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SWITCHING TRANSFORMATION FOR SOFT PNEUMATIC ADAPTIVE SHADING

Rakhmat F. Aditra*, Paolo Beccarelli+ and Carlos Jimenez-Bescos†

*+†Department of Architecture and Built Environment
University of Nottingham
University Park Campus, NG7 2RD, United Kingdom

*School of Architecture, Planning and Policy Development
Institut Teknologi Bandung
Jl. Tamansari 64, West Java, Indonesia

*e-mail: rakhmat.aditra@nottingham.ac.uk

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Summary. Soft pneumatic adaptive system could be categorized based on transformation occurred. One type of transformation that was rarely discussed is the switching transformation. It was only found in switchable fritted layer cushion structure. To keep the system rigid against external load but flexible to actuate, it alternately inflated its chambers without further stretching the material. A switching based soft pneumatic adaptive system was proposed in this article. The conceptual design and its geometrical parameters were discussed. The structural performance was analysed and discussed by analytical method and Finite Element Method. A prototype was constructed and actuated to discuss its improvement. The analytical method suggested that actuation pressure would only be resisted by the hinge friction, but the result from prototype showed that there was folding resistance on the membrane that also affected the actuation pressure. The structural analysis also suggested that the cap design would affect the angular stiffness of the wings insignificantly. The fabrication of prototype suggested several important criteria to be further developed, such as: (1) a simpler construction of the rigid layer of the pneumatic chamber is needed, (2) wings should be rigid to withstand wind load and light to decrease the hinge frictions.

1 INTRODUCTION

Zarzycki[1] explained soft pneumatic systems as: Active adaptive system that utilize soft expandable surfaces actuated through pressurized air and/or vacuum suction. This description is similar with soft pneumatic actuators. This description is also suitable with the aim of this research to proposed adaptive active system that could utilize the pneumatic system of cushion structure.

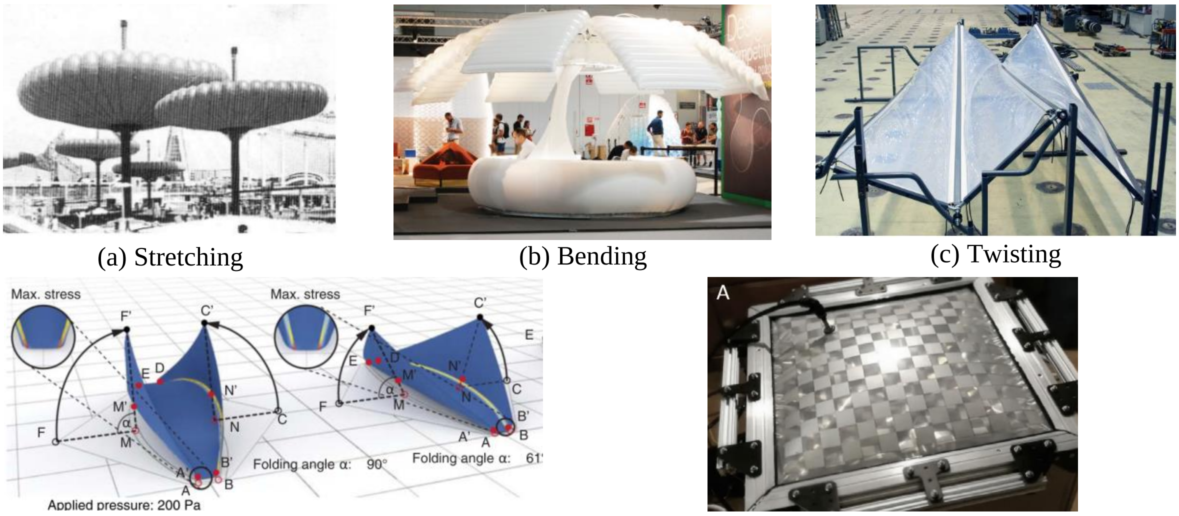
This description assumes 2 things: (1) There is always need of actuator, and (2) deformation response is only expanding. It omits switchable fritted layer cushion into this description. Pneumatic term itself means something that operated by air or gas under pressure.

Going with the purpose of introducing novel switching adaptive system, this article will broaden the concept of 'soft pneumatic adaptive system': Active adaptive system that utilize pressurized air and/or vacuum suction to move or transform the part of the system.

Some articles have reviewed adaptive system in different point of view, which include pneumatic structure [1–6]. But, since none of mentioned articles above discussed specifically about soft pneumatic adaptive system in architecture discipline, neither categorized this topic in detailed manner. While there were a lot of articles discussing about application of soft pneumatic system in topics of soft robotics[4,7–14], review about soft pneumatic adaptive system in architecture discipline was still limited.

Soft pneumatic adaptive system could be categorized based on the transformation occurred. All pneumatic structure transformation will always be based on inflation. But what makes them different with each other was the transformation of the pneumatic chamber shape. Most common transformation occurred was through stretching (Figure 1a)[1,12,14–17]. The system performs using the enlargement of the pneumatic chamber; either directly using the changed properties of the enlarged pneumatic chamber or using the pneumatic chamber to move or transform additional component. The enlargement of pneumatic chamber could be in 2-dimensional, 3-dimensional, or radial direction.

Another common transformation used was bending (Figure 1b)[10,11,18–20]. As the name suggested, it caused the pneumatic chamber to bend in one plane. The bending transformation was achieved either with a set of 2 series or more of pneumatic chamber that were pressurized in different pressure or combination of semi-rigid material.



(a) Stretching (b) Bending (c) Twisting

(d) Folding (e) Switching

Figure 1: Four transformation in Soft Pneumatic Adaptive System

Twisting transformation (Figure 1c)[5,14] and folding transformation (Figure 1d)[21–23] could also achieved with similar methods of combination of semi-rigid material. Examples of twisting transformation had its pneumatic chamber to twist in one axis. Meanwhile, some examples of folding transformation characterized by folding lines on the pneumatic chambers which made the pneumatic chamber material to folded during the actuation instead of stretching. Other example of folding transformation used folded plate that was actuated by pneumatic chamber.

The last type of transformation switching transformations (Figure 1e). It was only found in switchable fritted layer cushion structure[24,25] which, despite clearly actuated by changes of air pressure of pneumatic chamber, was rarely included as soft pneumatic adaptive system in other adaptive system reviews. Switchable fritted layer cushion characterized by 2 or more layers of chamber that were inflated alternately. Switching transformation happens when the inflated chamber was switched.

One of limitation of soft pneumatic adaptive system (SPAS) is its constant energy needed to maintain its pressure[1] due to leakage. Leakage could be minimized with lower pneumatic pressure. Thus, SPAS is required to be flexible enough for lesser actuation pressure, but still rigid enough to withstand external load. Based on literature review, there are several methods used to satisfy these criteria.

Some SPAS [15,22,23] used rigid part or counterweight which could resist external load during the deflated state. This method requires pressure that sufficient to deform the rigid part or move the counterweight. Other SPAS keep its rigidity by maintaining its pressure to prestress the pneumatic chambers [11,20]. The transformation happens by increasing the pressure to its or some of its chambers. With this method, the material of the pneumatic chambers has to be further stretched just to maintain its form.

Meanwhile, switchable fritted layer cushion foil structure uses the third method[24,25]. Its alternately inflated chambers enable it to keep the system rigid, while also does not require to deform rigid part or to stretch the material further (Figure 2). This method was only found in switchable fritted layer cushion foil structure. This could be one of reason why switchable fritted layer cushion foil structure only required 0.2-0.3 kPa to actuate and resist external load, while other recorded soft pneumatic system required 6-25 kPa just to actuate[18,21,23]. This article will propose a switching soft pneumatic adaptive shading (SSPAS) that is inspired by switchable fritted layer cushion foil structure.

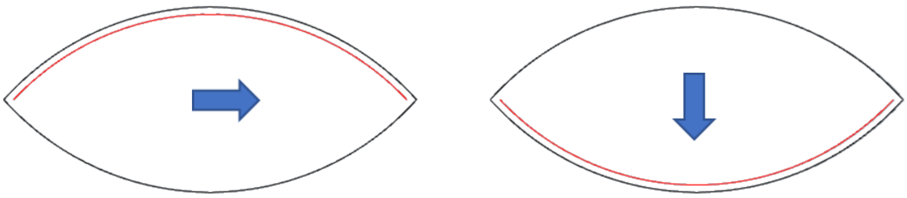
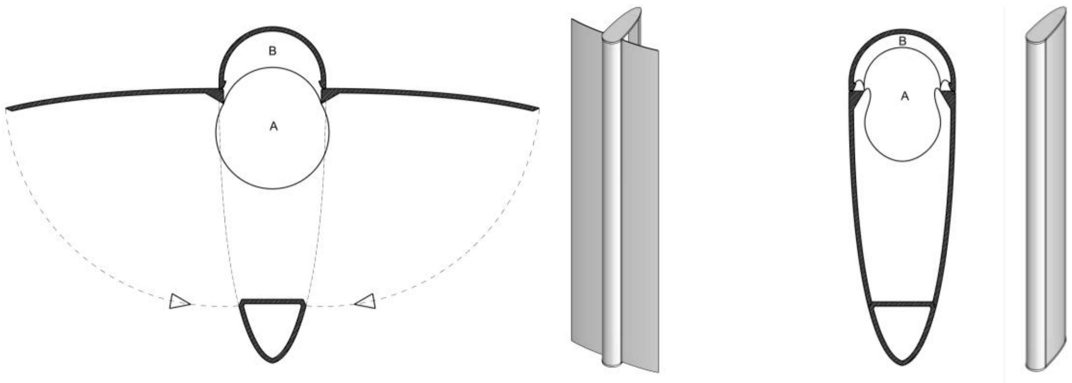


Figure 2: Switching transformation method

2 DEVELOPMENT OF SWITCHING SOFT PNEUMATIC ADAPTIVE SHADING

2.1 Conceptual Design

SSPAS consists of rigid part (blocked) and pneumatic membrane (one-line) (Figure 3). It has 2 chambers. First is the moving chamber which is attached on the wing arms. Second is the static chamber which is sealed at the rigid head part. It has open mode and close mode. During open mode, both chambers are pressurized to open the wing. During close mode, the static chamber is depressurized (negative pressure) to close the wing.



(a) Open mode (b) Close mode

Figure 3: Switching Soft Pneumatic Adaptive System

SSPAS has 2 modes only: open and close mode. Each mode has different actuation method, but same principle: rotating the wings by providing pressure and hoop stress on the wing's levers. Hoop stresses are given by the stressed membranes. The use of rigid chamber makes the hoop stress only exists in one layer of membrane. Locking mechanism in the wing details will stop the wing into the position during each mode.

2.2 Geometrical Parameters

Several geometrical parameters that could be taken into consideration in designing SSPAS were hoop stress tangent angle (θ), width of wing lever (l_l), and width of wings (l_w). Hoop stress tangent angle will affect the moment force. It is also combination of radius of stressed membranes and with of the chamber. The nearest it is to being perpendicular to wing lever, the higher the moment force generated. But, in case of open mode, it also increases the volume of chamber.

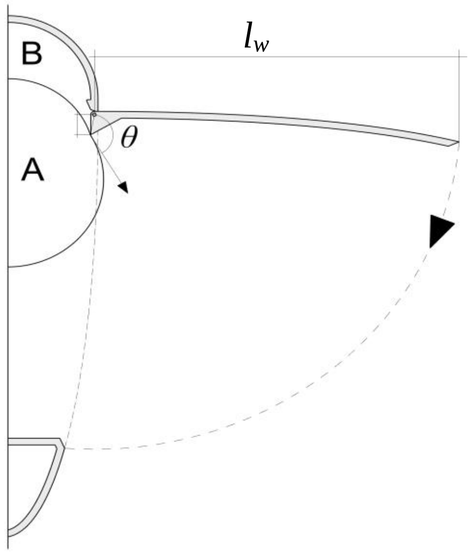


Figure 4: Geometrical parameters

Width of wing lever would affect the moment force generated by the hoop stress of membrane. While wider wing lever increase the generated moment force to counterbalance the wind load, it is still limited with the fabrication of the membrane. The crease created during the close mode could increase with wider wing lever.

Width of wings would affect moment force generated by the wind pressure and the adaptability of the SSPAS. The narrower the wings are, the lower moment forces generated are. But it also decreases the area of exposure difference between open and close mode, which could affect the effectiveness of SSPAS.

3 STRUCTURAL ANALYSIS

To analyze the structural behavior under wind pressure, an analytical method and finite element method was used. Equation 1 was used in the analytical method. It was moment force equilibrium of the wings equation, which consisted of moment force from hoop stress (M_h), lever pressure (M_l), and wind pressure (M_w).

$$\Sigma M = M_w + M_l + M_h = 0 \tag{1}$$

$$M_l + M_h = \pm M_w$$

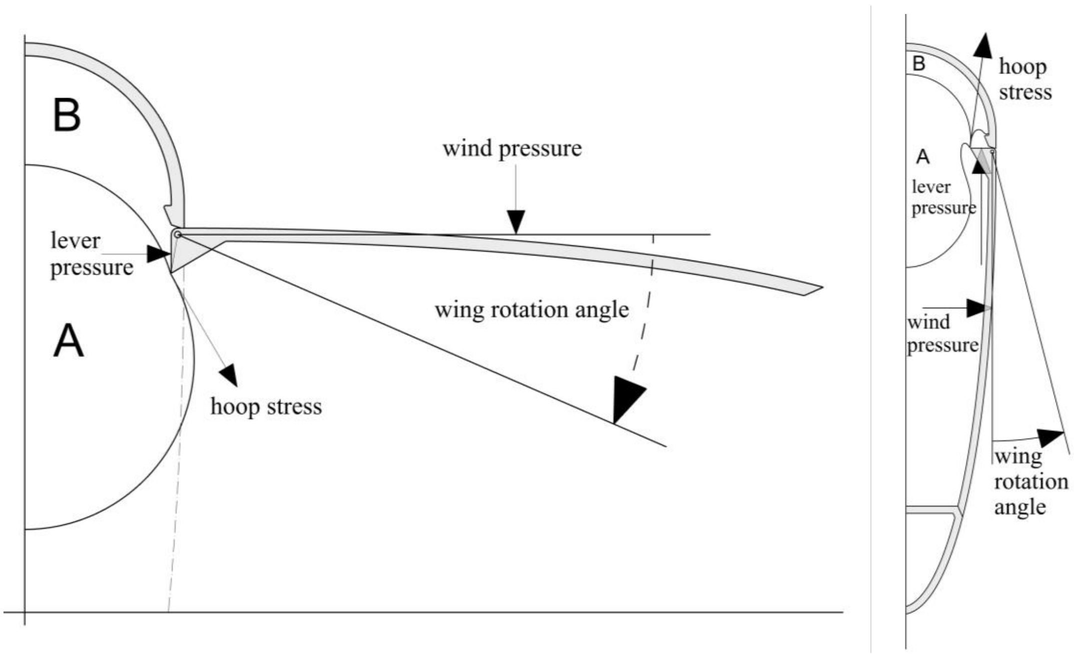
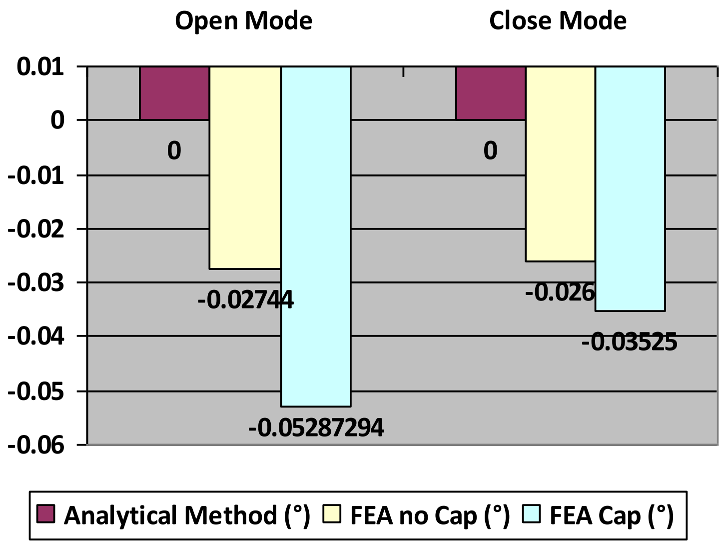


Figure 5: Force diagram : Open mode (left), and close mode (right)

From the analytical method, to reach the equilibrium in the wing moment force, the wind pressure of 187.26 PA for open mode and 194.65 PA for close mode were found. The result was then used as the input for the FEM. The wing rotation angle from both FEM model were compared with the zero rotation in the analytical method. The pneumatic pressure used in the simulations was 8 kPA.

The analytical method had not considered the 3-dimensional effect of cap design of the pneumatic chamber. To simulate this effect, 3D model of the shading was modelled in FEM software RFEM DLUBAL. Model with and without cap were both simulated in the finite element analysis. The pneumatic tube had 848 cm straight tube, with 20 cm cap on each end. The shape of the cap was based on the construction of the prototype. Since the aim of FEM was to see the effect of 3-dimensional design of the pneumatic tube, the rigid chamber and wings were simulated as rigid material. The membrane was simulated as typical coated fabric[26] with thickness of 0.2 mm.

The result showed that wings in FEM rotated outward during the open mode and rotated inward during the close mode. This difference might be due to the detail of the mesh used. Increasing mesh size in open mode and close mode in FEM showed lower and higher rotational displacement of the wing, respectively. The capped model rotated even more than one without cap. It showed that the cap increased the angular rigidity of the wing. But these differences were not significant.



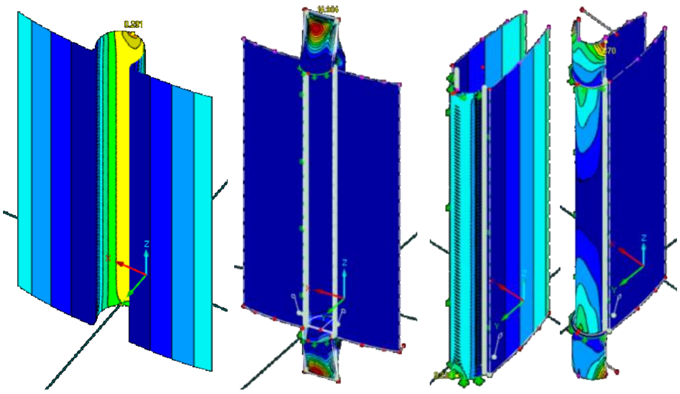


Figure 6: Structural analysis result (above), and FEM deformation diagram (below)

4 PHYSICAL PROTOTYPE

For this article, a full-scale prototype was constructed. The prototype was fabricated in 2 parts: pneumatic tube, and rigid shell. With limitation in infrastructure, the rigid shell was consisted of 3D printed parts as the frame and balsa wood as shell. The frame was consisted of the chamber frame and wing frame. Chamber frame held the rigid layer of the pneumatic chamber and the wing frames. The wing frames will be attached to the balsa wood plate as the wing surface. The wing frame and additional lever skeleton were attached to the welded part of the pneumatic tube.

The pneumatic chamber was fabricated from 3-layer polyurethane coated nylon membrane that were welded together. The longitudinal welded sides were attached to the lever to perform the rotation. To make the cap of the tube, the membranes were folded and welded together. The welded part of membrane that was attached to the lever was 85 centimeters in length, which left 13.5 centimeters of cap at each end of tube.

Upper layer of pneumatic chamber should be rigid to resist both positive and negative pressure. In this prototype, it was achieved by sandwiching upper layer with steel pipe from inside and balsa wood from the outside. The sandwiched layer was clamped using chamber frames and pair of aluminium extrusion to prevent it from sliding vertically.

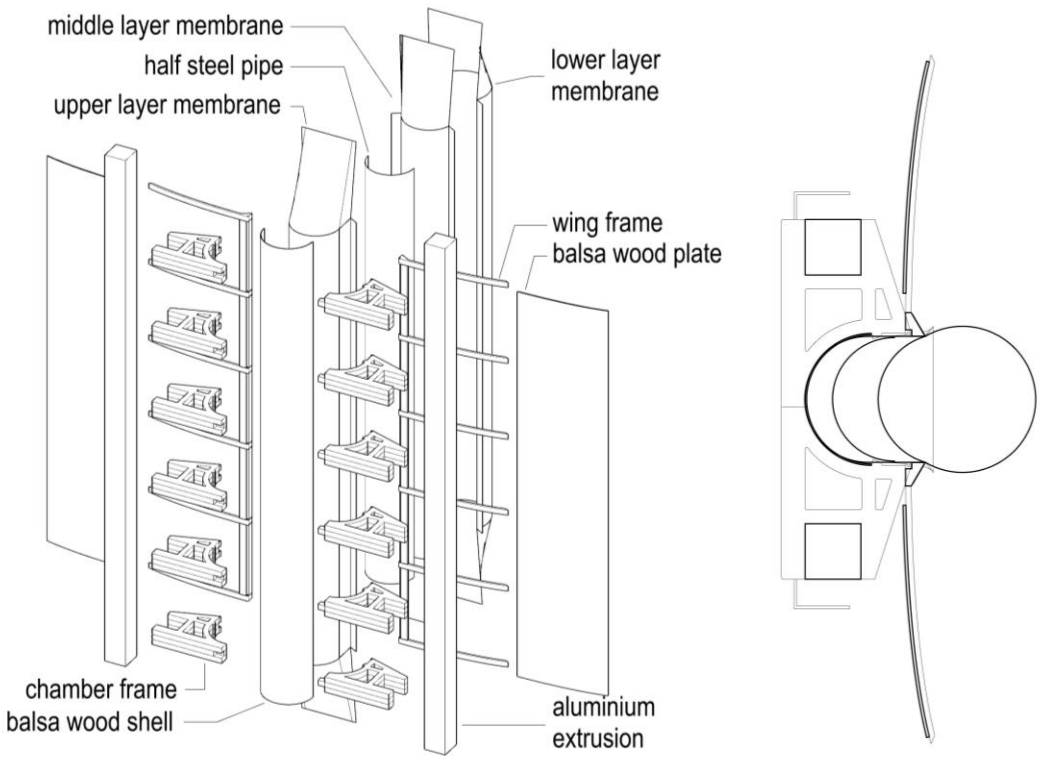


Figure 7: Full-scale prototype construction (left), and section (right)

The prototype was able to be actuated. One aspect that was missed during this prototype fabrication was also correlated to the problem of creating rigid upper layer. In the attempt to prevent the steel pipe to slide horizontally during the close mode actuation, stoppers were designed in the chamber frame. This caused the wings to not fully opened during the open mode actuation (Figure 8 left). In contrast, the wings were closed easily during the close mode actuation (Figure 8 right). There were also folding resistance of the membrane present. It was shown when the pressure was release after open and close mode, the wing rotated back slightly. This showed that certain pressure was needed to keep the wing stable.

Figure 8: Actuation experiment: Open (left) and close mode (right)

5. CONCEPTUAL FABRICATION IMPLEMENTATION

During the fabrication of the prototype, some difficulties were found that should be considered during the real scale prototype. First is how to make the top layer rigid and sealed. The solution used in this article was also the cause of the actuation problem. Hot welding membrane into steel plate might be done, but welding of the cap should be considered.

The construction of wings and its joints was also important aspect. Wings should be rigid enough to withstand the wind load but light enough to not create too much burden on the joints. In current construction, the thin joints were able to withstand the light material of the wings. In actual built construction, more durable and stronger design and material might be needed.

6. CONCLUSION

The structural analysis showed the potential of switching transformation for soft pneumatic adaptive shading. Based on the kinematics, it has the potential of low actuation load. With its two chambers, the angular stiffness of the wing could be controlled by pneumatic pressure. The prototype has showed the possibility of this concept. The cap showed no significant effect on the angular stiffness of the wings. Yet, it would be better for the energy efficiency to have lower cap to tube ratio.

The structural analysis in this article have not yet considered the friction and the folding resistance. Both factors would affect the angular stiffness of its wings. Further experiment will be needed to further inspect these factors.

Switching soft pneumatic adaptive shading (SSPAS) only has 2 modes. It is unable to have intermediate state which some soft pneumatic adaptive system had. It means that façade with SSPAS would require additional mechanical setup, which can control each set of fins, to control the adaptability of the entire façade. Thus, it is important to see the effect of this adaptability to the energy reduction performance.

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