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ELASTIC BEHAVIOR OF A SLENDER AIR TUBE COMBINED WITH WIRES INSPIRED BY ELONGATION OF PLANT STEM

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Summary. *Air tube is excellent in lightness as an element to transfer axial force, though is soft compared to other elements. To enhance stiffness, it is thought of effective to introduce tension to wires by air pressure. The method is like cell membrane and cell wall in elongation of plant cell. This paper report about experimental studies of behaviour of air column, which is a slender air tube combined with wires. In the structure air tube and wires are fixed at the ends, and tension is introduced by increasing internal air pressure. From the experimental result, it is revealed adding wire to air tube got air column stiffer than ordinary air tube. In addition, the structure was able to deploy stably and get 14mm longer by relaxing wires using turnbuckle. Air column has the potential to be applied to working platform which can stably move up and down by supplying air from the ground as plant stem grow up and stand much higher by absorbing water.*

1 INTRODUCTION

1.1 Air column

Air tube is noticeably light but its rigidity is comparatively low because its rigidity highly depends upon elasticity of air and material of the tube. However, it is possible to replace its rigidity to that of other material, mostly wires in this case, by using prestressing procedure. We call such a structure as "air column" in this paper and show an example in Fig.1.1. When this air column is pressed in axial direction, tube and prestressed wires will lose tension. In this process the apparent stiffness of the columns does not only owe to air but also to the stiffness of tube and wires.

The feature of such prestressed structure can be commonly observed in the plant cell. A room of cell membrane tends to expand by absorbing water. This generates so-called turgor pressure. Cell wall resists the expansion and becomes taut by this turgor pressure. Turgor pressure and tension in cell wall is in self-equilibrium state. Cell wall consists of mainly callouses and it is normally hard, but it relaxes in growth by plant hormonal effect[1] with keeping tension in cell wall. That is considered to the reason for plant stem to get longer stably while its tissue is still soft. Air column has been developed being inspired by such growing system of plant stem.

In tensairity,[2] recently developed by Luchsinger et al, air tube is reinforced by longitudinal stiffer members at the upper side and cable at lower side. The reinforcement restricts transverse deformation when air tube is loaded as a beam. However main application of tensairity is to be used as beams. Vine robot[3], researched by Blumenschein et al, is also inspired by plant stem. It consists mainly air tube and thread and can deploy form stowage state by eversion system. It can change its inflated length but cannot control its rigidity.

Air column has some advantages that it is relatively hard for its lightness and can be deployed. In this paper some results of experimental research about rigidity and deployment of air columns are reported.

1.2 Prediction of elasticity

When the prototype is loaded vertically by δ under loading N, predicted elasticity of air column can be expressed as:

$$K = \frac{N}{\delta} = \frac{P_{initial}A}{l} + nk_w + k_m - \frac{\Delta n \cdot RT}{l}\left(\frac{1}{\delta} + \frac{1}{l}\right) \tag{1.1}$$

where $P_{initaial}$ is differential pressure in self equilibrium state, A and l are cross section area and length of air tube, k_w and k_m are elasticity of wire and cable, n is number of wires, Δn is the molecular weight of leaked air and RT is the production gas constant R and temperature T, which can be regarded as constant. (Fig.1.2) In the above expression 1^{st} term on the right hand side represents air spring, 2^{nd} and 3^{rd} term represent elasticity of wire and membrane and 4^{th} term for the effect of leaked air. In the experiment membrane elasticity can be estimated to zero because many wrinkles were observed on membrane surface. Also, air spring effect and leaked air can be neglected by continuous air supply. So, in the range of small displacement, apparent elasticity of air column will be determined only by 2^{nd} term. If elasticity of wire is constant in the range of small deformation, deformation is expected to be proportional to loading weight.

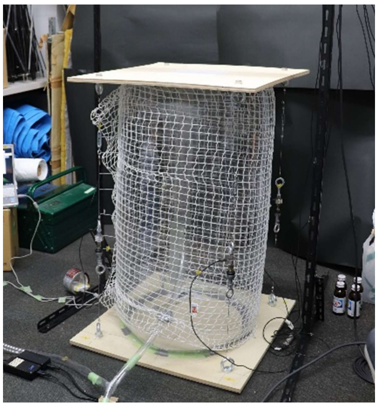

Fig.1.1: An example of air column, which is used by loading test

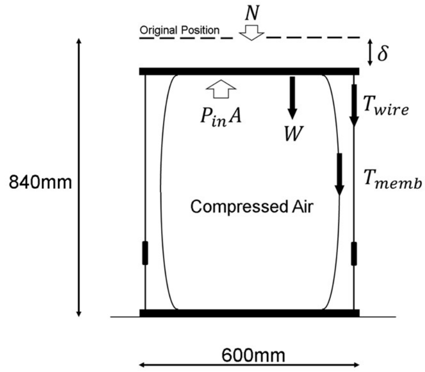

Fig.1.2: Schematic diagram of self-equilibrium state in ceiling board of air column

2 METHEDOLOGY

To measure the rigidity of the air column, loading test was conducted in December 2020 at small experiment room in our institute. Also, its deployment was checked to see if it is feasible or not. Fig.2.1 shows the set-up for the test. Atmospheric air was always supplied from air compressor and inner pressure was kept constant during the test. To prevent explosion a container in which water is filled was used as an airvent.

Fig.2.2 shows a horizontal section of the specimen. It consisted of air tube, 4 wires with turnbuckles and loadcells for measurement and 2 squared wood board at both ends of air tube. The configuration of the air tube model is a cylinder, of which radius and heights are 440 mm, 820 mm respectively and its weights was 1.2kg. Extension of inflated air tube was restricted by the boards at both ends. They were connected by way four sets of wires. Air tube was surrounded by mesh, which was expected to reinforce the membrane in hoop direction of the air tube. The specification of membrane and wire in specimen is shown Table.2.1. The total elasticity of wire with turnbuckles and loadcell was measured before the experiment and it was 12.5N/mm.

The table 2.2 shows the procedure of these experiments. In loading test, at first air column is inflated and tension in wire is adjusted so that the tension of all wires is introduced equally. Then, 2kg weight was put on the upper board of air column, one by one, at every 20 seconds. Loading is stopped when the strength of tension at any wires is lower than 10N to prevent sudden collapse of the tube during the test. After stopping loading the weight were reduced by 2kg at every 20 seconds, stepping back the loading process. In demonstration of deployment, 8kg weight was put on the upper board after adjusting tension. Then, wires are relaxed by turnbuckles little by little in turns so that air column gets longer stably.

The vertical displacement was measured with laser displacement sensor and recorded at every 0.5 seconds. Inner pressure of air tube and atmospheric pressure were measured and recorded by two barometers at every seconds. The force in tension in 4 wires were measured and recorded by load cells at every 0.1 seconds. The tensions were always able to check by datalogger.

Rigidity of the air column can be evaluated by the observing the slope of the load-displacement line, which was obtained by applying least squared method.

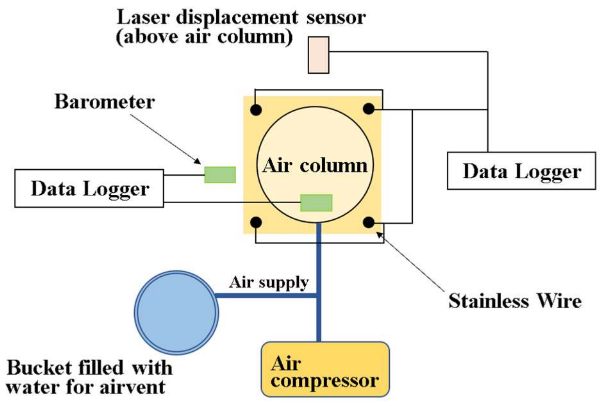

Fig.2.1: Schematic diagram of set-up of the experiment

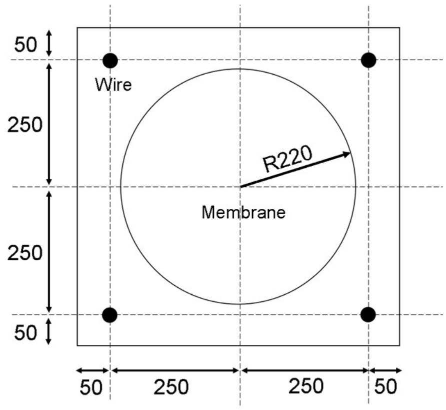

Fig.2.2: Cross section of specimen (Unit: mm)

Table 2.1: Specification of menbrane and wire in the specimen used by loading test

Membrane	Diameter	440mm
	Height	820mm
	Thickness	0.3mm
	Material	PVC (polyvinyl chloride)
	Others	Covered with net, which mesh is 25mm
Wire	Diameter	1mm
	Length	820mm (including turnbuckle and loadcell)
	Material	Stain less

Table 2.2: Procedure of the experiments, loading test and deployment

Loading Test	
1	Inflate air column and introduce pretension in wires
2	Wait until inner pressure is stable, and adjust pretension in wires
3	Put 2kg weight on air column one by one at every 20 seconds
4	Stop loading when tension in any wire is lower than 10N
5	Remove 2kg weight one by one, stepping back loading process

Deployment	
1	Inflate air column and introduce pretension in wire
2	Wait until inner pressure is stable, and adjust pretension in wires
3	Put 8kg weight on air column
4	Make 4 wires longer by turnbuckles in turns

3 RESULTS

3.1 Measurement of elasticity

Table 3.1 shows the result of the experiment and Fig.3.1 shows the time history of vertical displacement and tension in all wires of the specimen. Fig.3.2 shows difference between inner and outer pressure of air tube. In these graphs vertical displacement gradually decreases in accordance with change of tension in the wire. This means relaxing of wire and decrease of pretension corresponds to the vertical displacement of top board. Difference between inner and outer pressure was successfully kept constant.

Fig.3.3 show the relation between loading weight and vertical displacement obtained by the test. The experimental axial elasticity of the air column can be estimated as 51.2N/mm.

3.2 Deployment of air column

Table 3.2 shows the result of the experiment and Fig.3.4 shows the time history of the vertical displacement and tension in all wires in prototype during deployment. Fig.3.5 shows the time history of difference between inner and outer pressure of the air column. Air column was deployed and extend by 14mm compared to before extension. Rapid decrease was not observed in the level of tension during deployment.

Table 3.2: Experimantal result at loading test

Differential pressure	31 hPa
Estimated elasticity	51.2 N/mm
Loading capacity	235.2 N

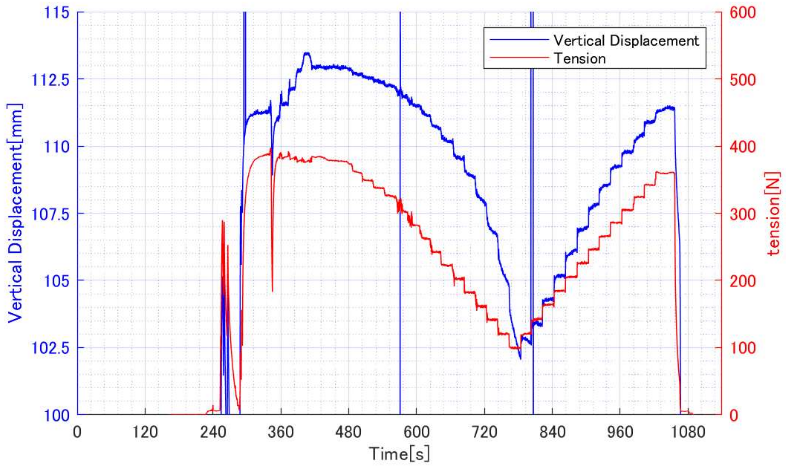

Fig.3.1: Time vs. vertical displacement and the sum of tension in all wires during the test

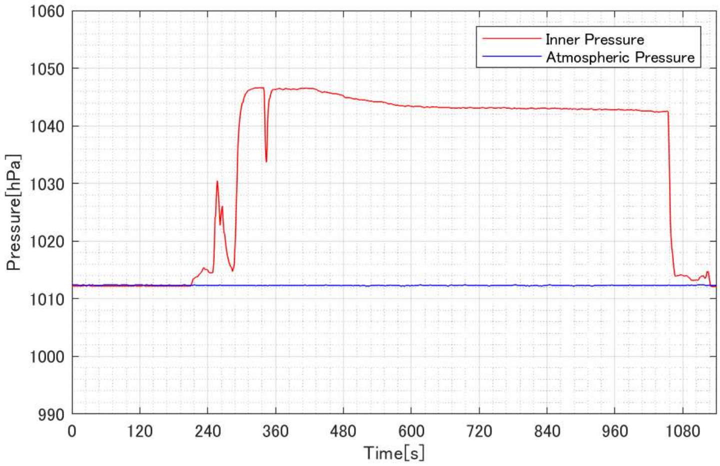

Fig.3.2: Time vs. inner pressure and atmospheric pressure of air tube during the test

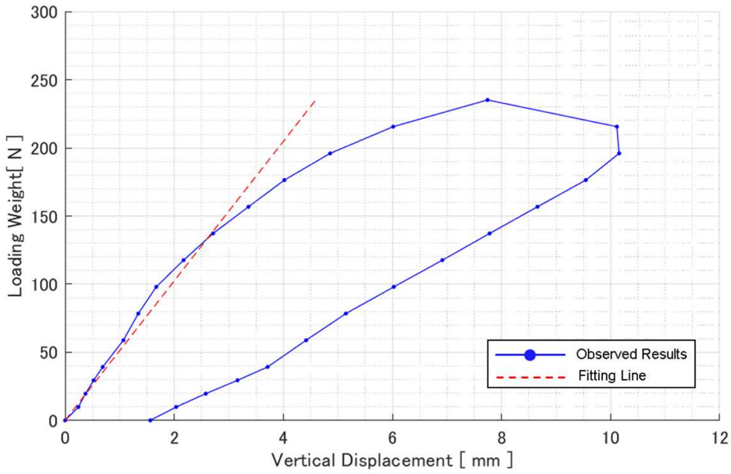

Fig.3.3: Relation between loading weight and displacement at upper board

Table 3.2: Experimantal results during deployment

Differential pressure	35 hPa
Loading Weight	8 kg
Extension Length	14mm

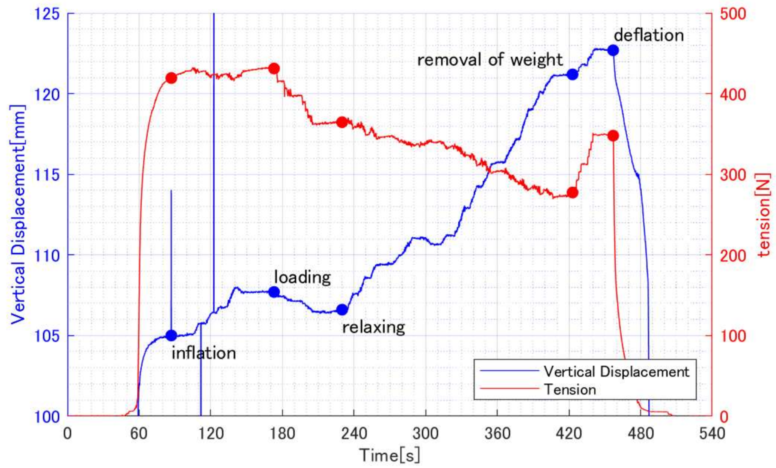

Fig.3.4: Time vs. vertical displacement and the sum of tension in all wires during deployment

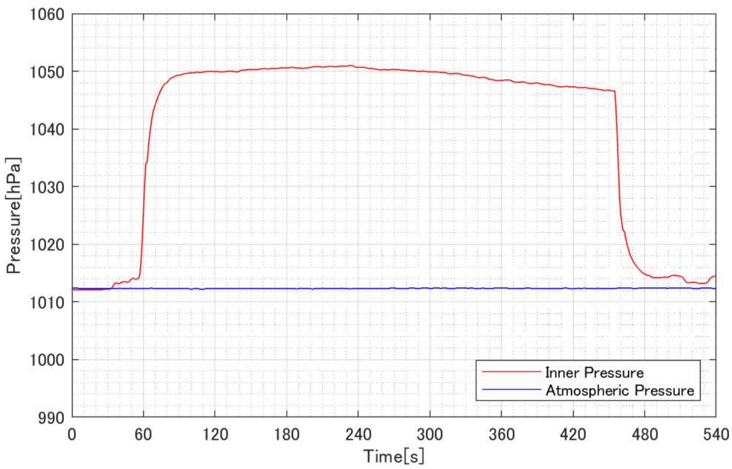

Fig.3.5: Time vs. inner pressure and atmospheric pressure during deployment

4 DISCUSSIONS

4.1 Comparison between experimental results and prediction

From the experimental result, axial rigidity of the air column was observed to be 51.2N/mm while prediction using eq.1.1 was 49.9N/mm. It seems that experimental result well corresponds to the prediction using eq.1.1. The experimental result should be lower than prediction since air leak, which is considered in the eq.1.1 originally, is also occurs in the experiment.

4.2 Deployment of air column

As shown in Fig.3.4 air column was extended by 14 mm while the tension in wire was kept constant. The extension length was determined based on the difference between the length of air tube and wire. If air tube were longer and there were more wrinkles in air tube, the air tube can be extended higher. In this experiment the length of wire was controlled by adjusting turnbuckles and extension length was within the stroke of the turnbuckles.

5 FUTURE WORKS

In this experiment atmospheric air was always supplied and air can move freely. If compressed air can be enclosed in tube, air spring will be added to overall elasticity and air column will become stiffer than this time.

Moreover, the parameter must be decided to specify the factor for high elasticity. For instance, the slenderness ratio, which is proportion between diameter and length, and the number of air chambers can be considered as parameters. More slender air column has a risk of buckling by pretension so other mechanical characteristic of air column must be studied.

6 CONCLUSIONS

- Reinforced air tube, which is called air column was introduced and tested. An equation to evaluate the axial rigidity of the column was proposed as well. Loading test was carried out for the prototype of air column made of thin PVC sheet to examine axial rigidity of the air column. As the result, the rigidity of the air column was estimated 51.2 N/mm using eq.1.1 The experimental result has well corresponded with this prediction.

- Apart from measurement of elasticity, the deployment procedure of air column was tried. The specimen was successfully deployed and extend by 14mm by controlling four wires.

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