \alpha \) smaller than 60\(^\circ\).

### 6. Conclusion

A new type of deployable shelter system based on the use of lightweight stressed anticlastic membrane and deployable arched frame has been proposed. Innovative deployable truss arch enables the shelter system to enclose large span space in a short time. The anticlastic fabric membrane helps to reduce the requirement for secondary and bracing structure. Different forms of the shelter system using either vertical arches or inclined arches have been introduced. Inclined arch arrangement facilitates fast-track deployment of the whole shelter and helps to tension the membrane efficiently. The erection time and cost therefore can be reduced. Shape efficiency studies have been carried out to determine the most optimum design parameters for the proposed deployable shelter. A full scale prototype of 17.8m shelter for container covering is being built. By the time of the Conference, more details and information on this prototype will be given.

### References

Eureka military tent, website: [www.military.eurekatents.com](http://www.military.eurekatents.com)