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MODULAR DEPLOYABLE COMPOSITE SHELTERS – TRUSS SYSTEM

T. Omar[1], G Van Erp [2] and P. Key[3]

[1,2] *Fibre Composites Design and Development, University of Southern Queensland, Toowoomba Australia*
[3]*Kencana Strarch Asia Pacific, Kuala Lumpur, Malaysia*

Abstract: Deployable shelters of various forms have been utilized since ancient civilization. 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 focused mainly on tent type structures, air beam technology and steel frames supporting soft fabric, yet none of these have fully satisfied the deployability requirements. The Military Modular Shelter System (M^2S^2) initiative is a research project that aims to develop a fiber composite re-deployable arched shelter system with rigid PVC or fabric cladding. The main frames are formed from modular fiber composite panels that are connected and stressed into 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 development and testing of some innovative fiber composite truss modules that were investigated as part of this project.

Keywords: *Shelters, Composites, Deployable, Hanger, Strarch, Truss*

1 Introduction

The need for deployable structures has existed since ancient times. For example, tent structures have been used in different places around the world for centuries. This need for deployable structures has not diminished over time and development continues for military forces, civilian humanitarian aid, and post-natural disasters.

From a load carrying perspective, deployable structures are not that different to normal structures in that they have to be stable and able to carry designated loads in their deployed status [6]. In addition to these basic requirements, they should also satisfy the deployability requirements of being able to be dismantled, stored and transported in a compact form. They should have an inherent deploying mechanism that allows the transition between the deployed status and the dismantled status and vice versa in a relatively quick and easy manner.

Deployable shelters are an important application of deployable structures. They are needed for military applications, temporary aircraft maintenance hangers, aid relief and remote structures. In recent times the need for these type of structures has increased significantly. This has prompted Strarch International to start a research project into a more efficient modular shelter system. The M^2S^2 initiative concentrates on the development of a fiber composite re-deployable arched shelter system with rigid PVC or fabric cladding. The main frames are formed from modular fiber composite panels which are connected and stressed into 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 starts with a discussion of different deployable shelter systems currently in use around the world. It then continues with a general discussion of the M^2S^2 concept followed by a detailed discussion of the development and testing of an innovative fiber composite truss module which will form the basis of the main frame structure.

2 Deployable Shelters

The basic components of deployable shelters are the structural system (primary load transfer) and the cladding system. The latter 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 or assist in carrying primary loads.

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[1] PhD Candidate, omart@usq.edu.au
[2] Professor and Managing Director, vanerp@usq.edu.au
[3] Manager & Engineering director, pwkey@strarch.com

Recent developments of deployable shelter technology can be categorized into two categories; air-inflated shelters and rigid frames supporting soft fabric shelters. Air-inflated shelters use air supported closed elements (pressurised) that act as structural elements to support fabric cladding [6]. Rigid frames supporting soft fabric shelters use cables and membranes for the cladding system and steel frames as the main load carrying system.

The United States military has been the most active organization driving development of deployable structures that can provide command and control, medical, and rest and relief functions with minimal time and effort [20]. They have developed many air inflated shelters since their first M-51 shelter in the 1960s. As the traditional woven air inflated beams are of limited span and unreliable and unsafe at high pressure, Natick Soldier Centre (NSC) introduced the concept of a high pressure braided air beam in the late 1980s [20]. The largest span accomplished in using this system was 25.3m for the Aviation Inflatable Maintenance Shelter.

Due to the limited spans of these inflated concepts, rigid frames supporting soft fabric shelters have been used widely in recent years. A good example of the latter system is that developed by Weatherhaven Resources Ltd. Their WideSpan range is a modular rapid erection shelter that does not need heavy equipment (cranes) or skilled labor to be erected (**Figure 1**). All installations are carried out on the ground. A standard 465m^2 shelter can be transported in a standard 20ft container. The maximum component size is 3.66m and weights 68kg [21].

Figure 1: Weatherhaven WideSpan shelter system

Another example of a rigid frame system is the Extra Large Deployable Aircraft Hangar System (XLDAHS). This is one of the largest deployable shelter systems commercially built for the US military to maintain the B2 stealth aircrafts. The shelter is 76.2m wide, 18.30m high and weighs 80 tons. The first two shelters of this type were assembled in December 2002. The assembly required twenty persons to spend more than 70 days constructing and erecting the shelters. Two temporary erection towers were used, with one person controlling both wenches, to place the shelters' trusses. Once in place, the truss is be anchored down with cables, and each successive truss is attached to the previous one. The shelter's covering is composed of huge sheets of fabric with eyelets through which rope is run manually, using personnel working on top of the structure, and strapped in with harnesses and safety lines [7].

Figure 2: B2 Shelter during erection

3 The Concept of M^{2}S^2

In order to improve on these existing systems Strarch initiated the M^{2}S^2 project. An extensive literature search was conducted in order to compile a detailed design specification. The Required Operational Capability (ROC) [11] was the only document found in the literature that specified the deployability requirements for deployable shelters. Among these were the requirements not to use any special tooling and being able to create a structure with minimum dimensions of 27.45mWx36.6mLx7.0mH.

Most deployable shelter systems currently in use do not fully satisfy the above requirements. In spite of being under development for a significant period of time, the spans that can be achieved with air beam technology are limited. 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. Both the size and the weight of the Widespan 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 concept of M^{2}S^2 is based on the stressed arch concept that was originally used in Strarch steel arches [17]. However, it overcomes the deployability short comings in this system by utilizing discrete truss panels to form the frames. Rotations between adjacent panels occur at discrete inter-panel joints in the top and bottom chords [13]. Standard panels are connected to each other in an up-right position at ground level to assemble each frame (**Figure 3**). One side of the frames is fixed to the foundation, while the other is free to move horizontally during the prestressing procedures. The prestressing cables are threaded through the bottom chord. Roof sheeting and other services are assembled while the frames are still on the ground prior to carrying out any prestressing (the assembly stage). After finishing the installation of services, the frames are stressed into an arch shape using prestressing cables. The bottom chord has gaps between the panels to allow for changing of the geometry to an arch shape during the prestressing process (Erection stage). Finalizing the stressing process, the prestressing cables are blocked and the moveable frame support is fixed, the shelter is complete and ready to use (Deployed stage).

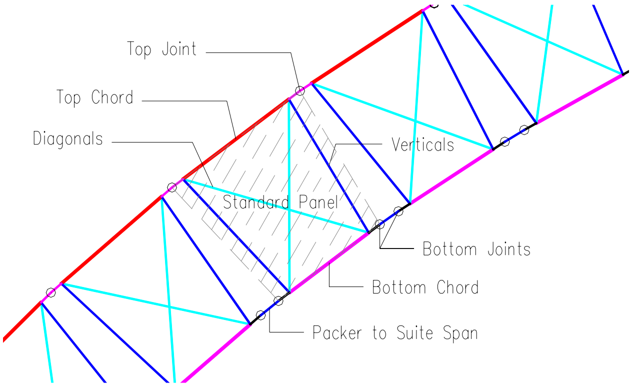

Figure 3: M^2S^2 Frame components

The inter-panel packers used at the bottom chord control the length of the bottom chord and hence the frame geometry. With 32 panels per frame of 1400mm dimension, changing the packer size from 200mm to 220mm changes the frame dimensions, in the erected position, from 36.7mWx12.1mH to 40.0mWx10.1mH. This ability to change the geometry of the structure with little effort is a major advantage of this new system.

4 2D-Truss Systems in Fiber Composites

The most important component of the M^2S^2 system is the modular fiber composite truss panel. Composite truss systems are not very common and only a few systems have been reported in the literature. The most widely used system consists of pultruded members which are bolted and/or glued together. A typical example of this system is the Pontresina Bridge that crosses the Flanz River in Switzerland. The bridge was constructed in the 1997. Cross diagonal bracing was used to reduce the joint forces and provide structural redundancy.

Figure 3: Pontresina Bridge, Switzerland

A non-conventional approach for composite trusses was proposed by Humphreys et al [9]. The Monocoque Fibre Composite (MFC) truss concept uses two planner skins, separated by a core material, that contain the fiber structure of the truss members, **Figure 4**. The truss derives its strength from the reinforcing skins while the core material separates the skins to provide lateral stiffness for the members' stability. Due to the difficulty in lapping the joints, the concept of strength and fill layers was introduced. Strength layers are layers in which the fibers extend through the joint while fill layers stop at the member intersections. In using different sequence of strength and fill layers in the chords, verticals and diagonals, each of these members can be connected to the joints (**Figure 5**).

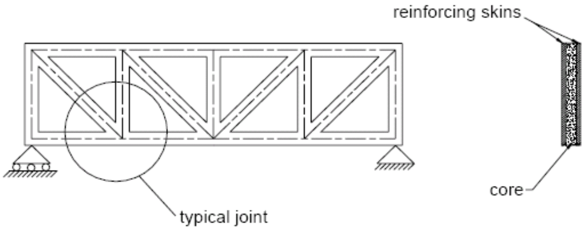

Figure 4: Monocoque Fibre Composite truss concept

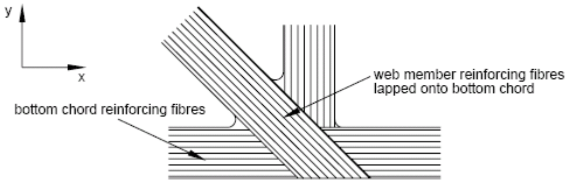

Figure 5: MFC concept of strength and fill layers

5 Innovative Truss System for M^2S^2

None of the truss concepts found in the literature were considered suitable for the M^2S^2 concept. Hence, early work focused on the development of different fibre composite panel alternatives. The parameters that were considered include; overall structural system, fabrication techniques, structural performance (such as capacity, ductility, stability, durability & fire resistance) and operational considerations (such as handling, assembly, dismantling & storage). In investigating different panel concepts, a weight limit of 20kg/m was set in order to satisfy handling and maneuvering requirements. To accommodate the prestressing cables, the top and bottom chord of the panel had to include a hollow section. Previous investigations have shown that it is recommended to have panels with flat-sided standard components, extended joint areas and structural redundancy [13]. The maximum member forces for a 35m span frame in a non-cyclonic zone B AS/NZS 1170.2-2002 [14, 15& 16] are shown in Table 1. Due to the arch geometry, the shelter frames are mainly subjected to axial forces. In addition, shear and bending moments are generated in the case of un-symmetric loading.

Table 1: Serviceability limit state member forces

Member	**Max Force (kN)***
Top chord	-200
Bot chord	-290
Verticals	±30
Diagonals	±45

* Refer to [13] for loading scenarios of deployable shelters.

The concept of a multi-pultrusion truss (MPT) was introduced to overcome the above mentioned challenges. The MPT uses three (or more) hollow pultruded section for the top and bottom chords and the vertical members (**Figure 6)**. The shear capacity of the panel is provided by two laminated skins that are anchored in between the pultrusions using an epoxy adhesive. The advantages of this approach can be summarized as follows:

- Pultrusions are among the most efficient and economical forms in composite sections;
- Using multi-sections significantly improves the lateral stability of the members in compression;
- Local buckling resistance of the top chord is good due to the use of multiple rather stocky pultruded sections;

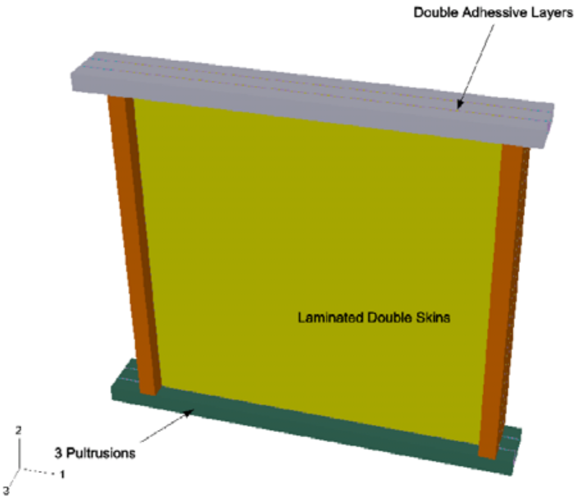

Figure 6: Multi-pultrusion truss concept

- Multiple hollow pultrusions allow for more than one cable to conduct the prestressing process. It also provides much more area to join with the adjacent panels;
- The laminated web acts as a diaphragm that is mainly loaded in tension, the favorite loading type for fiber composites;
- Having a diaphragm avoids stress concentrations in the adhesive layers and in the connecting parts by allowing force transmission through the continuous adhesive layers;
- Forces in the web are not interrupted by localized joints. However, they are directly transferred to chord and vertical members;
- The diaphragm web provides significant redundancy in the case of tensile failure of the laminated web;
- The panel durability and fire resistance is expected to improve due to eliminating the exposed joint area, by extending the web skins between pultrusions;
- The proposed panel is simple to manufacture;
- This concept was mainly developed for M^2S^2. However, it can be used as a general truss concept.

6 MPT Panel Test

To obtain an initial indication of the load carrying capacity of this new panel concept it was tested in a beam mode with loads applied at mid span. The tested configuration consisted of two panels of 650mm centerline dimension, with a 50mm gap at the centre (**Figure 7**). The overall structure consists of three identical frames of 50x50x5mm hollow square pultrusions which were adhesively bonded to two web laminates. Load, deflection and strains were recorded at the locations shown in **Figure 7**. 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 ±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.

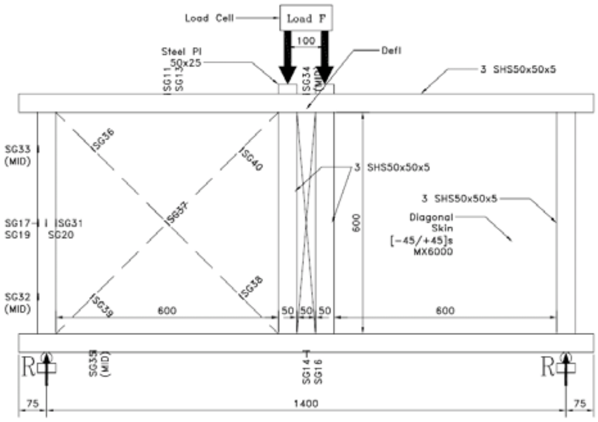

Figure 7: Test panel geometry and strain gauge positions

7 MPT Panel Test Results

The tested panel showed good performance. The load-deflection curve (**Figure 8)** shows that the panel retains a partial load carrying capacity of about 60% of the ultimate capacity after failure of the main tension fibers. Failure initiated at the top corner of the diaphragm, due to the combined tension in the diagonal direction and compression in the perpendicular direction (**Figure 9)**. 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. No failure was observed in the adhesive layers. This is a favorable result as adhesive failure is inherently brittle. The semi ductile behavior of the panel is attributed to the way in which the web carries the tensile loads. Figure 10 shows the tensile forces in the web predicted by the FE model at ultimate capacity. As shown, the middle 40% of the web carries 80% of the total tensile force. On reaching the ultimate strength, failure occurs in the middle region of the web. This releases some of the stored energy and reduces the panel stiffness. Regions adjacent to the failed section continue to carry load until reaching failure and so on. In releasing the applied load, the panel recovered most of its deflection (in spite of rupturing of the web).

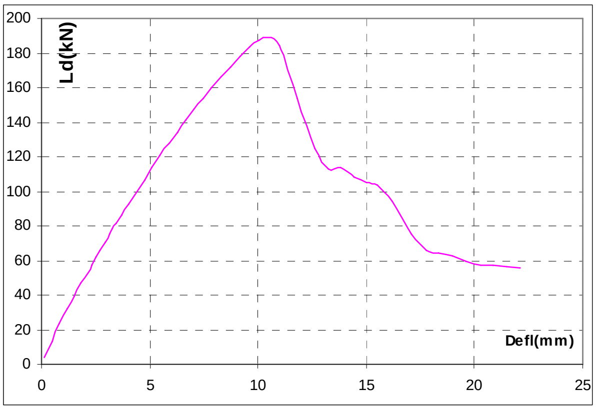

Figure 8: Test panel load-deflection curve

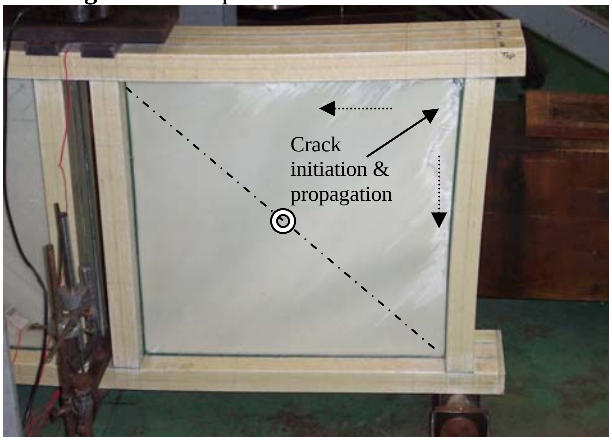

Figure 9: Test panel failure initiation and propagation

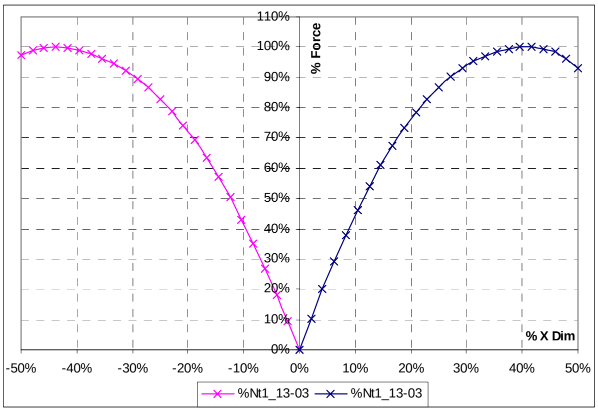

Figure 10: Diagonal force integrated along the cross diagonal

The strain gauge records, **Figure 11** to **Figure 14,** show that:

- Up to the ultimate load, the load-deflection curve and the strain-deflection curves are mostly linear;
- The system is effective in distributing forces between the panel frames, as equal strains were recorded across the panel at different locations;
- Strain distributions across the verticals changed from tension at the outer surface (SG17 to SG19, **Figure** 13) to compression at the inner face (SG31, **Figure** 13) with equal shift from the centre line gauge SG20. This indicates that the verticals are subjected to bending stresses;
- Strains recorded by top chord gauges (SG11-SG13, **Figure** 11) and verticals gauges (SG17-SG19, **Figure** 13) are identical with a slight change at the post failure region. This behavior is expected as both gauges are symmetrically located about the tensile diagonal in the web;
- Compressive strain at mid-span top chord (SG34, **Figure** 11) is approximately half the tensile strains (SG14-SG16, **Figure** 12) at the bottom chord. This can be attributed to bending stresses in the chords. As expected, both chords have similar axial force components albeit with different signs;
- In **Figure** 11, at ultimate load, SG34 recorded less strain compared to quarter span top chord gauges (SG11-SG13). With the start of failure propagation, SG34 strain level increased while SG11-SG13 reduced. This behavior can be attributed to the level of stress in the web laminate that applies both axial and shear forces on the connecting frame members. This results in bending moment and axial forces in such members. Combined stresses were higher at SG11-

SG13 compared to SG34. After failure, stresses in the web laminate reduced, due to rupturing of the web, leading to reducing strain in SG11-SG13. The increase in SG34 can be attributed to an increase in the member curvature with the less stiff damaged panel;

- Web strains (SG37-SG38) in tension are significantly higher than the strains recorded in the pultrusions. Nominal compressive stresses are recorded in the other diagonal direction (SG40). This validates the expected behavior of tension-only bracing web.

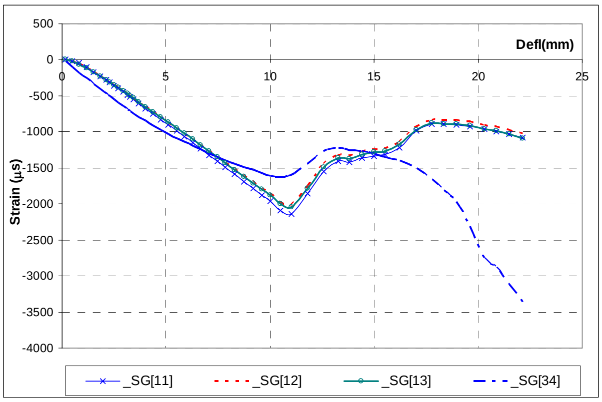

Figure 11: Strain-deflection curve at top chord

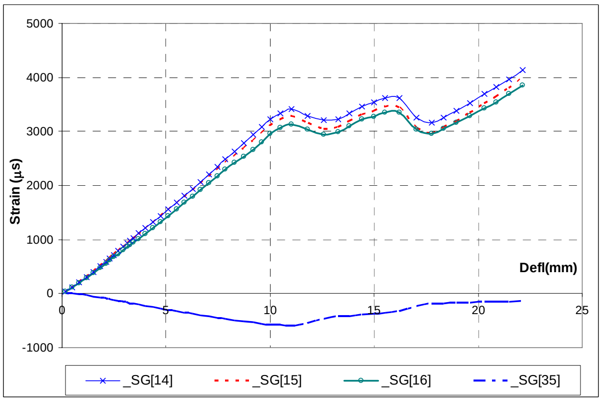

Figure 12: Strain-deflection curve at bottom chord

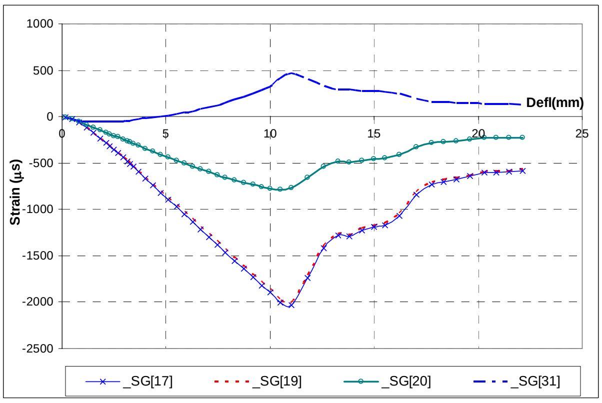

Figure 13: Strain-deflection curve at verticals

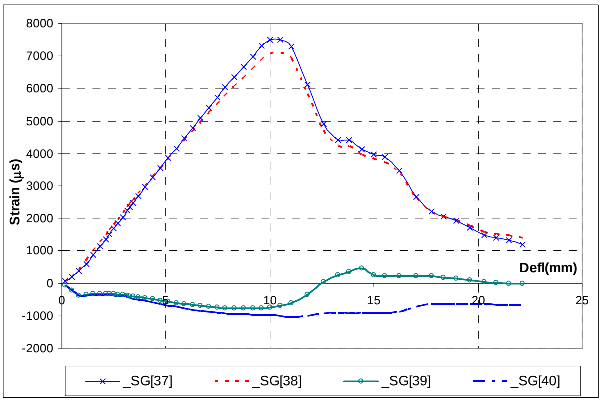

Figure 14: Strain-deflection curve at web laminate

8 Conclusions

The demanding performance requirements of modern deployable shelters have driven the development of more sophisticated structural forms and solutions. The M^2S^2 deployable shelter concept combines the effectiveness of an arch as a structural form, post tensioning technology and light weight composite materials. This innovative approach provides 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. By using different size packers in the bottom chord, different structural configurations can be obtained with little effort.

The multi-pultrusion truss module showed good load carrying characteristics. Providing an alternate load path after failure, no failure in the adhesive layers, recovering original geometry after removal of applied loads, ease of manufacturing and the possibility of having different prestressing cables are among the important characteristics of this system. Further research work is needed to investigate the detailed structural behaviour of this truss concept.

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