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Weightless Construction of High Tower to the Stratosphere

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Construction of a high tower to the stratosphere was first proposed by Canadian Thoth Company. Because of its enormous scale, people are hesitant to implement the project immediately. This paper proposes several next steps to its realization. Fundamental aspects of the structure are presented. Based on the models, treated are a long bridge over Tsugaru Straight, medium height towers for an inter-city rope way or a suspended rocket launcher in addition to the stratospheric tower. For a light weight structure, some inflatable models are tested to verify its effectiveness to the aerospace field of application.

Key Words: LTA, Inflatable Structure, High Altitude Platform

Nomenclature

A : cross-sectional area occupied by tissue structure
A_0 : cross-sectional area for buoyancy
b : breadth
C : axial load to a single inflated cylinder
D : representative diameter of tower
d : diameter of cylindrical tower
E : Young's modulus of membrane
$\bar{E}$: equivalent Young's modulus of tissue structure
h : height
I : geometrical moment of inertia
l : length of beam
M : bending moment
q : distributed load
r : radius of tissue element
t : thickness of membrane
w : wind speed
Z : modulus of section
Δp : maximum differential pressure
$\Delta p'$: differential pressure
ϵ : strain
η : compactness ratio
ρ : density of membrane material
σ_M : allowable stress of membrane
$\bar{\sigma}_M$: equivalent allowable stress of tissue structure
$\sigma_\parallel$: axial stress of membrane

Subscripts
1 : ambient or outer
a : air
p : gas to pressurize

1. Introduction

The authors have examined feasibility of the proposed tower by Thoth Co. But, original proposed structure is not clearly defined. We first study fundamental characteristics of a tissue structure composed of fibers, each of which is an inflatable cylinder. The condition for weightlessness is also presented. Feasibility of the high tower to the stratosphere is verified again on the basis of the fiber aggregation structure. To avoid altitude effects, a long bridge between Honshu and Hokkaido is treated as a horizontal structure in more detail. For more preliminary applications, usefulness of a medium height tower is exemplified. To those applications, several useful technologies are experimentally demonstrated.

2. Fundamentals

2.1. Single inflated cylinder

The element of tissue is an inflated cylinder. Since its membrane is so thin that the shape holds as long as a tensile stress is applied on the membrane. For the allowable hoop stress,

$$\sigma_M t = \Delta p r. \quad (1)$$

As a note, Δp is the allowable maximum differential pressure of the inflated cylinder. For axial stress, following condition must be satisfied.

$$2\pi r t \sigma_\parallel = \pi r^2 \Delta p - C \geq 0. \quad (2)$$

Note that $\sigma_\parallel < \sigma_M$. A single inflated cylinder can stand a simple bending moment ($C = 0$)

$$M = Z\sigma_M \cong \frac{1}{8}\pi d^2 t\, \sigma_M. \quad (3)$$

2.2. Beam with tissue structure

Assumed cross section is exemplified as in Fig. 1. Element of tissue structure are inflated cylinders stuck each other to effect stiffness of the aggregate. The length of each element is short enough compared with the total dimension of the structure. So, each element takes tension or compression to the external force. A thick walled cylinder is shown in Fig. 1. The wall consists of stuck numerous inflated cylinders. The wrenched off surface is shown in Fig. 2. To the stratospheric tower, each tissue element is an inflated cylinder of which length is short enough compared with the height of the tower. Those tissue elements are stuck together solidly each other.[1)]

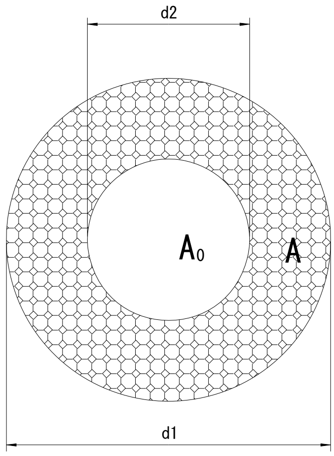

Fig. 1. A cross section of a beam with a tissue structure.

Fig. 2. Broken view of a tissue structure.

Refs. 2) and 3) treated a model for an inflated single cylinder. Their primary concern is the deflection after a wrinkling or a slack takes place. Its characteristic is common qualitatively also for a beam of aggregate consists of numerous cylinders. Since the purpose of this paper is to confirm whether its strength and rigidity can withstand a bending moment applied to the beam, pressurization is chosen so as not to occur a wrinkling. Accordingly, we can define an equivalent allowable maximum stress $\bar{\sigma}_M$ for the aggregate as follows.

$$\bar{\sigma}_M = \eta\sigma_M\, t/r = \eta\Delta p. \tag{4}$$

where η is the area ratio of the pressurized area to A indicated in Fig. 1. To fill-up the structure, $\eta \cong 0.91$. Similarly, equivalent Young's modulus $\bar{E}$ is given by use of Eq. (1) :

$$\bar{E} = \frac{\eta\Delta p}{\epsilon} = \eta\Delta p\frac{E}{\sigma_{\parallel}} = \eta\frac{2t}{r}E. \tag{5}$$

For the indicated thick-walled cylinder,

$$I = \frac{\pi}{64}(d_1^4 - d_2^4), \tag{6}$$

$$Z = \frac{\pi}{32}d_1^3\left(1 - \left(\frac{d_2}{d_1}\right)^4\right). \tag{7}$$

2.3. Weightlessness condition

In order to make the structure weightless, it is preferable to use a lighter gas than the air. To this purpose in general, we have to provide a cavity inside the structure. Each area is indicated in Fig. 1, as A and A_0. The condition to weightlessness is

$$(\rho_{a1} - \rho_{p1})A_0 =$$

$$\{2\rho\,\Delta p/\sigma_M - [\rho_{a1} - \rho_{p1}(1 + \Delta p'/p_{a1})]\}\eta A, \tag{8}$$

where ρ is the density of membrane. The area ratio is expressed as

$$\frac{A_0}{\eta A} = -1 + \frac{2\rho\Delta p/\sigma_M + \rho_{p1}\Delta p'/p_a}{\rho_{a1} - \rho_{p1}}. \tag{9}$$

Three sample numerical values are shown below for the following sections. On using helium for light gas, first let's assume at the sea level condition,

$$\Delta p = \Delta p' = 1\text{ MPa}, \quad \sigma_M = 1.5\text{ GPa},$$
$$\rho_{a1} = \rho_a = 1.225\text{ kg/m}^3, \rho_{p1} = 0.179\text{ kg/m}^3,$$
$$p_{a1} = p_a = 0.1013\text{ MPa}, \quad \rho = 1.5 \times 10^3\text{ kg/m}^3.$$

Then, we have

$$A_0/(\eta A) = 2.62\,. \tag{10}$$

But, on assuming $\Delta p = \Delta p' = 0.7$ MPa,

$$A_0/(\eta A) = 1.64\,. \tag{11}$$

As an example of the high altitude condition, at an altitude of 10 km,

$$\Delta p = \Delta p' = 0.1\text{ MPa}, \quad \sigma_M = 1.5\text{ GPa},$$
$$\rho_{a1} = 0.4135\text{ kg/m}^3, \quad \rho_{p1} = 0.06\text{ kg/m}^3,$$
$$p_{a1} = 0.0265\text{ MPa}, \quad \rho = 1.5 \times 10^3\text{ kg/m}^3,$$

we have

$$A_0/(\eta A) = 0.206\,. \tag{12}$$

We can design a cylinder with $d_2/d_1 = 0.5$.

3. Tower to the Stratosphere

Assuming a typical wind profile (shown in Fig. 3) in midwinter at Sapporo, the root bending moment is figured out in Fig. 4. The assumed tower is a simple thick walled cylinder, and the moment is given by

$$M = \int_0^H \frac{1}{2}C_d\rho_{a1}w^2 Dhdh$$

$$\cong \int_0^H \frac{1}{2}C_d\rho_a e^{-h/10{,}000}w^2 Dhdh, \tag{13}$$

$$D = d_1 = 100\text{ m}, \quad \rho_a = 1.225\text{ kg/m}^3.$$

The drag coefficient for a cylinder is $C_d = 1$.

For a thick wall cylinder $d_1 = 500$ m, $d_2/d_1 = 0.8$,

$$Z = 7.3 \times 10^6 \text{ m}^3. \quad (14)$$

If $\Delta p = 0.7$ MPa, then allowable moment is

$$M \approx 5.1 \times 10^{12} \text{ Nm}. \quad (15)$$

On the other hand, proportionally to the value of Fig. 4, the moment at root of a tower 500 m in diameter amounts to 2.5×10^{10} Nm approximately. We can estimate that the tower can be designed with an enough safety factor. The altitude effect influences the detailed design so complex that we only show feasibility of a design at a high altitude. Similarly, Fig. 5 indicates moment at 10 km high to the same wind profile. Again from Fig. 5, the moment at 10 km of a tower 500 m in diameter amounts to 3.5×10^9 Nm. Since the buoyancy condition is dominant, taking area ratio of Eq. (12), we have for $d_2/d_1 = 0.5$,

$$Z = 10.7 \times 10^6 \text{ m}^3. \quad (16)$$

On using $\Delta p = 0.1$ MPa allowable moment is given as:

$$M \approx 1.07 \times 10^{12} \text{ Nm}. \quad (17)$$

Those selected parameters are appropriate as far as the strength concerns. But, many alternative choices of Δp enable us to design with a variety of parameters. To the buckling, at least the Euler buckling never occurs because the axial load is absent owing to its weightlessness. Other mode of buckling should be examined carefully in a detail design phase.

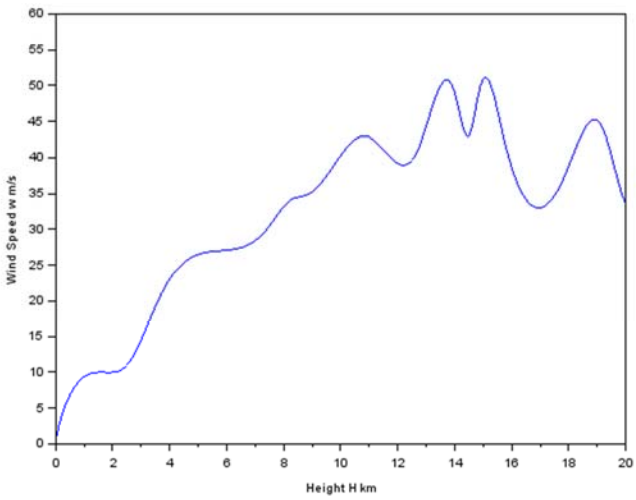

Fig. 3. Wind profile.

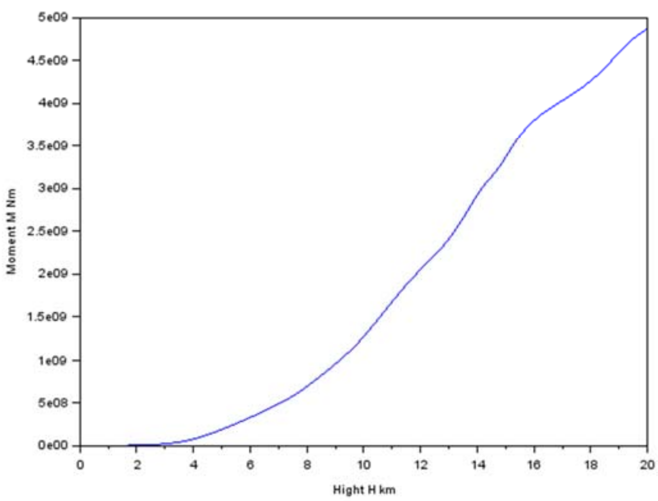

Fig. 4. Moment at the root.

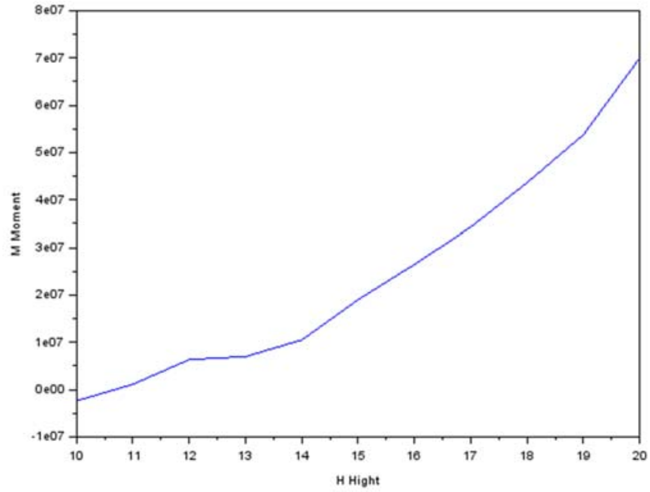

Fig. 5. Moment at 10 km high.

4. Honshu-Hokkaido Bridge

If stratospheric tower should be constructed horizontally, it crosses over Tsugaru straight without bridge piers between both ends. Also altitude effects will be negligible. In this case, the predominant external load is the wind blowing horizontally. Since a circular cross section is unnecessary, a hollow rectangular cross section is adopted to the bridge as shown in Fig. 6.

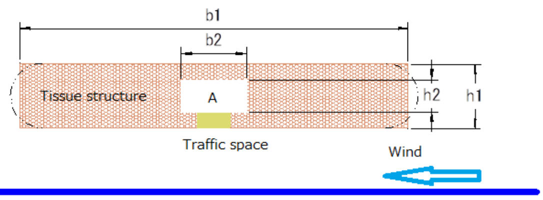

Fig. 6. Cross section of Honshu-Hokkaido Bridge.

For the simplicity of analysis, we examine feasibility of design without cavity A in an extreme case. In order to be weightless, Δp must satisfy the relation from Eq. (9):

$$\Delta p = \Delta p' \leq \frac{\rho_{a1} - \rho_{p1}}{2\rho/\sigma_M + \rho_{p1}/p_a}. \quad (18)$$

On using parameters at the sea level condition given to Eq. (10),

$$\Delta p = \Delta p' \leq 0.28 \text{ MPa}. \quad (19)$$

On neglecting a small cavity, following dimensions are assumed for numerical examinations below.

outer height: $h_1 = 100$ m
outer breadth: $b_1 = 600$ m
and
cavity height: $h_2 = 0$ m
cavity breadth: $b_2 = 0$ m

To reduce drag force due to the wind, both ends would be streamlines practically as shown in virtual lines.

To the horizontal direction, modulus of section is

$$Z = \frac{1}{6} h_1 b_1^2 = 6 \times 10^6 \text{ m}^3. \quad (20)$$

If both ends are fixed, the maximum moment takes place at ends, that is

$$M_{max} = \frac{ql^2}{12} = 3260 C_d \text{ GNm.} \tag{21}$$

for a uniform wind of $40\,\mathrm{m/s}$ blowing horizontally. Numerically, $q = 980\ \mathrm{N/m^2}$, and $l = 20\,\mathrm{km}$. For a flat box, the drag coefficient is assumed to be $C_d \cong 0.6$.

Again, to hold weightless condition, for $\Delta p = 0.28\,\mathrm{MPa}$, $\eta = 0.91$, we can conclude

$$M = Z\eta\Delta p = 4370 \text{ GNm} > M_{max}. \tag{22}$$

Also for the vertical direction,

$$Z = \frac{1}{6} b_1 h_1^2 = 1 \times 10^6 \text{ m}^3. \tag{23}$$

So, the bridge is able to bear a vertical load about $1/6$ of the maximum horizontal load. At present study, no vertical loads are specified yet. Extensive studies will be necessary to treat those other requirements in the detail design phase.

5. Usefulness of the Medium Height Tower

5.1. Zero gravity experiment facilities

For the coming era of the human space activity, one must learn of zero gravity environment more and more, in particular of microgravity technology. So called 'Drop Tower' is the most simple and easy ground facility. Although major those facilities were closed owing to their expensive operational cost in Japan, there are many potential demands among space communities, if inexpensive facilities are available. Weightless construction will be able to provide inexpensive high tower for those facilities. The first author has developed a series of zero gravity devices,[4] in which both up and down legs are utilized for the microgravity repeatedly, since its capsule is always suspended by a string, easy operation, low cost and safety are the feature of those devices. Inexpensive medium height towers will bring some human rated microgravity facilities to encourage future manned space activities.

5.2. Rope ways

Rope way for the transportation mean has a long history. Most of them are observed in resort areas, but few are seen in urban areas for civil transportations. Population is now concentrating to big cities. Our urban environments tomorrow need vast improvements in mobility sector. It is said that the urban ropeway represents a clean, ecological and modern solution. If the aerial height of the rope way is higher, it will bring extensive benefits to intercity transportations. In particular, modern development of high strength materials will accelerate its progress.

5.3. Launch site of aerial vehicles

If aerial vehicles are launched at a high altitude, environmental problems will be reduced remarkably. Spreading a large net over several high towers enable us to provide them a runway or a cushion to landing as if it were a trampoline net. Weightless vehicles could be moored there. Rockets exhaust intensive noise to surroundings. Rockets themselves often take severe damage. Keeping distance two dimensionally is hard even in an unpopulated area in Japan. High altitude launch and recovery of launch vehicles will bring immeasurable benefits to the future space launch business.

5.4. Weightless vehicles

Extended applications of weightless structure enable us to design vehicles unknown yet. Present light weight structures have area densities lying around 1kg per square meter. Membranes treated in this paper are lighter by one order of magnitude.

An example is the hybrid kite that is a weightless kite. It couldn't lift in a quiet air, but even a breeze floats it on air. Its characteristics are advantageous to UAV, for it is quiet in operation and safe in an accident. Figure 7 shows two designs, one is dumpy the other is flat. Both models have enough lift/drag ratios to stay at visible positions above their tethered points. And once it is equipped with a propulsive force, it will easily lift off from high altitude platforms.

(a) (b)

Fig. 7. Hybrid kites, a dumpy model (a) and a flat model (b).

6. Conclusion

An inflatable tissue structure is proposed. A simple analytical theory is developed. And a weightless condition is given. Use of a light gas for the pressurization is effective to reduce the weight of pressurized gas. Feasibility of a high tower to the stratosphere is confirmed based on those theories. Similarly, a feasibility study shows a conceivable configuration of Honshu-Hokkaido Bridge. On the assumption of the economically eligible weightless construction, there are many promising applications of medium height towers. Some preliminary experiments are conducted to demonstrate those future applications.

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