Bio-inspired wooden hygro-actuators: bilayer structures

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Context and objectives

Wooden hygro-actuators are a sustainable solution for mechanisms that require cyclic movements. These actuators are inspired by natural phenomena. To adapt to their environment; many plants use hygroscopic movement which is a shape changing movement that does not consume energy (Zhan et al 2023). This hygroscopic movement can be reproduced thanks to wooden bilayer structures using the differential shrinkage and swelling of wood.

The bilayer is a wooden structure which uses the differential shrinkage and swelling between two linked pieces of wood in order to make the system curve (Fig. 1). This differential shrinkage is created by choosing two wooden layers from different spices of wood with different shrinkage rate and by using pieces with the direction of the fibers orthogonal from one to the other, which allows, when the relative humidity changes, one layer cut along the tangential direction (called active layer) to shrink more than the other layer cut along the longitudinal direction (called the passive or resistive layer).

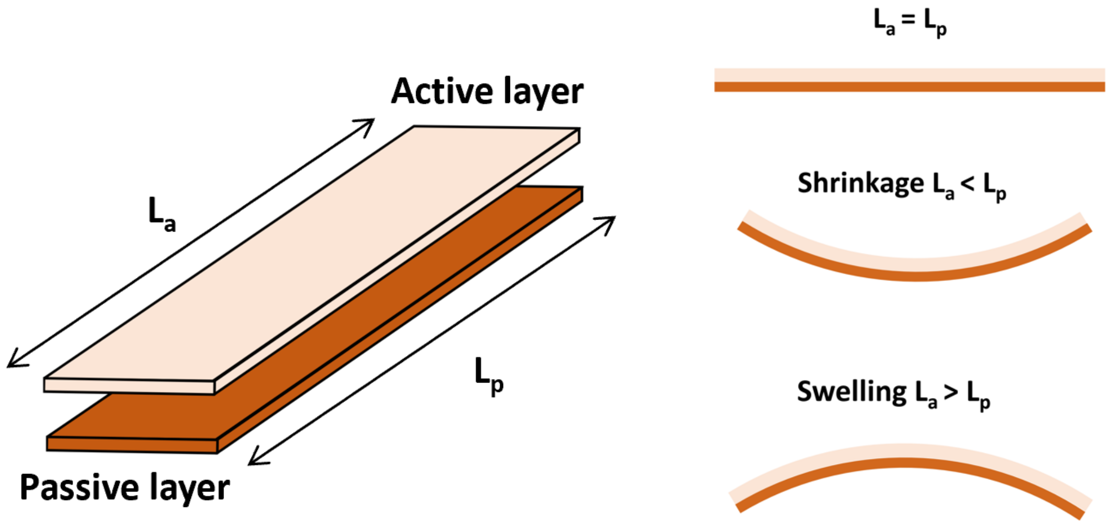
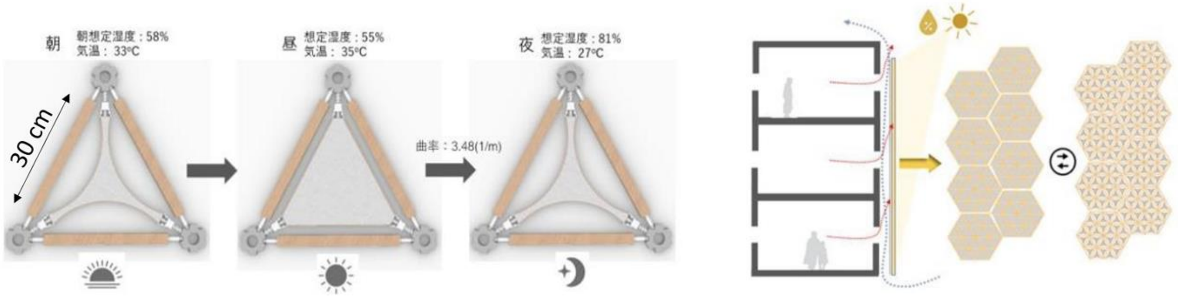


Fig. 1: Bilayer concept

The aim of the following research, in collaboration between Kyoto University and the Japanese company Kozo Keikaku Engineering, is to develop a triangular system of bilayer structures equipped with a fabric that will extend to produce shadow when humidity is low, i.e. when the sun is high during the day, without requiring an energy supply to operate.

The final aim of the project consists of assembling several triangle frames (Fig. 2a) into a large structure which could be used as a facade in front of a building (Fig. 2b). This facade would bring sunlight and air into the building by autonomously adjusting the solar shading area by letting in or blocking light in response to changes in relative humidity during the day. The goal of this present research is to study the feasibility of the smart umbrella project by studying the behavior of some prototypes and by studying the impact of a long period of use on the mechanical properties of the bilayers. The objective is to lead experiments which aim to characterize the wood used (hygroscopic and mechanical behavior) and the behavior of the prototypes in outdoor situations and controlled environments.



(a) (b)

Fig. 2: Project : (a) Prototype ; (b) application concept (Yucel et al 2023).

Material and methods

Four prototypes of frames were considered and equipped with two different types of fabric (Fig. 3), one rigid and thick, the other one very flexible and thin, in order to test them and compare their behavior. Two methods were used to assemble the fabric on the bilayers: the use of adhesive (frame 1) and the use of staples (frame 2 and 4).

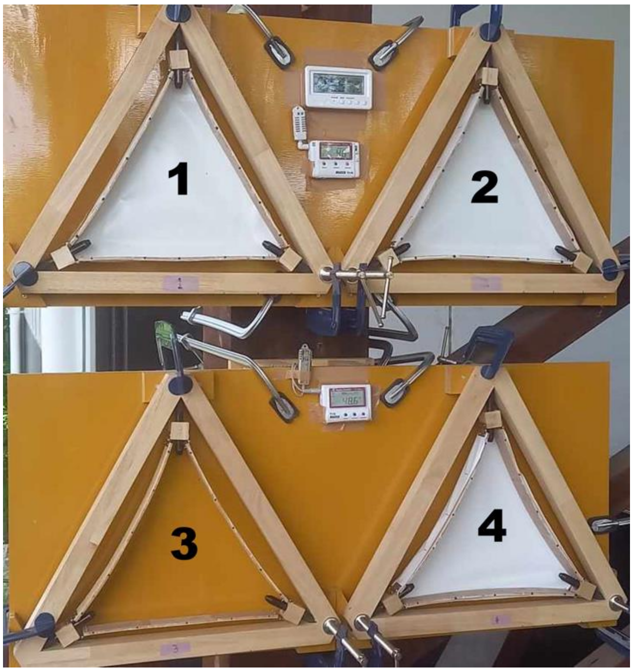
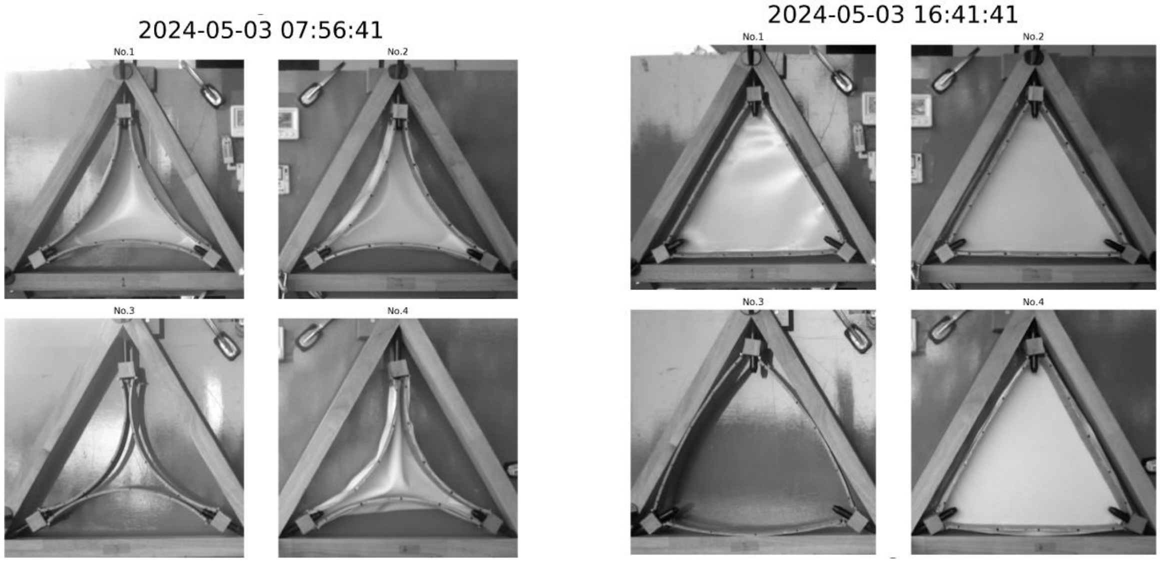


Fig. 3: The four prototypes. 1: Fabric: glass fiber coated with polyvinyl chloride (0.53 thick), assembled using adhesive. 2: Fabric: glass fiber coated with polyvinyl chloride (0.53 thick), assembled using stapler. 3: No fabric. 4: Fabric: polyester, assembled using a stapler.

The frames were left outside for eight days and filmed with a camera (TLC 200 from Brinno, Format JPEG 1280x720) taking one picture every five minutes (pictures examples on Fig. 4) with humidity and temperature sensors. The images were analyzed by a deep learning model, based on the work of Olaf Ronneberger (U-Net) (2015), which, after training, is able to measure the curvature of each bilayer for each picture.



(a) (b)

Fig. 4: Pictures taken by the camera: (a) Prototype closed (RH80%); (b) Prototype open (RH30%)

Results and discussion

The results (Fig. 5) show that the curvature of the frames follows the same trend as the evolution of the outside relative humidity, which was expected. Moreover, there are some differences between the curvature of each frame. The maximum curvature (highly visible on the morning of the three first days) is the largest for frame 3, then frame 4, and finally frame 1 and 2. This shows that the rigid fabric is restraining the movement of frames 1 and 2, whereas frame 4 with the elastic fabric has a larger curvature that is smaller than that of frame 3 which has no fabric. In addition, when the humidity is lower than 45% (humidity aimed for flat state) the bilayer is supposed to curve in the opposite direction, however at the end of the afternoon, this reverse curvature was visible only for frame 3 (no fabric), thus the frames with fabric cannot curve in the other direction, indeed the fabrics being not very elastic, it prevents the frames to curve in the other direction, which may create some internal forces that could damage the prototype in the long-term.

As the final product is supposed to be used outside for a long time, the long-term behavior of the prototype is important. In order to characterize the behavior of the bilayers during time, four bilayers were subjected to a one-month experiment in a controlled chamber. The chamber was set in a way that the relative humidity inside follows an evolution close to the evolution of the outside humidity for one day, and this cycle was repeated every day for 26 days. The four bilayers were put in the chamber with the same camera used during the outside experiment, a picture was taken every five minutes, and the curvature was measured with the deep learning model. Thus, the results obtained on Fig. 6 display a decrease in the maximum curvature reached by the bilayers every cycle. This decrease is very small (less than 5% after 26 cycles) so it does not compromise the use of the prototype, however, tests on a longer period (6 months or one year) would be interesting to conduct, in order to see if the decrease continues or if the value of the maximum curvature stabilizes from a certain number of cycles.

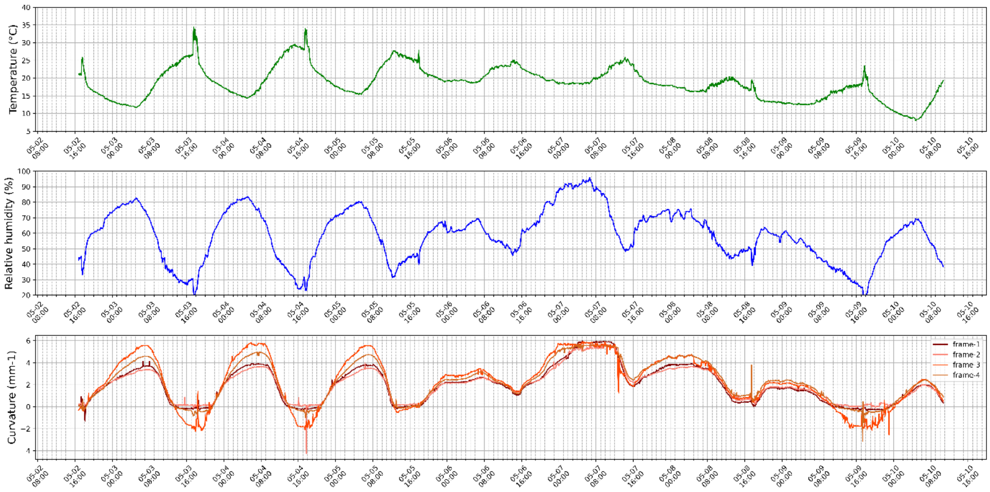


Fig. 5: Results for the eight days outdoor experiment.

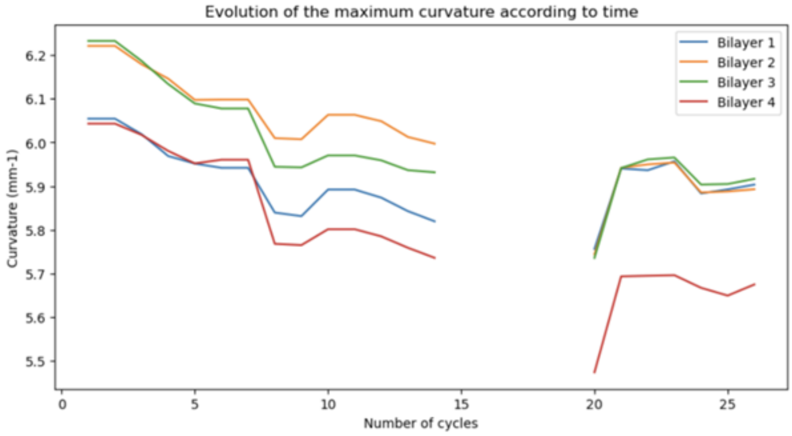


Fig. 6: Evolution of the maximum curvature of the bilayers according to the number of cycles undergone.

Finally, although the long-term behavior of the bilayers is not clearly known, the prototypes are working, the cycle of opening and closing of the frames follows the natural cycle of humidity outside as intended. Regarding the assembling of the fabric on the frame, two methods have been tested: the use of adhesive and the use of a stapler. The adhesive gives a good and reliable result however, the glue takes some time to dry and the fabric has to be held against the wood while the glue is drying, which is not suitable for an industrial process. On the other hand, the use of a stapler is more efficient and quicker but the staples, when put in wood, can damage the prototype and create some cracks in the wood. To improve the assembling method, a way of putting the staples that prevents any cracks from appearing should be designed in order to have a reliable and efficient process.

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