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Laminated foam-based soft actuator for actuatable flexible structure

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***Abstract*—Recently, in the search for alternatives to conventional robots, various types of soft actuators and their applications have been studied. In particular, pneumatic soft actuators have the advantage of being lightweight and high power. One of the uses of these soft actuators is as a substitute for an electric motor to actuate the joint of a structure, such as a link mechanism. Another use involves their fusion with a flexible structure. The features of this concept are a simplified system, in which almost all interfaces can be configured as flexible structures. However, because these actuatable flexible structures are made with rubber, silicone, or flexible resin, it is difficult for them to support their own weight owing to the effect of the square-cube law in the case of increasing size. Hence, these structures are limited to a size of approximately 1×10^{-2}–1×10^{-1} m. If an actuatable flexible structure with a size of 1×10^{0} m can be realized, the concept of soft actuator–flexible structure fusion is expected to provide novel solutions and applications. Herein, as a feasibility study, large actuatable flexible structures were developed. The proposed structure, LayerCAKE, is a laminated open-cell and closed-cell foam structure; cell foam is a lightweight and flexible material that can be used to realize large actuatable flexible structures. LayerCAKE is actuated by using the concept that open- and closed-cell foams contract differently when they are vacuumed. The bending-motion model and was experimentally verified, and different types of LayerCAKE models that could exhibit various types of motion were developed and tested. Furthermore, a complex-shaped LayerCAKE model (in the shape of a human hand) was developed. A large actuatable flexible structure of approximately 900 mm was realized. Furthermore, it was confirmed that the bending motion could be controlled by pressure.**

I. INTRODUCTION

To improve interaction between humans, objects (robots), and the environment, flexible and lightweight soft actuators have been researched and developed [1]-[12]. These differ from the industrial robot arm that has a structural design comprising electric motors, a metal body, and a construction machine with a hydraulic actuator. Hence, soft actuators are expected to provide novel solutions and applications. In particular, soft actuators driven by air are easy to handle and mount. One of the uses of these soft actuators is use as a substitute for an electric motor, pneumatic cylinder, etc. to actuate the joint of the structure, such as a link mechanism. In this case, pneumatic artificial muscles are typically used provide liner contractions [1][2], for example, a McKibben actuator. These actuators are used for the purpose of reducing the actuator mass, realizing actuation in an environment where electricity cannot be used, realizing variable rigidity joints, etc. Another use is fusion with a flexible structure and actuator [3]–[5]. The features of this concept are a simplified system and the ability of almost all interfaces to be configured as flexible structures. For example, a soft actuator hand [5] was developed. Instead of carrying out complicated control and handling, it is possible to reduce the control load by utilizing the structural effect that the entire flexible hand adapts to the grasped object. Because it is made of rubber or silicone, there is an advantage in that it can be constructed at a relatively low cost, and it is easy to clean and the interfaces are exchangeable.

However, these actuatable flexible structures are made with rubber, silicone, or flexible resin, and it has difficulty supporting its own weight by the effect of the square-cube law, in the case increasing the size.

The area increase rate is squared of size (representative length) increase rate and the volume (self weight) increases rate is cubed of size (representative length) increase rate. The pneumatic actuator is basically a force generation principle that is proportional to the area. On the other hand, the self weight increases in proportion to the volume. The amount of air required for operation of actuators also increases in proportion to the volume. Therefore, with the same shape and operation principle, various characteristic changes become an issue as the size changes. In order to maintain the same shape and increase the size, it is necessary to change the elastic modulus of the material. In the case of maintaining the same material of actuators and increasing the size, it is necessary to make changes such as a thicker shape to increase the second moment of area of the actuator.

If merely the size is increased, the feature of flexibility is lost. Hence, existed actuatable flexible structures that must support their own weight are limited in size to approximately 1×10^{-2}–1×10^{-1} m, as shown in Table 1. Inflatable robots [6]–[10] have been studied as a method of constructing a large and lightweight structure by using a thin-film bag without using stretchable materials, such as rubber and silicone. A method for realizing light-weight and large- sized structures has been by investigated by incorporating helium into the structure of a robot [6][7]. A robot arm [8] consisting only of plastic bags that support the structure by pneumatic pressure was developed. Growing robot [10] soft pneumatic robot made with long plastic bags that is capable growing substantially in length from the tip. However, these inflatable robots use a bag structure filled with air as a skeleton, and, because a specific joint structure is separately provided, it is difficult to generate adaptive deformation.

In this research, an attempt is made to realize large actuatable flexible structures. The purpose of this is to make it possible to apply features of the actuatable flexible structures

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so that the entire structure deforms and adapts to the object or environment in large-size applications (such as 1×10^0 m).

Therefore, the focus was on cushioning materials containing air, such as sponge and cotton, which are structures that are easy to mold into a lightweight and complicated structure and that can keep their weight without air pressure being applied. This can be observed in stuffed animals and cushions that are able to maintain flexibility and light weight even when they are relatively large in size.

An actuator using a sponge [11] [12] has been studied. Robertson at al. [11] developed V-SPA, which bends three resin-coated sponges. It can bend by decompressing the sponge chamber inside a resin coating. It is applied to one that makes a motion similar to that of the human spine and one that realizes locomotion movement [12]. Although they can produce flexible and complex stretching and bending motions, they are not designed to be lightweight and large. Therefore, an attempt was made in this study to realize a large actuatable flexible structure by laminating sponges with different characteristics in a bag, as shown in Figure 1. Depending on the number of bubbles inside the sponge, the characteristics change, as shown in Figure 2. Open-cell foam that connects the bubbles is reduced by decompression. Closed-cell foam that does not connect the bubbles is not reduced by decompression. The actuatable flexible structure is made by laminating these sponges and placing them in a bag. In this way, bending and various deformations are achieved because of the difference in volume change by depressurizing inside the bag. Here, the bending motion model and its verification are discussed. The LayerCAKE, which exhibits various types of motion, was developed and tested. Furthermore, a complex-shaped LayerCAKE resembling a human hand was developed.

Table 1. Length of actuator length of soft body

No.	Name	Actuator length
1	Flexible microactuator [3]	160 mm
2	Starfish robot [4]	60 mm
3	Soft grip [5]	90 mm

Figure 1. LayerCAKE: Laminated foam soft actuator.

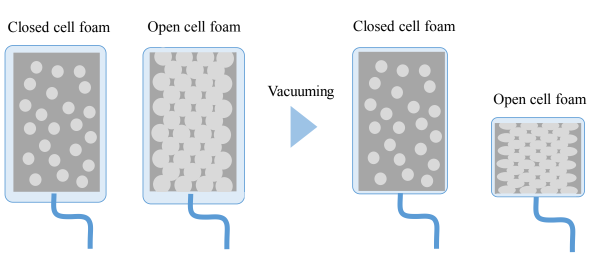


Figure 2. Structure of foam.

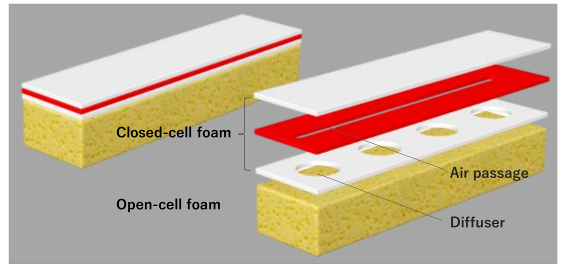
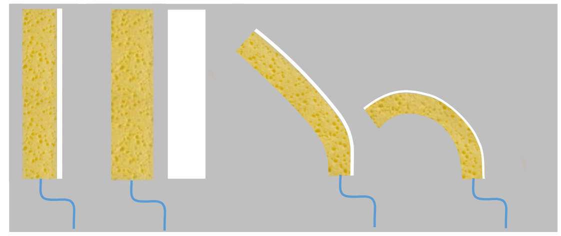
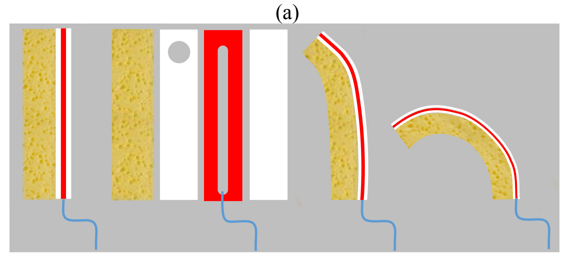


Figure 3. Basic structures of LayerCAKE providing bending motion.



(a)



(b)

Figure 4. Bending motion of LayerCAKE in case of air passage (a) near the actuator base and (b) near the actuator bottom.

II. Laminated-Foam Soft Actuator

A. Cell foam

Foam is categorized into two types, depending on the distribution of bubbles: closed- and open-cell foam. The foam features are set according to the degrees of distribution of the bubbles. Usually, bubbles inside a closed-cell foam are separated from each other; therefore, the foam has low water-absorption ability and breathability. In an open-cell foam, the bubbles are connected, and, therefore, the foam has high water-absorption ability and breathability. The case of putting the closed-cell foam and open-cell foam in the bag and decompressing is shown in Figure 2. Because the open-cell foam can also reduce the pressure of the air bubbles inside the foam, the volume of the foam decreases. However, the closed cell foam has no volume change. In this study, urethane foam was used as the open-cell foam. In the foam, fine bubbles of approximately 0.5-mm diameter constituted the whole volume, and large bubbles of approximately 1 to 4 mm were dotted in the bubbles. A chloroprene rubber foam was used as the closed-cell foam. It was composed of fine bubbles of 0.1 mm or less. In addition, a bag made of polyethylene and with a thickness of 0.006 mm was used for sealing. The polyethylene outer shell sealed by heat sealing machine.

B. Overview

The LayerCAKE has a laminated structure featuring these different foams. Its construction is illustrated in Figures 3 and 4. It is actuated by decompression. Actuators that drive by decompression have been studied [11]-[14]. Buckling Pneumatic Linear Actuators [13] are an artificial muscle capable of integrally molding a structure with silicone rubber, and they generate tensioning force. Lia at al. [14] developed an actuator that efficiently converts the decompression force into an actuation force by applying an origami structure. They are flexible at atmospheric pressure, but they cannot maintain a structure by supporting their own weight. These actuators can produce light weight and high output. The reason for this is that it is possible to reduce the internal force of the actuator material and to reduce the weight by utilizing it to contact the actuator in generating the actuation force. Therefore, the driving principle using this decompression was also used in LayerCAKE. The actuator, as shown in Figure 4, is a foam laminated in the axial direction. The yellow sponge (named BASE) in Figures 3 and 4 is an open-cell foam, and the others are closed cell foam. The closed cell foams are named TOP, MIDDLE, and BOTTOM. LayerCAKE consists of TOP and BASE, as shown in Figure 4(a) or TOP, MIDDLE, BOTTOM, and BASE, as shown in Figure 4(b). These are included in a thin bag structure, and a tube is attached for decompression. Using this difference in volume change, the motion of LayerCAKE is generated. Each closed-cell foam has a task. MIDDLE passes suction air. BOTTOM spreads the suction air. In the case of the LayerCAKE in Figure 4 (a), the air passage is arranged to the base; thus, the actuator first bends from the base. In contrast, in the case of Figure 4 (b), the air passage is arranged at the top of the actuator by the passage of MIDDLE, causing the actuator to bend from the top. This is because a time lag occurs in the propagation of pressure in the open-cell foam (BASE). Various shapes and deformations are realized by changing the laminated pattern and the shapes of various sponges.

III. MODELING OF LAYERCAKE

This section describes the model of LayerCAKE; the bending static angle of the actuator with vacuuming was determined during the modeling process. In case of the open cell foam is vacuumed, the volume should decrease equally in all directions. On the other hand, considering the long shape of LayerCAKE, axial change is dominant in motion. Hence, we focus on axial deformation only as the first step of modeling.

The actuator comprises both static and dynamic characteristics. The static bending angle of the actuator is determined by the equivalence between the contraction force due to decompression and the repulsion force caused by the elastic deformation of the foam. The static bending motion of the actuator was determined by the equivalence between the contraction force caused by decompression and the repulsion force resulting from the elastic deformation of the foam and absorbing resistance of the open-cell foam. The hardness K_1 [Pa] of the open-cell foam is obtained through a compression test, as shown in Fig. 5(a). The open-cell foam was crushed with a weight, and its displacement was measured. The sectional area of the test piece foam was 0.0092 m^2, and the height was 0.054 m. The weights were added by 0.25 kg. The result, converted per unit volume of the sponge foam, is shown in Fig. 5(b). The relationship between hardness K_1 [Pa] and spring coefficient of open-cell foam k_1 [N/m] is shown in Figure 6. From this result, the K_1 was calculated as 4.3×10^4 [Pa]. The structure of the LayerCAKE shown in Fig. 4(a) is modeled in Fig. 7, where l is the length of the structure, and w_1 and w_2 are the widths of the open- and closed-cell foams. The lengths when the foam was vacuumed are l_{s1} and l_{s2}. The depth of the actuator on paper is h, and the elastic coefficient of the open-cell foam is k_1 [N/m]. The pressure inside the bag is P. The elastic coefficient of open-cell foam k_1 of the actuator is calculated as Eq. (1)

$$k_1 = \frac{K_1 w_1 h}{l} \tag{1}$$

The balance of force of the open-cell foam part while vacuumed is shown in Fig. 7(a). F_s is the pressure receiving force in the cross section of the open-cell foam of the LayerCAKE caused by decompression. F_f is the elastic force of the open-cell foam. The balancing condition is given as

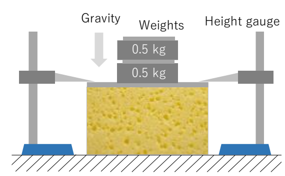
$$-F_s = F_f$$
$$-Pw_1h = k_1(l - l_{s1})$$
$$-Pw_1h = \frac{K_1 w_1 h}{l}(l - l_{s1}) \tag{2}$$

Therefore, from Eq. (2), the relationship between pressure and contraction can be given by Eq. (3).

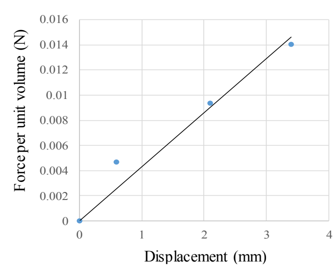
$$-P = \frac{K_1}{l}(l - l_{s1}) \tag{3}$$

Next, the bending posture of the LayerCAKE was considered. The volume change of the closed-cell foam while vacuumed is negligibly smaller than that of open-cell foam. The length of the TOP (closed-cell foam) does not extend from its natural length, because it adheres to a stretchy bag.

Therefore, assume $l_{s2} \fallingdotseq l$. Then, w_2 is smaller than w_1, and



(a) Experimental setup



(b) Experimental result of relationship between force and displacement of the open-cell foam

Figure 5. Properties of open-cell foam.

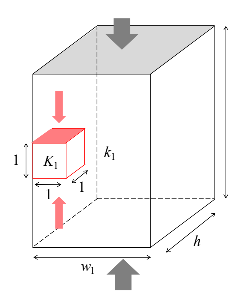
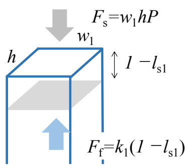


Figure 6. Relationship between hardness K_1 and spring coefficient k_1.

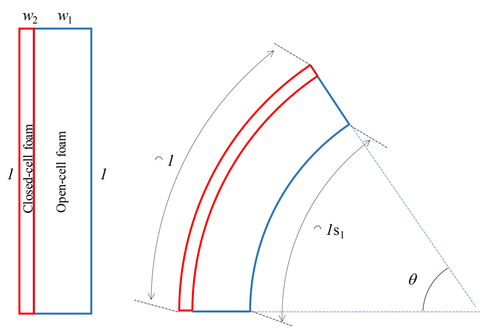
the bending rigidity of the thin TOP is much lower than the bending rigidity of the BASE. Therefore, it is assumed that the rigidity of the TOP does not influence the movement of the actuator. In addition, the static bending shape is assumed to have an approximate arc shape, as shown in Fig. 7(b). According to this relationship, the bending angle θ is given by Eq. (2) as

$$\theta = \frac{l - l_{s1}}{w_1}$$

$$\theta = -\frac{l}{K_1 w_1} P \qquad (4)$$



(a) Balance between the contraction force F_s due to sucking air and the elastic force F_f of the sponge



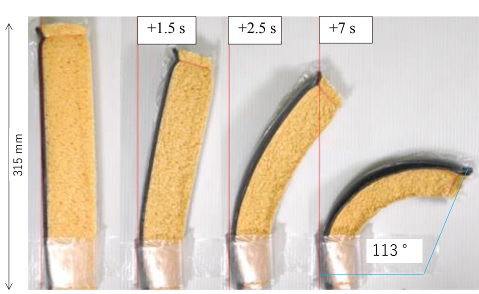
(b) Bending model

Figure 7. Model of the LayerCAKE.

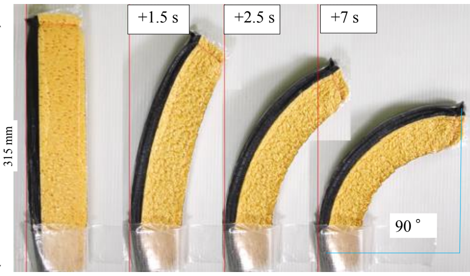
IV. VERIFICATION OF ACTUATION OF LAYERCAKE

A. Overview of the experiments

To confirm the motion of the LayerCAKE, the structures of the bending type in Figs. 8(a) and (b) were developed and tested. The length of the bending type was 315 mm, and the widths of the open-cell and closed-cell foams were 50 and 3 mm, respectively. This actuator was driven by the suction air. The suction air was provided by a vacuum generator (VBH12-66P, Pisco). The degree of vacuum arrival was -93 kPa, and the maximum suction amount was 13 l / min. This maximum suction condition was used in the experiments. The transient characteristics of bending deformation are qualitatively grasped. Specifically, the actuator shown in Fig. 8 (a) was divided into two as shown in Fig. 9 (a), and the deformation angle of each section was measured from the movie. The results are shown in Fig. 9 (b). The time constants of the root and tip regions are almost equal to 5.8 and 6.2 seconds, but the dead time is nearly doubled to 0.9 and 2.1 seconds. From this result, it is thought that the transient deformation operation can be designed by explicitly utilizing the dead time in the longitudinal air path length (the actuator length).

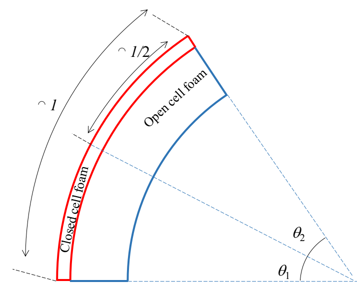


(a)

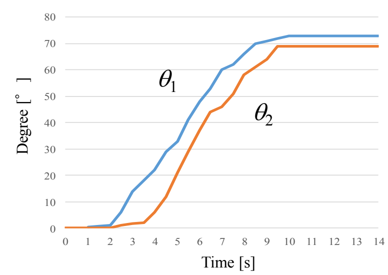


(b)

Figure 8. Dynamic bending motion after blowing air at (a) bottom and (b) top of the actuator.



(a) Bending model 2



(a) Result of the experiment

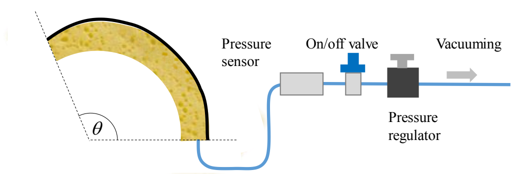
Fig.9 Relationship between time and bending degrees of the LayerCAKE

B. Experiments of bending motion

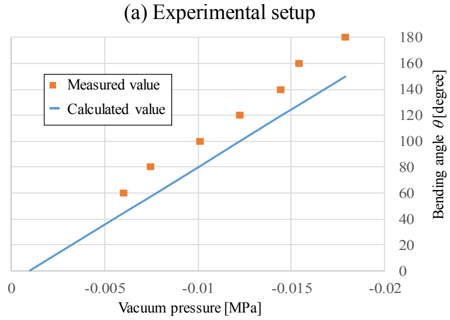
Two types of bending LayerCAKE were developed and tested: one with air blown at its base, as shown in Fig. 8(a), which is the same structure as in Fig. 4(a), and the other with air blown at its top, as shown in Fig. 8(b), which is the same structure as in Fig. 4(b). As shown in frame 2 of Fig. 8(a), the base part of the actuator starts bending first. In contrast, frame 2 of Fig. 8(b) shows that the whole actuator starts bending uniformly. The static bending angles of both actuators are almost the same. The dynamic bending angle of the actuator in Fig. 8(a) is larger than that in Fig. 8(b). The difference could result from the difference in width of the closed-cell foam (black-colored foam). In the case of Fig. 8(b), the wide closed-cell foam section that is triple laminated closed-cell foams (9 mm) prevents bending of the actuator.

C. Measurement of relationship between pressure and angle

The measurement of the angles of LayerCAKE in Fig. 4(a) are shown for each suction pressure for comparison with the model in Section II. In the experiment, a LayerCAKE was used whose length was 315 mm, h was 40 mm, and w_1 was 55 mm (cross-section area of 2200 mm^2). The measurement setup is shown in Fig. 10 (a), in which one side of the LayerCAKE is fixed and the suction pressure is kept constant by a suction generator and a pressure sensor. In the angle measurement method, each bending angle was measured for each pressure change. The method for measuring the angle was as follows. The actuator was bent to each angle from 60° to 180° by 20° by adjusting the suction pressure. Fig. 10 (b) shows the result of the angle-measurement test with the values obtained from Eq. (6). The measurement value of the bending angle of the actuator was approximately equal to the designed value with the whole measurement pressure, as shown in Fig. 10 (b). LayerCAKE was found to bend linearly with suction pressure. Hence, the bending angle of the LayerCAKE can be controlled by the suction pressure. The difference between the designed value and the measured value does not take into account the reaction force of the bending deformation of the cell foam.



(a) Experimental setup



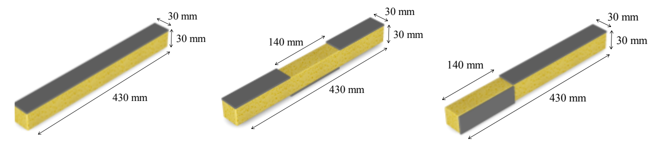
(b) Result of the experiment

Figure 10. Relationship between pressure and bending degrees.

V. Generation of 3D Deformation

A. Generation of 3D deformation

LayerCAKE which generates bending deformation by laminating open-cell and closed-cell foam, was designed. By arranging a laminate of closed-cell foams, as shown in Figure 11, 3D an attempt was made to develop deformation with one actuator as well as multidirectional bending. These shapes were made, and the motion of these was confirmed. The thickness of the closed-cell foam was 3 mm, the open-cell foam was a square with a cross section of 30 × 30 mm, and the length was 430 mm. For these driving methods in the test, a decompression method the same as in the other experiments was adopted. Figure 12 shows the test results. A chameleon tongue, as shown in Figure 12 (a), was made by making the result in Figure 8(a) longer in the axial direction, realizing not only bending but also winding. A snake, as shown in Figure 12 (b) successfully curved alternately by alternately placing closed-cell foams. By arranging closed-cell foams on the top and sides of the open-cell foam, a screw, as shown in Figure 12 (c), realized an action to bend the whole body by twisting. As described above, it was clarified that complicated movement can be realized by arranging closed-cell foams.



(a) Chameleon tongue (b) Snake (c) Screw

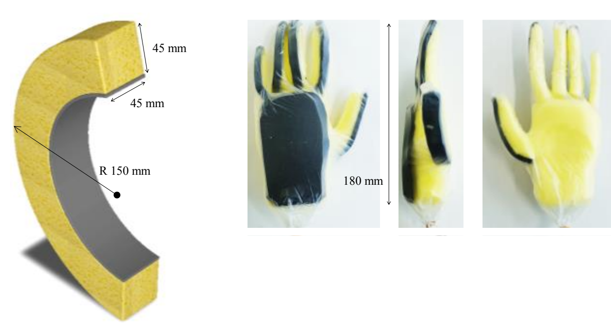
Figure 11. Arrangements of the closed-cell foam of LayerCAKE.

(a) Chameleon tongue (b) Snake (c) Screw

Figure 12. Motions of test types of LayerCAKE.

B. Complex shape LayerCAKE

LayerCAKE, where a sponge is used as the main component, can realize a flexible structure with a relatively complex shape. Two LayerCAKEs were designed, as shown in Fig. 13, to demonstrate feasibility. The thickness of the closed-cell foam was 3 mm. A C type, as shown in Figure 13 (a), has a curved shape, and it becomes a linear shape by decompression. A hand, as shown in Figure 13 (b), is the shape of a human hand and can be grasped by decompression. PVC gloves with a thickness of 0.08 mm were used as the outer bag shape. For each finger, a structure similar to that of Figure 8 (a) is arranged according to the finger size. In addition, the closed-cell foam was placed in the back of the hand. The open-cell foam was placed on the palm. The test results are shown in Figure 14. As in Figure 8 (a), pressure reduction begins from the root; thus, it can be seen that the deformation moves from the proximal part. The C shape was deformation to linear shape. In addition, the hand was also confirmed by the hand grip operation. As described above, an actuatable flexible structure of various shapes can be realized by devising the shape of the open-cell foam of LayerCAKE.



(a) C type (b) Hand

Figure 13. Complex-shape LayerCAKE.

(a) C type (b) Hand

Figure 14. Motions of complex-shape LayerCAKE.

C. Large size LayerCAKE

The foam laminate structure is unlikely to be affected by the square-cube law, and an increase in size can be expected. Therefore, we made a trial of LayerCAKE with a total length of 900 mm and confirmed its feasibility. The structure is the simplest lamination method of Fig. 8 (a). With increasing size, the thickness of the open cell foam was increased to the root. The results of the experiment are shown in Fig. 15. As a result of the experiment, the movement in the vertical direction was confirmed. In the future, we will consider the realization of larger size actuator and complex movements at large sizes actuator.

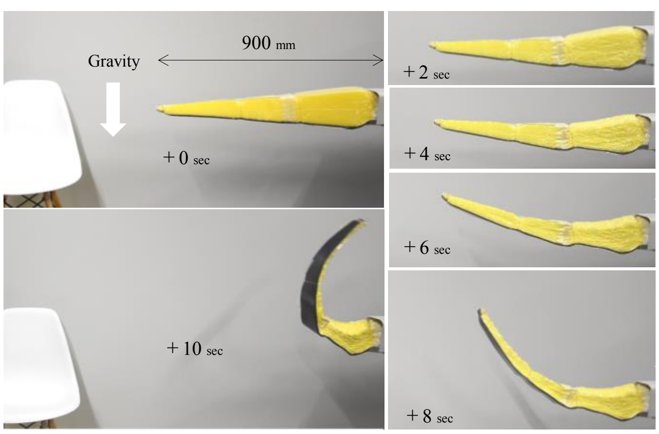


Figure 15. Large size LayerCAKE.

CONCLUSIONS

In this study, a laminated sponge foam called LayerCAKE was developed to provide a drivable lightweight flexible structure. The following results were obtained.

- A vacuum-powered laminated soft actuator was proposed with open- and closed-cell foam.
- Bending construction motions were observed by changing the laminated structure.
- Dynamic motion was designed by arranged air passage with laminated closed-cell foam.
- The relationship between the bending angle and pressure of the LayerCAKE model was described.
- The bending angles were measured at each pressure, and the measured value coincided with the value of the model.
- Complicated movement can be realized by arranging closed-cell foams.
- A flexible structure of various shapes can be realized by devising the shape of the open-cell foam

ACKNOWLEDGEMENTS

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