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Origami-Based Developable Membrane Tensegrity Roof

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Abstract

In lightweight membrane structures, wind loads are almost always dominant in terms of structural capacity. In other words, if the membrane structure can be deformed to a safe state under conditions of wind speeds above a certain level, it is possible to create an inexpensive, ultra-lightweight roof with minimal structural components. Focusing on this point, we developed a method of effortlessly erecting the membrane structure, which is developed almost flat under normal conditions, by folding it like origami only when it is in use. The membrane structure we propose is highly novel, having the following features. (1) It is ultra-lightweight with little frames using the idea of tensegrity, (2) it is always stable during deployment by using bending-active, bowed CFRP rods, and (3) it is developed rather than folded for storage. We designed a 10m square, quadruple-supported membrane roof structure using the developed method. This open roof structure, when erected, provides a sunshade for the outdoor sumo arena, and when unfolded and lying close to the ground, it protects the dirt surface of the arena from rain and sun, so it is fixed and cannot be folded down. The ultra-light weight improves safety in the event of a collapse, and eliminates the need for temporary structures or power to erect the structure, making it possible for users to manually erect it in a short time on this scale. This paper presents findings on the developable membrane tensegrity roof obtained through actual construction.

Keywords: membrane tensegrity structure, origami, transformable structure

1. Introduction

One of the historical features in the development of large space structures is the attempt to reduce weight. Beginning with the form and thickness of the masonry arches and domes, weight reduction has subsequently been achieved through the introduction of new materials and technologies. The advent of membrane structures further accelerated weight reduction, with air membrane structures appearing in the 20th century reaching around 20 kg/m^2. However, further weight reduction is not considered to be of much benefit. This is because the determining factor in design is not the weight of the roof, but the effect of wind, for example. This wind problem is solved in this paper by making the structure deformable, resulting in an ultralight structure of only 2 kg/m^2.

To create such a lightweight and retractable structure, this study combines origami, tensegrity and bending-active techniques. Chapter 2 introduces relevant deployment structures and tensegrity research, Chapter 3 describes specific design methods and mechanisms to control movement, and Chapter 4 describes a mock-up to verify feasibility.

2. Related works

Several retractable roof structures have been proposed.

One example is the foldable scissors mechanism [1,2,3]. Arch or dome deploying mechanisms have been devised, some of which move in one degree of freedom and some of which are controlled by cables. Other roofs consist of foldable panels like origami [4]. All of these structures consist only of a framework and panels, and the membrane is added afterwards, so they have the problem of being heavy.

Membrane tensegrity structures are known as lightweight membrane structures. This is a type of tensegrity structure in which the membrane is used as a tensile material, and the structure is formed by the balance of forces between the compressive materials even if they do not touch each other [5,6]. Membrane tensegrity structures are very compact if the compressors are removed, but there are still no membrane structures that can be folded with the compressors attached.

In addition, most of these membrane structures are folded for storage when not in use, and then expanded when in use. In contrast, we propose a structure that is rather unfolded and lying down when not in use.

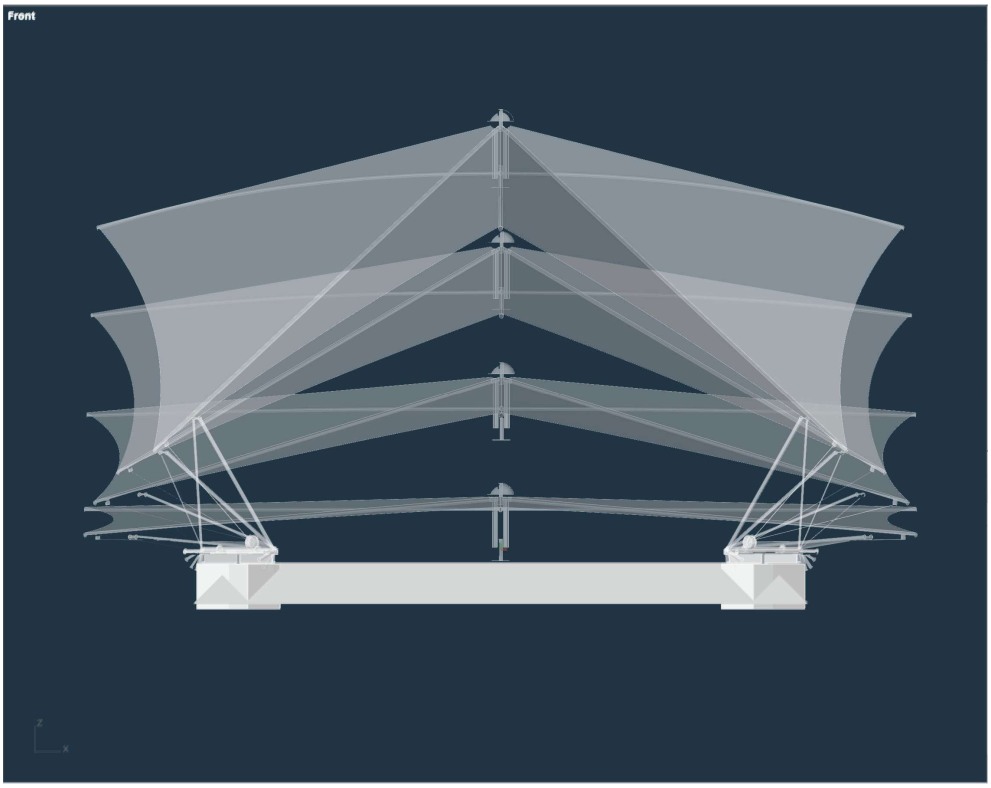

Figure 1: The deployment process of our designed membrane tensegrity roof.

3. Design and geometry developable membrane tensegrity roof

The membrane structure designed in this study is highly novel, fulfilling all of the following conditions. (1) It is ultra-lightweight with little framework using the idea of tensegrity, (2) it is always stable during deployment by using bending-active, bowed CFRP rods, and (3) when not in use, it does not fold up small, but spreads out wide to function as a ground cover.

This is made possible by an idea that focuses on the similarities between origami and tensegrity. Tachi points out the theoretical equivalence of an infinitesimal folding mode of a polyhedral surface and the equilibrium of forces to show that the same shape can be used as a shaky polyhedron and as a tensegrity structure [7]. The mountain and valley fold lines of origami correspond to the compressive and tensile (or tensile and compressive) memberss of the tensegrity structure (Figure 3). This principle may also hold true when cables are replaced by membranes [6].

In the present design, the base geometry is a fall with four mountain folds and four valley folds that intersect at a single point in the centre. This fold is also represented in the traditional crane origami process (Figure 4).

It was found that introducing a tensile force at the mountain fold and a compressive force at the valley fold results in a balance of forces around the vertex. Therefore, steel rods are placed as climbing beams in the valley-fold section. The mountain-fold section is a membrane, and CFRP bent into a bow is installed so that tension is always introduced during the unfolding, folding and deformation processes. The component structure is shown in Figure 5. When the four corners of this structure (the lower ends of the climbing beams) are brought closer together, the structure rises up like a folded piece of origami. A triangular frame that can be erected with a wire is then connected to this position, and the wire is connected to a winch so that it can be wound (Figure 6). At the apex, a joint is provided to connect the four climbing beams. In addition, four posts are mounted below them, so that the crossed CFRP can slide up and down between the posts (Figure 7).

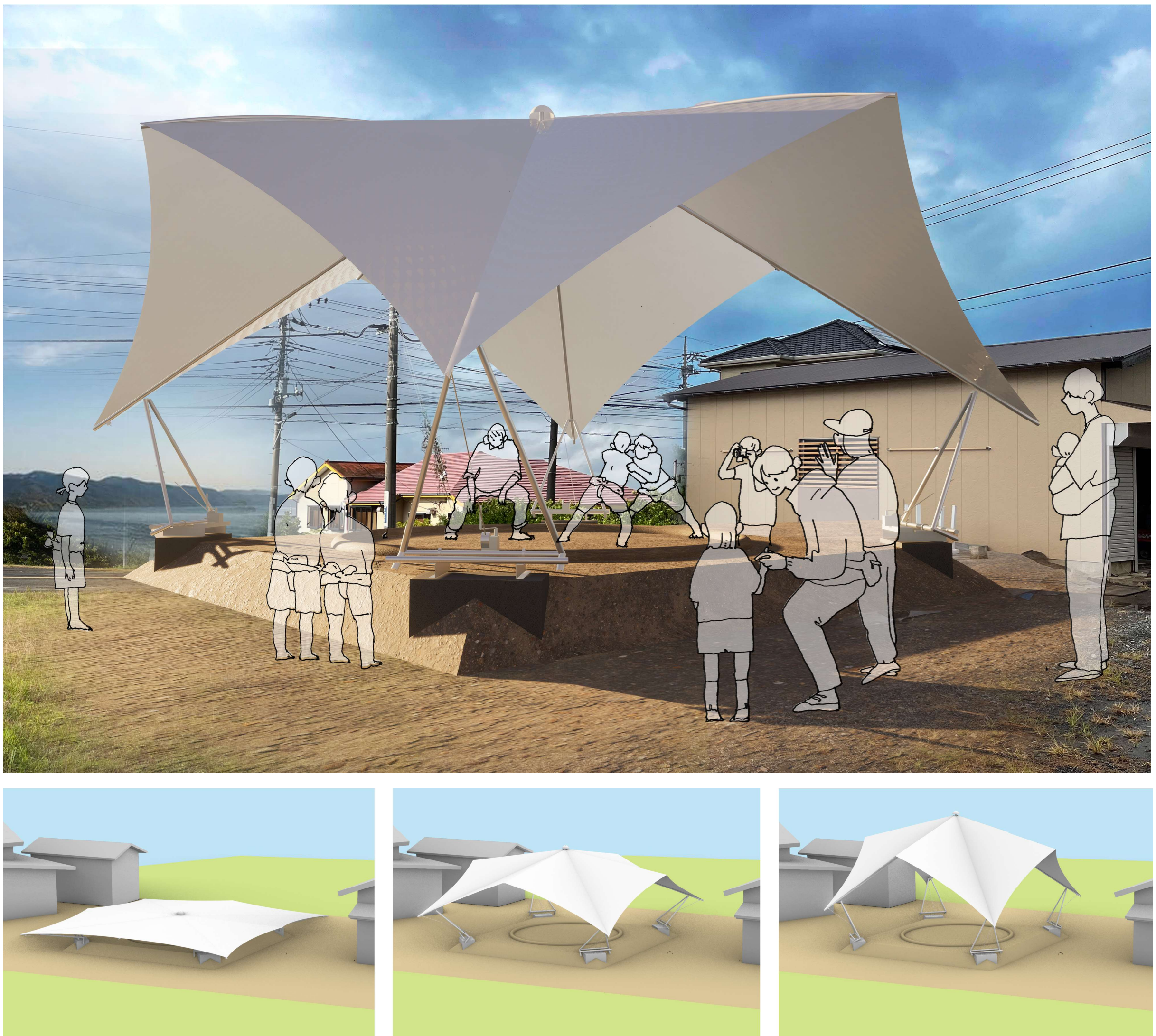

Figure 2: Our designed membrane tensegrity roof used as a sumo arena, and its deployment process.

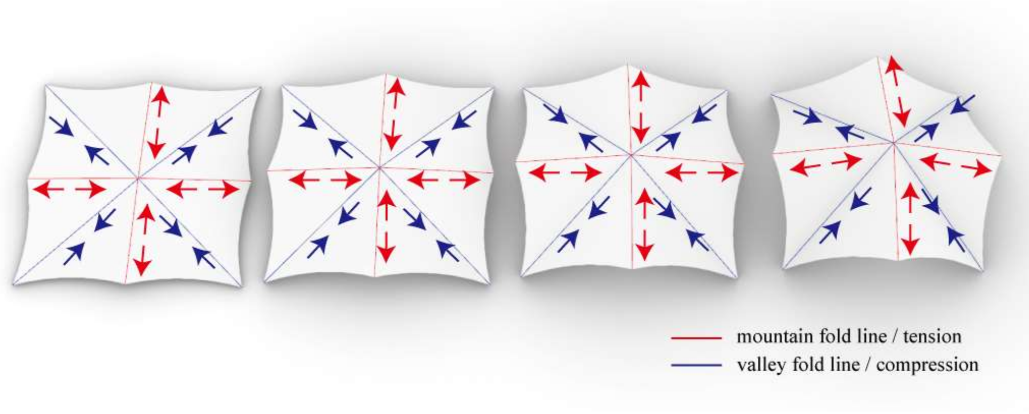

Figure 3: The mountain and valley fold lines of origami correspond to the compressive and tensile (or tensile and compressive) members of the tensegrity structure.

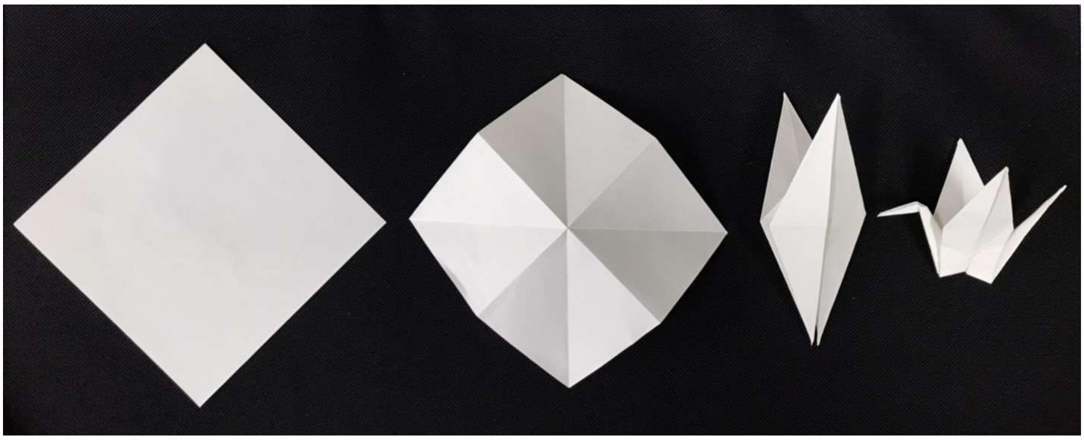

Figure 4: The process of folding a traditional Japanese paper crane. The second process from the left corresponds to the shape of the membrane structure in this case.

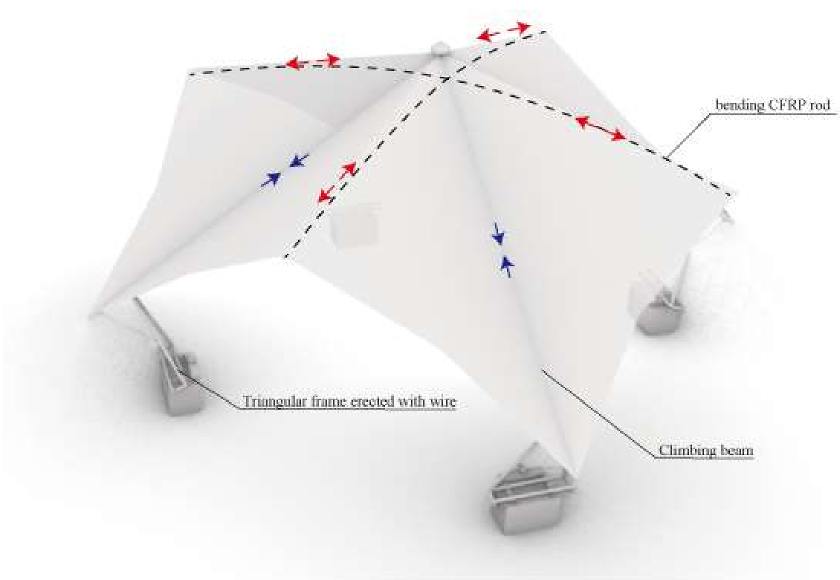

Figure5: The component structure.

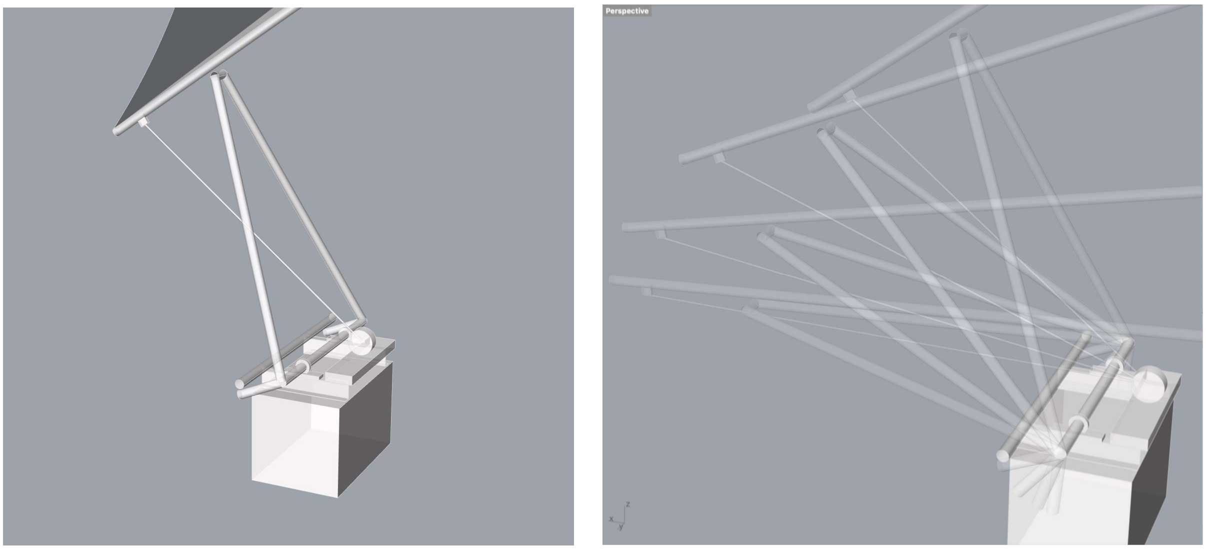

Figure 6: Triangular frame attached to the underside of the climbing beam. The frame is slowly raised as the wire is wound up by a winch fixed to the foundation. This mechanism draws in the end starting point of the membrane, which in turn raises the entire roof.

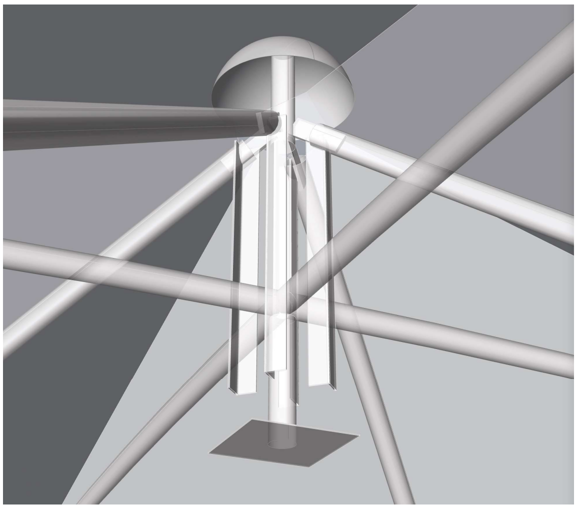

Figure 7. Joints at the apex. Four posts are attached below the apex joints connecting the climbing beams, and the cross CFRP can slide up and down between the posts.

4. Mock-up prototyping and validation

4.1. Purpose of mock-up verification

In designing this roof, we conducted a 1/3-scale mock-up test. In this paper, we report on the construction and structural experiments of this mockup. The purpose of this experiment was to verify the structural stability of the roof structure, the construction procedure, and the validity of the winch hoisting method, as well as to measure the deflection of the membrane material and compare the calculated deflection with the experimental deflection for use in actual construction.

4.2. Overview of mock-up design

4.2.1. Selection of membrane materials

As with the actual roof design, we used polyester membrane for outdoor use made by HIRAOKA & CO., LTD. for the roof membrane in this mock-up test. The size of the membrane was 1/3 of the actual size, and the required bearing capacity was assumed to be 1/9 of the actual capacity, and the membrane material was reinforced with attached fabric.

We sewed pockets 120 mm long (about 6 times the diameter of the beam pipe) into the membrane where we fixed the ends of the climbing and bending beam.

In the center of the climbing beam, we attached a tube through which a pipe member could be threaded. The roof top of the membrane has an octagonal hole 120 mm in diameter to avoid interference with the top hardware that connects the beams. The perimeter and the roof top folded and sewn around the holes to prevent the membrane material from tearing. We attached reinforcing fabric to the membrane to prevent the membrane from being subjected to high tension at the point where the curved beam meets the membrane.

4.2.2. Climbing beam

The climbing beams, which support the membrane roof from four directions, are subject to axial forces and bending moments when the roof is raised. We used agricultural steel pipes Φ19.1mm, t=1mm for the climbing beams. They were approximately 2100 mm long, and a deformable structure was fabricated by attaching rotatable joints to the top and legs.

For the metal joint at the top where the four climbing beams connect, we used "flexible T-bands" for temporary agricultural buildings, attached to aluminum angles in a crisscross pattern to create a metal joint that allows the climbing beams, which extend in all directions, to rotate at the top. The angle is fixed to the top and bottom of the flexible band with separate bolts, and washers are placed on the bolts to ensure that the climbing beam can rotate sufficiently.

Table 1: Assumed physical properties of climbing beams

Cross-sectional area	A=0.568[cm2]	Short-term allowable bending moment	5.856[kgfm]
Cross-sectional secondary moment	I=0.233[cm4]	Bending moment at erection	0.900[kgfm]
Cross-sectional coefficient	Z=0.244[cm3].	Long-term axial force	21.2[kgf]
Reference strength	σ =2.4[tf/cm2].	Buckling load	109.506[kgf].
Radius of cross section	i=0.640[cm]		
Length of material	L=2.1[m].		
Slenderness ratio	λ =327		

4.2.3. Bending beam

The bending beam bends in a bow as the roof is raised, and the repulsive force between the edges introduces tension into the membrane to prevent flapping and sagging of the membrane material. For the bending beam, which requires elasticity to introduce tension into the membrane material when it is erected, we prepared two types of CFRP φ10mm and φ15mm to compare the difference in reaction force due to deformation and the shape of the beam. The length was set so that the membrane material would be sufficiently tensioned even in the prone position. We spliced 3 pipes together to make a 3000 mm length pipe, since only L1000 was available in the ready-made products of the relevant CFRP diameter. To join the pipes, we prepared a short-cut bolt (L200) that just fits into the inner diameter of the pipe, temporarily fixed it to the end of the pipe with hot-melt glue, and joined the two pipes together. In addition, end caps were made by a 3D printer to adjust the length; Poly-Lactic Acid (PLA) was used as the resin for 3D printing. Simulation results for a bending rigidity of 2000[tf/cm2] (200[GPa]) are shown in Figure 8.

Even for ready-made pipes made of CFRP pipe, the material properties vary depending on how the pipe is fabricated and how the carbon fibers are layered. Therefore, we conducted a three-point bending test by loading CFRP pipes with only springs before the experiment to measure the Young's modulus of the

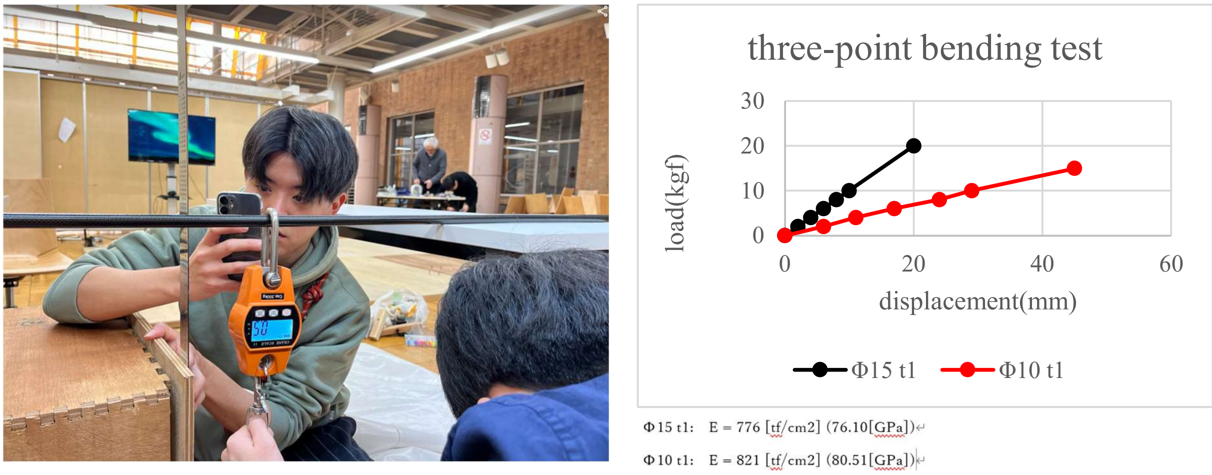

Figure 8: Experiment results of bending stiffness of CFRP

pipes used. The measurement results showed that the stiffness was about 1/3 of the assumed 2000[tf/cm2].

4.2.4. Legs

We used agricultural steel pipes for the legs as well as for the climbing beams. We used "flexible bands," which are widely used in agricultural buildings, to form an isosceles triangle with three pipes that intersect at two different angles, and attached a pipe at the top that would serve as the axis of rotation for the climbing beam. The joint between the climbing beam and the axis of rotation was clamped using temporary pipe clamps, and the swash material and the axis of rotation were clamped using a universal joint, and the clamps were loosened to allow the climbing beam to rotate freely about the axis of rotation. The bottom pipe was fitted with a lightweight bearing unit at the end to allow smooth rotation against the ground.

4.2.5. Winch and rope for building up

For the winch, we used a winch that can be manually turned to hoist up to 150 kg of force. In addition, we used ropes used for tents instead of a wire for erection. The rope had a capacity of 150 kg, and was matched to the winch's performance.

5. Construction of the roof

At the beginning of the construction phase, we marked the location of the footings on the plywood that would be the ground plane, and plywood-mounted the bearing members that would attach the triangular footings. We threaded the climbing beam pipes through the pockets in the membrane material and attached the apex hardware joint to the pipes. Because the apex hardware joint was disassembled and installed, washers and other parts of the joint fell out, loosening the joint between the apex and the pipe.

We attached and aligned the climbing beams to the rotary shafts of the legs. We tied the ends of the rope attached to the winch to the ends of the climbing beams at the four corners. The rope was wound by the winch on the outside of the roof through a pulley on the inside of the leg (Figure 9).

Finally, we attached a 10 mm dia. CFRP bending beam to the center pockets of the four sides of the tent membrane. During the installation phase, the edges hit the floor and other surfaces, and the 3DP beams attached to the edges broke at the connection points. Since it seemed to be able to resist the compressive force as it was, the installation was continued with the ends in the pockets.

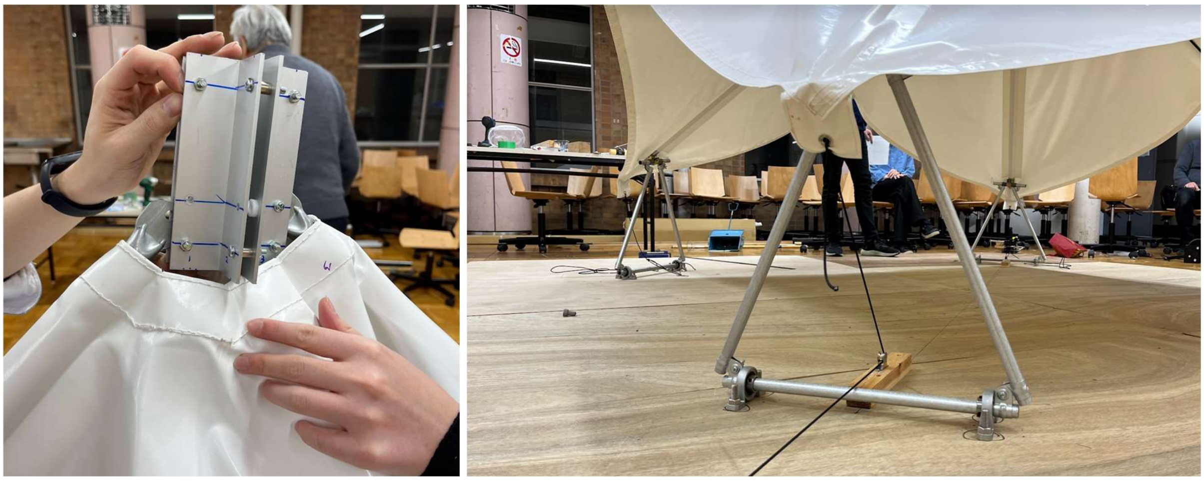

Figure 9: Assembly of top and leg hardware

6. experimental results and improvements

6.1. Confirmation of roof deflection

The roof was lifted by turning the winches at the ends of the four corners with the φ10mm CFRP bending beam fixed to the membrane material. When the roof was raised to the planned height, a large deflection of the roof was observed, about 120 mm at the edge of the membrane material. Visual observation of the cross beams from below revealed that the crossed beams rotated in a swastika shape, causing buckling in the lateral direction.

We further conducted a similar experiment with a 15 mm dia. CFRP bending beam anchored to the membrane material. In this case, too, the roof deflection was significant, and deflection of about XX mm was observed at the edge of the membrane material. Visual observation of the crossed bent beams from below revealed that the crossed beams rotated in a swastika shape and buckled in the lateral direction. Furthermore, when the roof continued to be lifted, the center of one of the CFRP pipes in the crossbeam broke off and ruptured.

6.2. Improvement of Bending Beams

The extension caps at the CFRP ends were removed, the cross beams were shortened and reattached to the membrane material, and when the winch was wound up in the same manner, the four sides of the membrane material were also subjected to normal tensile force and the deflection of the membrane material was eliminated (Figure 6).

7. Discussion and Improvements of the Design

Based on the results of the 1/3 mock-up, a future task is to design and construct a full-scale structure. The results of the analysis showed that 2 kg/m^2 ultra-lightweight structure was achieved when the structure was designed to withstand wind speeds of up to 15 m/s (Figure 12).

The design of such a kinetic structure requires a dynamic three-dimensional model to verify the form and clearances of the moving parts at each stage of the design. The parametric model created in Rhino Grasshopper was designed to simulate the trajectory of all moving parts when properly erected. Various suggestions from the structural dynamic conditions were fed back into the model to study the movement of the actual constructable joints and other details. This was an example of the effectiveness of parametric modelling in the design of kinetic structures.


Figure 10: Crossed beams rotated in a swastika shape

Figure 11: Mock-up made of shortened CFRP and adjusted so that the membrane is applied in the same shape as the scale model, and its deployment process.

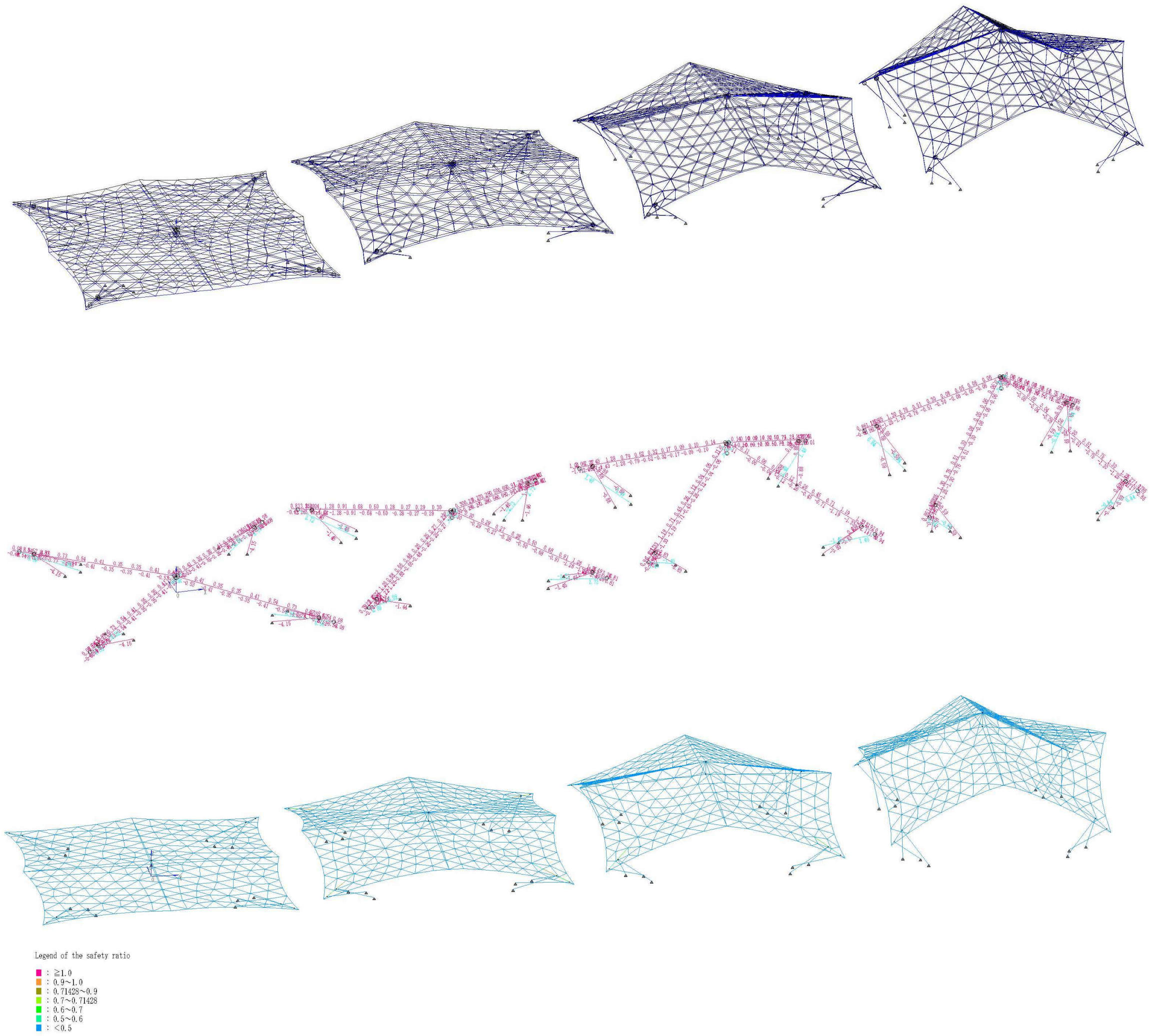

Figure 12: Analytical model of full-scale mock-up.

Long-term deformation (top) long-term axial force (middle) safety ratio (bottom).

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