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STRESSED ARCH MODULAR DEPLOYABLE COMPOSITE SHELTERS CONCEPT AND DEVELOPMENT

T Omar
(PhD Candidate, Fibre Composites Design and Development, University of Southern Queensland, Toowoomba, Australia)

G Van Erp
(Professor Fibre Composites Design and Development, University of Southern Queensland, Toowoomba, Australia)

P W Key
(Manager & Engineering director, Kencana Strarch Asia Pacific, Kuala Lumpur, Malaysia)

ABSTRACT
Deployable shelters of various forms have been utilised since ancient civilisation. The need for these systems has not diminished over time and development continues for military forces, civilian humanitarian aid, and post-natural disaster scenarios. Recent developments have focussed mainly on tent type structures, air beam technology and steel frames supporting soft fabric, yet none of these systems have fully satisfied the deployability requirements.

The Military Modular Shelter System (M^2S^2) initiative is a research project that aims to develop a fibre composite re-deployable arched shelter system with rigid or fabric cladding. The main frames are formed from modular fibre composite panels that are connected and stressed in position by prestressing cables. Different geometries can be obtained using this system by changing the number of panels per frame and the packer sizes between panels.

This paper presents the concept of M^2S^2 with background about existing systems followed by the development and testing of an innovative, simple to manufacture, truss module that was investigated as part of this project. The test results showed good characteristics. These include having alternate load paths and failure initiated and propagated in the web with no, undesirable, failure observed in the adhesive layers.

KEYWORDS
Shelters, Composites, Deployable, Hanger, Strarch, Truss.

1. INTRODUCTION

The need for deployable structures has existed since ancient times. Deployable structures are similar to normal structures in that they have to be stable and able to carry designated loads in their deployed status (Gantes, 2001). In addition, they should satisfy the deployability requirements of being able to be dismantled, stored and transported in a compact form. They should also have an inherent deploying mechanism that allows the transition between the deployed status and the dismantled status and vice versa. Deployable shelters are an important application of deployable structures. They are needed for military applications, aircraft maintenance hangers, aid relief and temporary and/or remote structures.

Over time, the performance requirements of modern deployable shelters have become more demanding, which has driven the development of more sophisticated structural forms and solutions. The basic components of deployable shelters are the structural system (primary load transfer) and the cladding system. The cladding system can have different functions depending on its inherent properties and those of the structural system used. For example, cladding systems can be used to stabilize the structural system, assist in carrying primary loads, or can be integrated with the overall load carrying system. Consequently the two sub-systems are generally dependent on each other. The recent developments of deployable shelter technology can be categorized as air-inflated shelters; rigid frames supporting soft fabric shelters and stressed arch systems. These developments were reviewed by Verge (www.natick.army.mil) and Omar et. al. (2006). These reviews showed that the currently used deployable shelter systems do not fully satisfy the shelter deployability requirements. Air beam technology has not satisfied the needs for deployable shelters in spite of being under development for a significant period. Low pressure air beams can only be used for short spans. High pressure air beams store significant amounts of energy and still can not be used for large spans. The state-of-the-art deployable shelter system may well be the Widespan by Weatherhaven. The system can be used for large free spans. However, steel frames are used for the main panels with a dimension of 3.66m in length and a weight of 68kg (http://www.weatherhaven.com/). Both the size and the weight of these panels are more than the legal carrying capacity of two persons, in Australia. This may necessitate using some form of cranage to erect this system. The Weatherhaven systems use soft fabric for the cladding which creates the impression of a temporary structure that accommodates large deformations.

The M^2S^2 research project aims to investigate the behavior of a composite arch deployable shelter system that uses the post-tensioning prestressed technology as a deploying mechanism. One of the core components of this system was its modular panel. An innovative, simple to manufacture, adhesively bonded truss panel system was developed for this purpose. In this paper, the M^2S^2 concept is presented followed by the development and testing of its panel.

2. M^2S^2 CONCEPT

The concept of the prestressed arch technique has been implemented successfully in Strarch steel frames (Strarch 1999). The continuous nature of the top chord, the plastic deformation during stress erection and the strength to weight ratio associated with the steel trusses all provide challenges to the deployable functionality of conventional Strarch frame systems.

The M^2S^2 concept is similarly based on the stressed arch concept. However, it is adapted to the requirements of deployability by using more manageable (approx. 1500mm square), light-weight truss panels that do not require plastic deformation. The top chord deformation is concentrated at discrete joints (Figure 1). The concept of M^2S^2 can be summarized as follows:

1. Frames are manufactured, mostly, from identical standard panels;
2. Standard panels are stacked to form each frame on the ground;
3. Panels are then connected by inter-panel top hinged joints. The difference in dimension between the top chord and the bottom chord allows having initial gaps at the bottom chord;
4. One side of the frames is fixed to the foundation, while the other is free to move horizontally during erection. The prestressing cables are threaded through the bottom chord;
5. Roof sheeting (rigid type) and other services are assembled while the frames are still on the ground, prior to carrying out any prestressing (Assembly stage);
6. Finishing the installation of services; frames are stressed using prestressing cables. The bottom chord gaps allow the geometry to change to an arch shape during the prestressing process (Erection stage);
7. The prestressing cables are stressed to the level that allows for losses and/or relaxation in addition to ensuring that the bottom chord will be in compression under any serviceability loads. The cables are then blocked and the moveable frame support is fixed. The shelter is complete and ready to use (Deployed stage).

The concept of M^2S^2 is quite flexible. The number of panels per frame and the packer sizes define the frame span and height in the deployed position. Table 1 shows the effect of increasing the packer sizes from 200mm to 220mm on the frame geometry (frames are based on 32 standard panels). Increasing the packer size increases the frame span, reduces the rise/span ratio and the subtended angle. This flexibility should be accounted for when investigating the behavior of such frames.

Table 1 Effect of packer size on frame geometry

Frame Alternative	A1	A2	A3
Packer Size(mm)	200	210	220
Rise/Span – Radius(m)	12.1/36.7– 19.9	11.1/38.4- 22.1	10.1/40.0- 24.8
Rise/Span Ratio	0.330	0.289	0.252
Subtended Angle (deg)	133.3	120.3	107.2

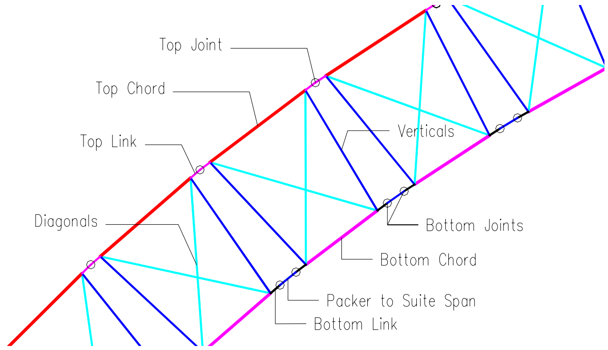

Figure 1 M^{2}S^2 system – main components

3. THE M^{2}S^2 MODULAR PANEL

The panel system is the core of the M^{2}S^2 concept. Accordingly, it was the first investigated component. As per the requirement of the system, the panel should have hollow sections for the chords to accommodate the prestressing cables. Previous investigations showed that it is recommended to have panels with flat-sided standard components; extended joint area and alternate load path after failure (Omar et al, 2006). Using a multi-pultruded panel with diaphragm bracing system satisfied these requirements. In addition, it was simple to manufacture and allows the use of multi-cables for prestressing.

Due to the arch geometry, the shelter frames are mainly subjected to axial forces. In addition, shear and bending moments are generated due to the un-symmetric loading of wind and live loads. In using standard pultrusion sections for the chords and vertical members, the member capacity under axial loads can be predicted using design codes. However, the diagonal skins and connections to the chord and vertical members need further investigations. These necessitated conducting prototype panel testing by applying shear forces on the panel to investigate its behavior. The panel was tested in beam mode with loads applied at mid span. The tested configuration had two panels of 650mm centerline dimension, with 50mm gap at the centre (Figure 2). The overall structure consists of three identical frames of 50mmx50mmx5mm hollow square pultrusions which were adhesively bonded to the two web laminates using a toughened epoxy adhesive. Load, deflection and strains were recorded at locations shown in Figure 2. Strain gauges located across the panel thickness were used to locate any differential stress and strain distributions. Gauges located on the laminated web were used to measure the tensile and compressive strains in the $\pm$45deg direction. Loads were applied using an Instron loading ram with a 500kN capacity. The structure was loaded using a displacement controlled loading rate of 2mm/min.

4. PANEL TEST RESULTS

The tested panel showed good performance with a load-deflection curve shown in Figure 3. The load-deflection curve indicates that the panel still reserves partial load carrying capacity (about 50% of its ultimate capacity) after failure in spite of continuous increase in the applied displacement. Failure initiated at the top corner of the diaphragm, due to the combined tension in the diagonal direction and compression in the perpendicular direction. Compressive forces were due to the confinement of the web with the tendency of the angle between the vertical and top chord members to reduce under the applied loads. Failure propagated along the inner faces of the vertical and top chord following the pattern of the formed wave of the buckled web (Figure 3). No failure was observed in the adhesive layers. This was another desirable feature as adhesive failure is inherently brittle. In releasing the applied load, the panel restored most of its deflection (in spite of rupturing of the web). More detailed behavioral investigation of this panel will be the subject of future publication where a finite element model was developed at the micro level to provide an insight of the panel is good attributes.

5. CONCLUSIONS

Combining the effectiveness of the arch as a structural form, the post tensioning prestressing technology and composite light weight materials has significant potential for developing effective deployable shelter systems. The M^{2}S^2 concept seems able to deliver a flexible deployable shelter system that satisfies the deployment requirements and the flexibility needed by the end users. The flexibility is achieved by using modular panels of manageable size and weight which are within the carrying capacity of two persons. In using packers at the bottom chord, different structural configurations can be obtained with different span to height ratio.

Using a multi-pultrusion panel system with diaphragm web showed good characteristics with the advantages of having alternate load paths, simplicity of manufacturing and allowing the usage of multi-prestressing cables. For the panel tested, failure initiated and propagated in the laminated web with no failure observed in the adhesive layers. The laminated web was able to restore the panel original geometry after releasing the applied loads.

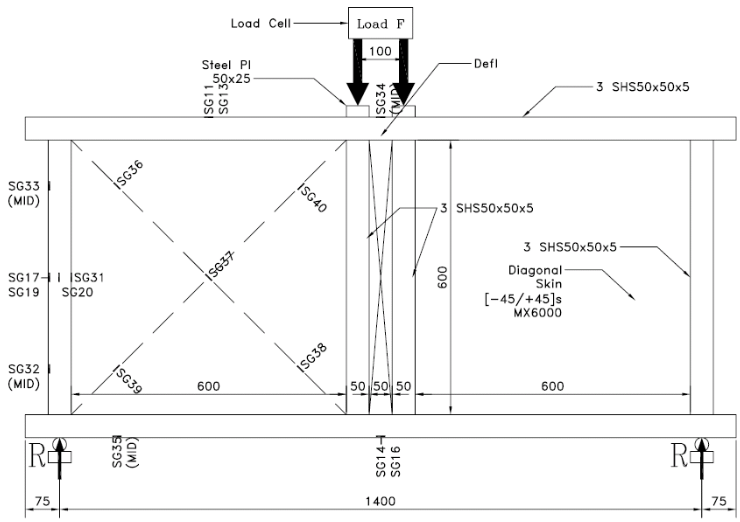

Figure 2 Test panel geometry and strain gauge positions

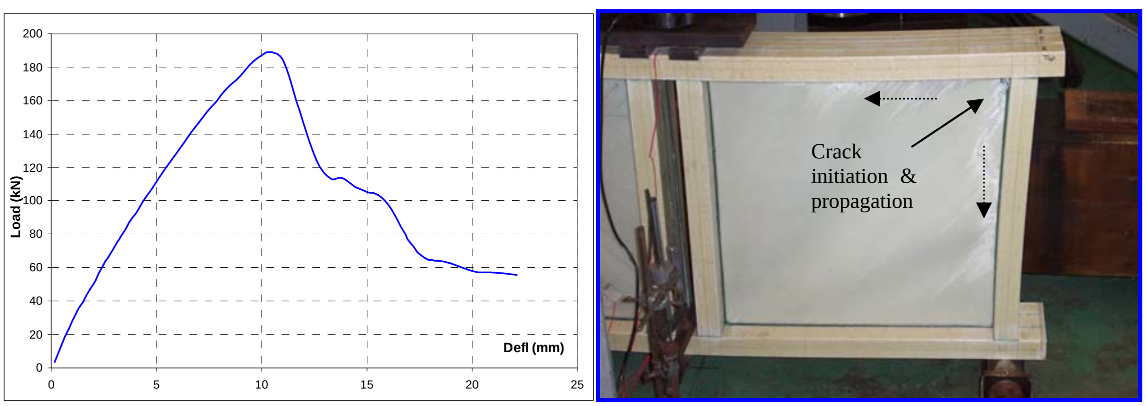

Figure 3 MK III load deflection curve and failure mode

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