Designing an adaptive building envelope for warm-humid climate with bamboo veneer as a hygroscopically active material

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ABSTRACT: To address climate responsiveness, most of the envelope strategies experimented by architects so far has incorporated automated high-tech systems, electronic sensors and actuators, increasing our energy consumption. As our climate continues to change concomitant to our reliance on non-renewable energy sources, low-tech passive façade systems require a more thorough investigation to adapt them for large-scale application. This includes an in-depth focus on sustainable building materials to generate a technologically independent, carbon-neutral building façade. Materials such as bamboo, due to its hygroscopic nature, undergo constant expansion and contraction with changing levels of atmospheric humidity. From a crafting and construction perspective, this spontaneous dimensional change is seen as an inherent drawback of working with bamboo, with attempts being made to control, or mitigate, the change. But in order to develop a passive system of responsive architecture, it is time we look at the hygroscopic movement intrinsic to bamboo as an opportunity, rather than a challenge, and integrate it within the material performance of architecture itself. This paper looks into bamboo veneer as an adaptive material to help rethink building facades as organic, breathable skins rather than a mechanized barrier between human and nature. The methodology incorporates a series of physical experiments to study the deformation of a bilayer bamboo composite consisting of a bamboo veneer bonded with a clear cellulose film. The film, being non-reactive to climate, amplifies the curving motion of bamboo, along with its return to the initial position. The module was then used to explore different façade patterns to study the opening and closing mechanism that could potentially generate maximum ventilation. The outcome of the research will consist of a working, demonstrable prototype for a no-tech adaptive façade pattern that, while undergoing a bio-mechanical response, will perform particular functions including shading and/or ventilation, leading to a truly material-integrated architecture.

KEYWORDS: Adaptive envelope, Responsive, Bamboo, Hygroscopy

INTRODUCTION

One of the earliest forms of adaptive envelopes that made use of embedded material properties to create a responsive architecture was the black Bedouin tent. By employing passive strategies, the fabric of the tents absorbed moisture and ensured a continuous airflow, thereby reducing air temperature through evaporative cooling. Thermal comfort was achieved throughout the interior space while ensuring little to no energy waste. This concept of climatic adaption was taken on by Buckminster Fuller in 1967 in his design for the *United State Pavilion* at the Montreal Expo; in a geodesic dome enveloped in computer-controlled transparent acrylic sheets that could retract themselves with changing levels of solar radiation. This development marked the beginning of a design strategy that allowed building systems to respond to external environment with the help of a technologically-imposed intelligence. Climate-adaptive envelopes were further explored in Jean Nouvel's 1980's creation, *Institut du Monde Arabe* in France. With hundreds of light-sensitive apertures that open and close with changing sunlight levels this design was one of the most innovative technological marvels of its time. However, this design approach of contemporary high-performance buildings, while offering improved internal comfort, often gets overshadowed by the associated dependency on external energy, higher cost, complex construction and maintenance issues. In order for people to survive within today's rapidly changing climate with minimum energy depletion it is time building systems are rethought for a more sustainable solution. Buildings are already consuming more than 40% of all energy; if building materials could be made to passively adapt themselves to the climate there is a chance that our reliance on active mechanized systems, leading to energy waste, could be brought down to a minimum.

1.0 ADAPTIVE FACADES

Loonen et al. defined climate-adaptive buildings as being characterized by their ability to repeatedly and reversibly change their features and configurations with changing climatic parameters with a view to achieving an improved building performance (Loonen 2013).
Adaptive façade strategies typically follow two approaches. One is where the entire system of climatic response is mechanized with complex automated devices, and the other is where façade responsiveness relies entirely upon material behavior and material properties without the need for any intricate mechanical system. The former is identified as being an *active* system with extrinsic control while the latter is a *passive* system having intrinsic control (Loonen 2013).

The *passive* system, while going through continued research, has two acclaimed pilot projects so far: Doris Sung's research pavilion in Los Angeles called "Bloom" and Achim Menges's "HygroSkin" pavilion in Germany (Fig.1). Both these systems take advantage of a material's inherent climate reactive properties, with temperature-reactive thermo-bimetal (Sung 2010) and humidity-reactive wood respectively (Reichert, Menges, Correa 2015). Calling the building envelope a third "skin", Sung believes that this kind of passive responsive architecture has the potential to bring human closer to nature by incorporating an elevated sensitivity in its surface. Reichart, Menges and Correa (2014) agree with this idea of "material as a machine" and explain that material embedded actuation can eliminate any instance of technical malfunction by incorporating the atmosphere for control and actuation. While advocating for an increased interaction with environmental dynamics, they suggest materials be physically programmed, rather than superimposed with technical devices. This, as they believe, will "enable a shift from a mechanical towards a biological paradigm of climate-responsiveness in architecture". (Reichart, Menges, 2012)

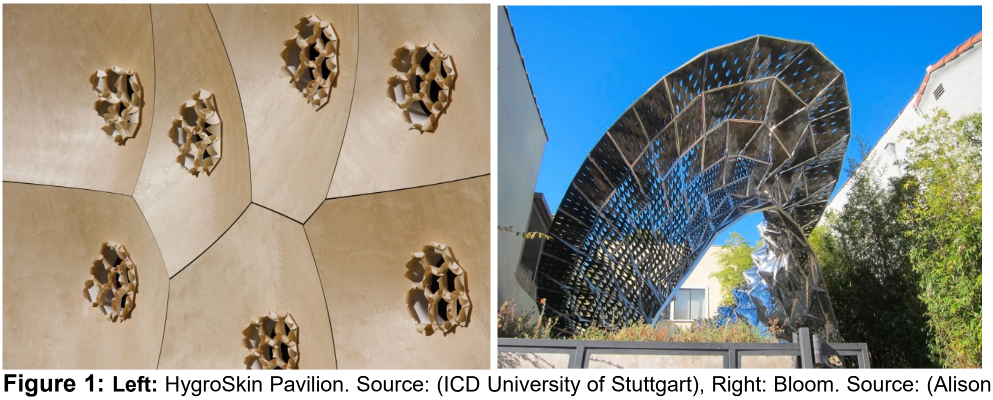

Figure 1: Left: HygroSkin Pavilion. Source: (ICD University of Stuttgart), Right: Bloom. Source: (Alison Furuto 2012).

2.0 BAMBOO FOR WARM-HUMID CLIMATE

A rapidly renewable plant, bamboo is a more sustainable alternative to wood. With some species shooting up to approximately 0.6m (2 feet) per day, it is the fastest growing plant in nature. Bamboo is native to Asia, South America and parts of Africa (Fig.2).

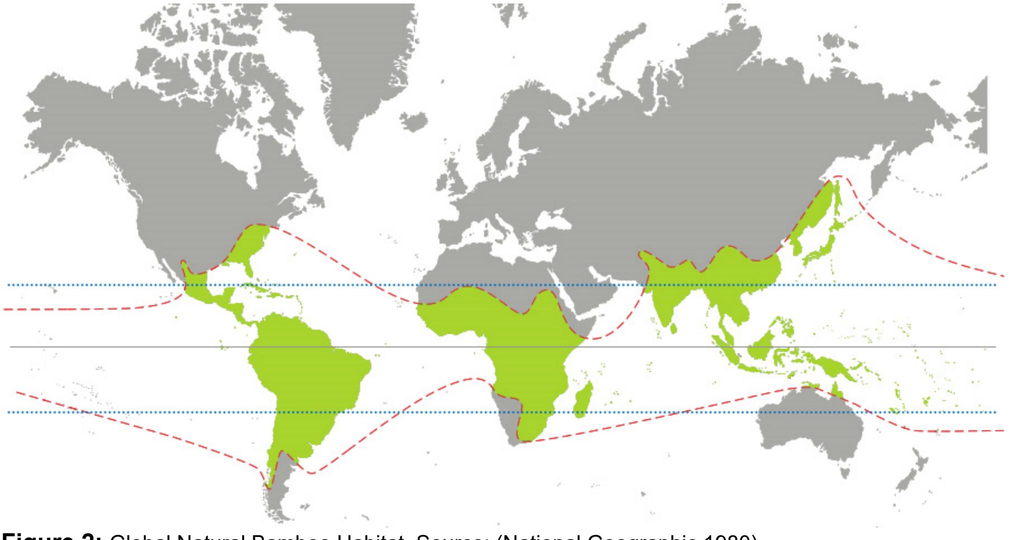

Figure 2: Global Natural Bamboo Habitat. Source: (National Geographic 1980)

The stem is hollow, except at nodes, and, when mature, can be 40m (130 feet) high. Most bamboo species become mature within 2 to 3 years.

The structural nature of bamboo, with its remarkable tensile strength, reveals that the strength and stiffness that it tends to achieve along its grain following the longitudinal direction is far greater than that in the transverse direction. Similar to wood, the major chemical constituents of bamboo are cellulose, hemicellulose and lignin. The cellulose micro-fibrils are present in an amorphous solution of lignin and hemicellulose (Tomalang et al. 1980). Any such fibrous material absorbs moisture in two forms: bound water and free water. The absorption or release of free water, occurring inside cell cavities, has negligible impact on bamboo, however swelling and shrinkage occurs with changes in bound water content, occurring inside cell walls. As bound water is absorbed the cellulose micro-fibrils expands transversely along with the lignin matrix, leading to swelling of bamboo. Similarly, as bound water is removed, shrinkage of bamboo is observed. (Dinwoodie, 2000)

Its never-ending sustainable qualities include carbon-di-oxide sequestering, reducing soil erosion, low embodied energy and low use of nutrients, extremely high tensile strength, light-weight construction and low-cost (Schroder 2011). The major drawbacks of using bamboo are perceived to be its vulnerability to moisture, leading to dimensional changes, and high cellular starch content, leading to fungal attack.

3.0 EXPLORING BAMBOO VENEER

Though the research was aimed toward a warm-humid climate, and not any particular geographic location, three locations were selected to be representatives of the climatic region namely, Florida, Bangladesh and Vietnam. Each of these regions has their own share of strengths and challenges concerning bamboo availability and constructions. While architecture constructions in Bangladesh and Vietnam have incorporated bamboo in a myriad of ways for a long time, in Florida, however, despite the easy availability and suitable climate bamboo still has not became the material of choice for many. For the purpose of the research, a number of bamboo species was explored that were native to such regions and, at the same time, were also easily available in the region where the research was being conducted. Finally, the species *Phallostachys edulis* (Moso) was selected for the study as it is a north-temperate bamboo species and commonly grows in the regions being studied. Moreover, being the most widely available bamboo species in the US, the ease of availability was also a major determining factor in selecting this particular type. The veneer was 0.5mm (0.02 inches) in thickness and was kiln dried by the supplier to 6-9% of its moisture content. A series of physical experiments were conducted with the particular bamboo specimen to understand its hygroscopicity. These experiments looked into different shapes, sizes and grain angles of the veneer (Fig.3). The conclusions derived from the observations informed following experiments, thereby pushing the work forward.

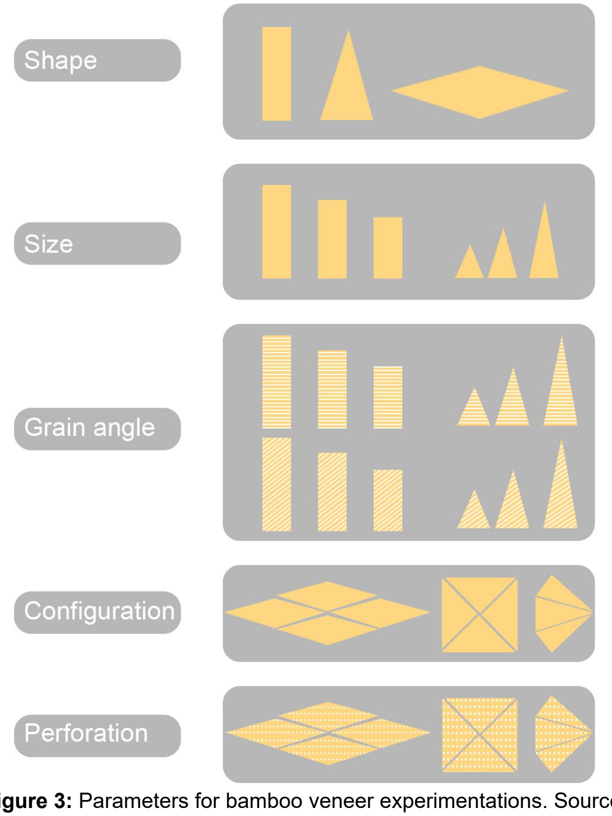

Figure 3: Parameters for bamboo veneer experimentations. Source: (Author 2018)

3.1. Veneer behaviour study

The study began with an experiment consisting of two sets of three rectangular pieces, each of which had veneers 7”, 6”, 5” in length and 2” in width. Three of these had grains perpendicular to the longer dimension and three had grains at an angle of 15 degrees. After the humidity was raised from 51% to 93% it was observed that the higher the width-to-height ratio of a veneer the greater was its deformation. The deformation was also higher in pieces that were cut perpendicular to the grain direction. So the 7” long piece with grains perpendicular to the longer side showed the maximum deformation. (Fig.4)

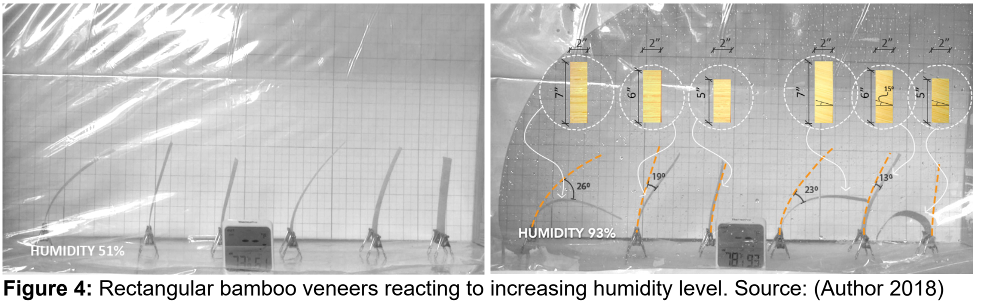

Figure 4: Rectangular bamboo veneers reacting to increasing humidity level. Source: (Author 2018)

A similar experiment was conducted with triangular pieces and was observed to have a greater deformation than rectangles. The reason is that in a triangular piece as the veneer extends forward from the base toward the vertex it has increasingly less material along the grain and hence less resistance to deformation. However, when the humidity was decreased it was found that the veneer, on its own, was unable to return to its initial state, and it nearly took a period of 24 hours before it came back to its original state.

In order to have a consistent bending action throughout the length of the veneer and to allow the veneer to return to its initial position within a relatively short time a bi-layer composite unit was made with a non-reactive layer bonded to the veneer. The non-reactive layer was chosen to be a clear cellulose film 0.127 mm (0.005 inches) thick. This passive layer essentially restricts the linear hygroexpansion in bamboo, forcing it to bend. It also allowed the composite to come back to its initial state much faster. The recorded time for this was only 10 minutes.
Thickness of the composite was also an influencing factor in the bending motion. Thicker veneers were observed to have more inherent stability and were able to resist the bending motion while thinner veneers were more reactive. However, reduced thickness also translates to less material strength, leading to cracking and warping under strong winds. Holstov et al. believes that thinner composites are more prone to mechanical failure due to continued bending, biological failure due to fungal and insect attack and photo-degradation of lignin in cells. (Holstov et al. 2015)

How the two layers in the composite are bonded also has a significant role to play in its responsiveness. The bonding needs to provide flexibility to the composite to ensure repeated bending and, at the same time, be stiff enough to hold the layers together under different weather conditions. Although significant researches on bio-resins continue to be undertaken, according to R.D. Adams (2005), epoxy resins are currently the most suitable adhesive in the market that provides good strength, durability and ease of curing, without effecting hygroexpansion, despite environmental concerns.

3.2. Generating modular patterns

Following the veneer study, the research continued with constructing various patterns of modular façade and observing the degree of opening a particular façade would generate. The intention was to arrive at a certain geometry that would produce maximum opening to allow for maximum ventilation.

The study started with two-dimensional façade systems, with a diamond shaped composite unit. The particular shape, being wider in the middle and narrower toward the two ends, forced the composite to curve faster at its ends. During this stage small perforations were laser cut throughout the body of the veneers to study the behavior of perforated versus non-perforated material and observe whether getting rid of excess material aid in the deformation process by making them more reactive. The analysis later moved on to three-dimensional module studies to give the veneers an elevation to begin with. The triangles, acting as tetrahedrons, created a much bigger opening while deforming the same amount (Fig.5). However, during this time perforated veneers were seen to deform less since the grains ended up being divided at regular intervals due to the perforations. Hence, the research went back to using non-perforated veneers with a three dimensional modular pattern.

3.3. Incorporating façade with the climate

Once a suitable modular pattern with a certain shape and size was selected through a number of experiments with tetrahedrons, the wind directions of each of the three chosen regions were studied to integrate them with the modules. All three regions have most of the summer winds coming in from south/south-east direction, which was utilized to further modify the façade modules (Fig.6).

Figure 5: Experiments with modular patterns to generate maximum opening. Source: (Author 2018)

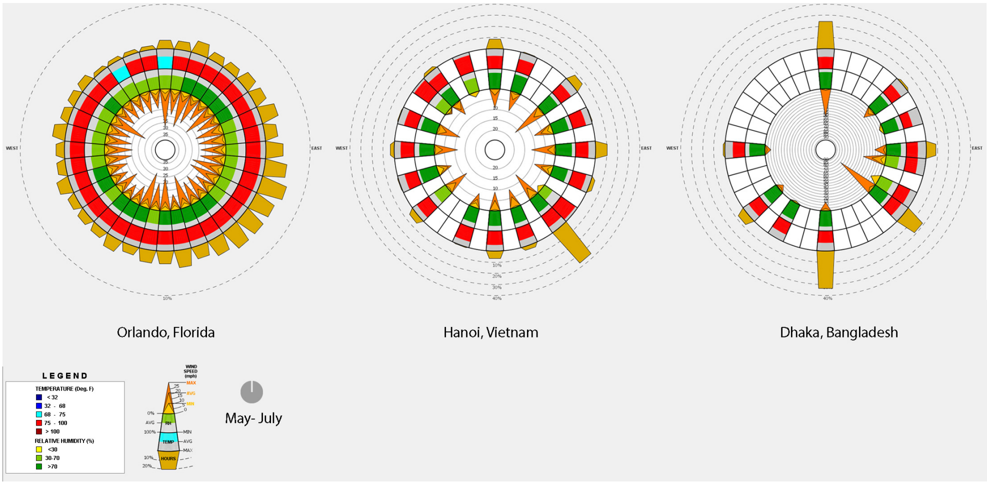

Figure 6: Climatic features of Orlando, Hanoi and Dhaka. Source: (Climate Consultant 2018)

To catch the south-east wind, a range of 40-50 degrees of angle from the horizontal line was determined to be incorporated into the façade structure. In order to do that, the façade was constructed in a way that the veneers would be attached to the façade frames at an angle of approximately 22-25 degrees. All three triangular pieces making up a module needed to have their deformation axis perpendicular to the base to generate maximum deflection. As the air becomes humid the veneers begin to absorb the humidity and open up to an angle within the range of 40-50 degrees at roughly 93% relative humidity level. As such, the cool south-east wind is expected to be allowed inside the space. (Fig.7)

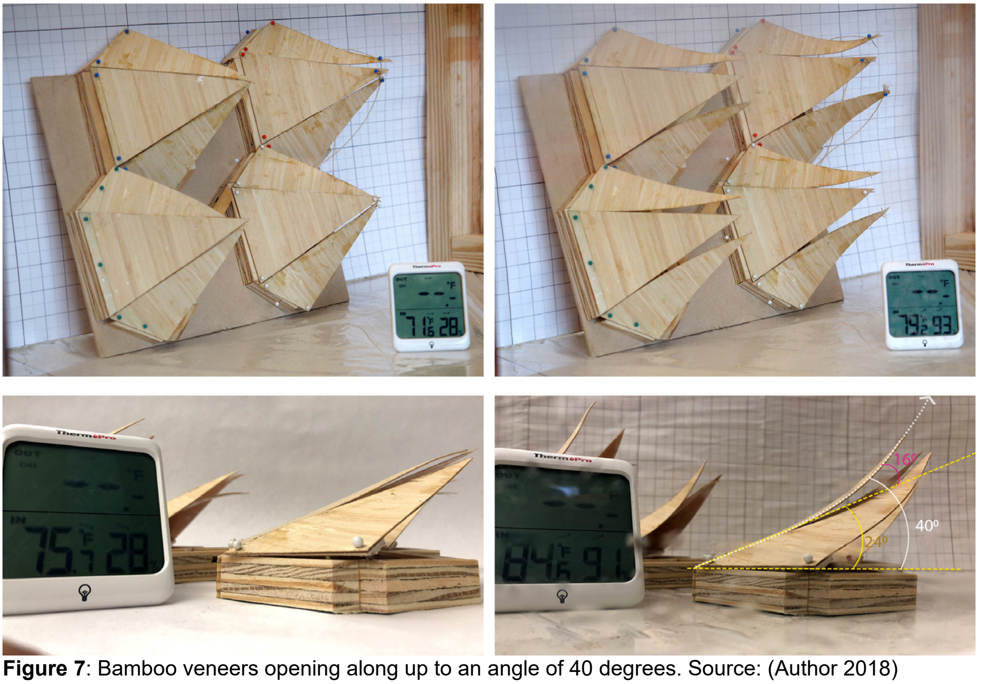

Figure 7: Bamboo veneers opening along up to an angle of 40 degrees. Source: (Author 2018)

What is interesting to note is the behavior of the triangular veneers at a micro scale. At high humidity, when the veneers reached their most ‘open’ state the maximum angular difference was observed to occur in the middle of the triangles. The veneer would begin to increase its deformation angle from the base of the triangle and arrive at a maximum difference in the middle, after which it goes up and down in its angular differences as it moves toward its apex. The observation, although unpredictable, was confirmed after repeating the same experiment multiple times. (Fig.8)

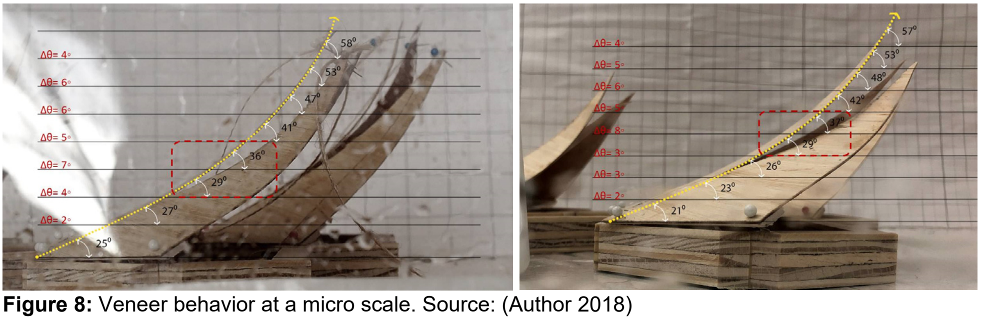

Figure 8: Veneer behavior at a micro scale. Source: (Author 2018)

The resultant façade design would have the veneers facing inwards toward the interior space when constructed on facade that face incoming fresh air, and outwards on facades facing outgoing used air. Since the three regions have incoming air from south-east, the southern façade will have veneers angled toward the inner space, whereas the northern and western façade, mostly utilized to expel air, will have veneers angled toward outside. On a micro scale, the former creates a shaded interior from southern solar exposure and the latter creates a shaded outer façade keeping it cool throughout the day, which is essential for west facing facades in warm-humid regions. Additionally, the former case where the veneers would face inward on the southern façade will create a venturi effect, forcing outside fresh air to come inside through smaller inlets into a much bigger interior space, thereby increasing wind speed leading to a cooler and more comfortable interior.

4.0 SCALE OF APPLICATION

While the veneers are expected to act as individual units that make up the adaptive façade, it can incorporate the pieces in varying scales. When the location and the context permit, the façade can act as an adaptive one entirely and create a stunning visual effect throughout the day, for example in the case of a museum lobby or an exhibition space where the architecture itself becomes a thing to 'see'. However, whenever the functional aspects of the façade is expected to dominate, the modules can act together as a component of certain size and shape instead of discrete units and be 'plugged-in' as a component itself. This will eliminate the need to construct the entire façade as an adaptive one if it gets in the way of furniture placement in the interior, and instead the particular component can be fitted in places where the wind direction is most favorable to allow a cross ventilation to take place.

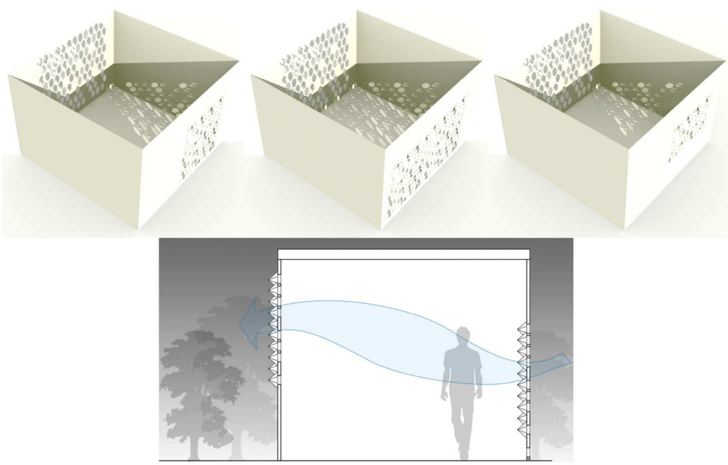

Figure 9: Possible scales of application of a hygroscopic façade system. Source: (Author 2018)

In terms of full-scale prototyping getting the initial angle of 25^0 integrated into the frame proved to be a challenge, which was later accomplished by using CNC-machine. Both sides of the frames were made angular so that one side helps to attach the veneers while the other side helps in giving a direction to enhance the angular airflow. Another challenge was the transition of mechanical fixing from simple pins to screws, which, when drilled through the composite, tended to detach the active and passive layers wherever the bonding would not be consistently applied.

5.0 FUTURE RESEARCH

The unique quality of responsiveness inherent in bamboo, coupled with its easy constructability, makes it a favorable material to investigate deeper into adaptive envelopes. Understanding the different potentials of the particular research it can be carried forward by manipulating the orientation of bamboo grains on a more micro level to further control the curvature of the bilayer composite. Similarly, instead of a homogenous cellulose film, passive layers with different grain directions can be juxtaposed with those of the active layer, possibly resulting in interesting and unpredictable results. One of the limitations to working with bamboo being its vulnerability to fungal attack, exploring adhesives that can double as preservatives against fungal and insect attacks will contribute to increasing the durability of the composite. However, when the material does start to degrade it will be easily replaceable, costing very little. Their impact as waste is also very low. Due to limitations of time the exploration of façade patterns needed to be finished at a certain point in order to move ahead with the later phases of the research but there is no denying that there is potential to generate more creative and sophisticated façade patterns with better performance, particularly in response to inclement weather including heavy rain, storm, hurricane and so on. Moreover, using a monitoring and tracking system to monitor the deflection in the composites more accurate results could be achieved. Apart from veneer deflection, material degradation, fading of color and strength of the bonded composite could also be monitored over a one-year period to assess their long-term performance. The motion sensing method to track the hygroscopic response in wood samples in real-time by Abdelmohsen et al. (2018) can be adopted to express the physical material on a computational interface to get accurate measurements.

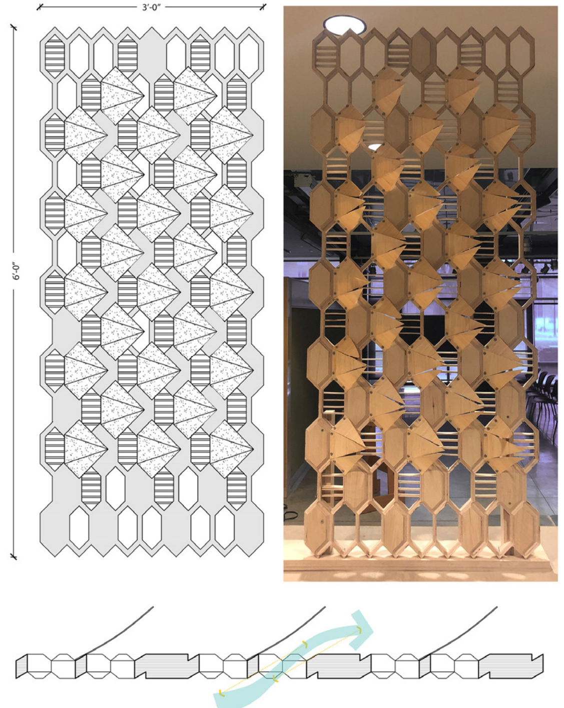

Figure 10: Full scale prototyping. Source: (Author 2018)

CONCLUSION

Up until very recently, facades in architecture that are able to adapt themselves in response to changing climatic conditions had typically been identified with having high-tech complex automated mechanisms, using electronic sensors and actuators. The low-tech and no-tech passive strategies of adaptive façade design based on material responsiveness were still in their infancy. Passive strategies minimize energy and material use while maintaining occupant comfort. This is precisely why such methods require a greater emphasis today as we investigate deeper into the realms of Responsive Architecture. It goes without saying that using natural heating, cooling and lighting reduces building energy use. But in today's drastically changing climate reliance on natural forces is not sufficient to maintain comfortable interior living conditions. We need building systems that have the ability to adapt to this changing environment. Extensive research has already begun exploring passive envelope systems using timber, even though bamboo, being a rapidly renewable, carbon sequestering plant, is the greenest material on the market. Bamboo is an incredibly sustainable alternative to wood that can be used to lessen our exploitation of rainforest trees. Because of its hygroscopic property it has a natural inclination to climate adaption that can be exploited to design climate-responsive façade systems with no added energy input. Native to Asia and South America and fast-growing, bamboo, as a material, has not been exposed to much experimentation as far as façade systems are concerned. As such, bamboo provides a greater potential in rethinking building facades as organic, breathable skins – rather than a highly mechanized barrier between human and nature.

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