PROGRAMMABLE SKINS

A HYGROMORPHIC APPROACH FOR LOW-COST ADAPTIVE BUILDING FAÇADES

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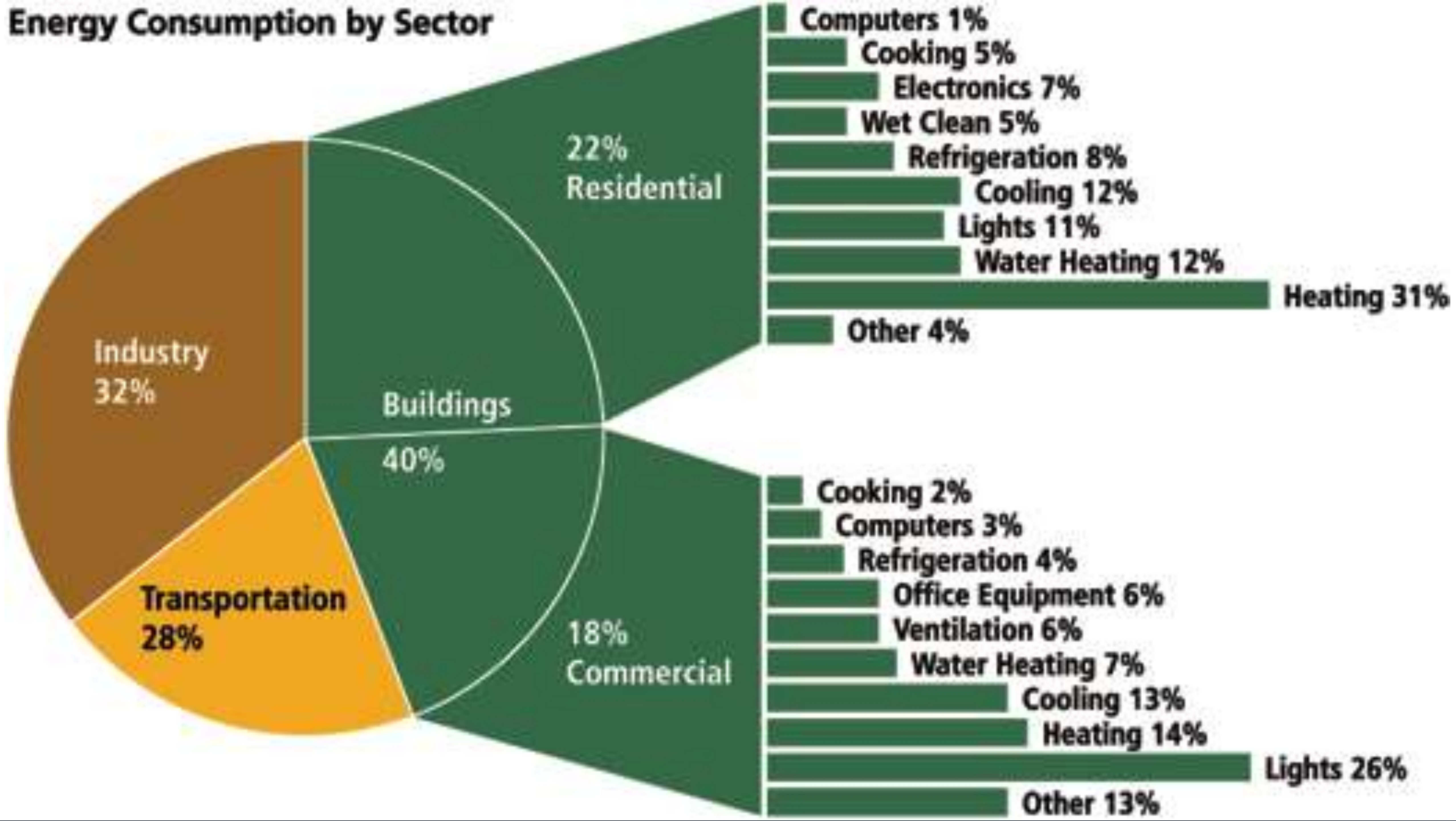
DEVELOPMENT, SECURITY, AND COOPERATION
Policy and Global Affairs

Background

The American University in Cairo

Department of Architecture, School of Sciences and Engineering



30% of greenhouse emissions

40% of energy consumption

As building skins act as filters regulating energy flow between building interior and exterior.

Conventional shading devices can decrease building annual cooling load by 20%.

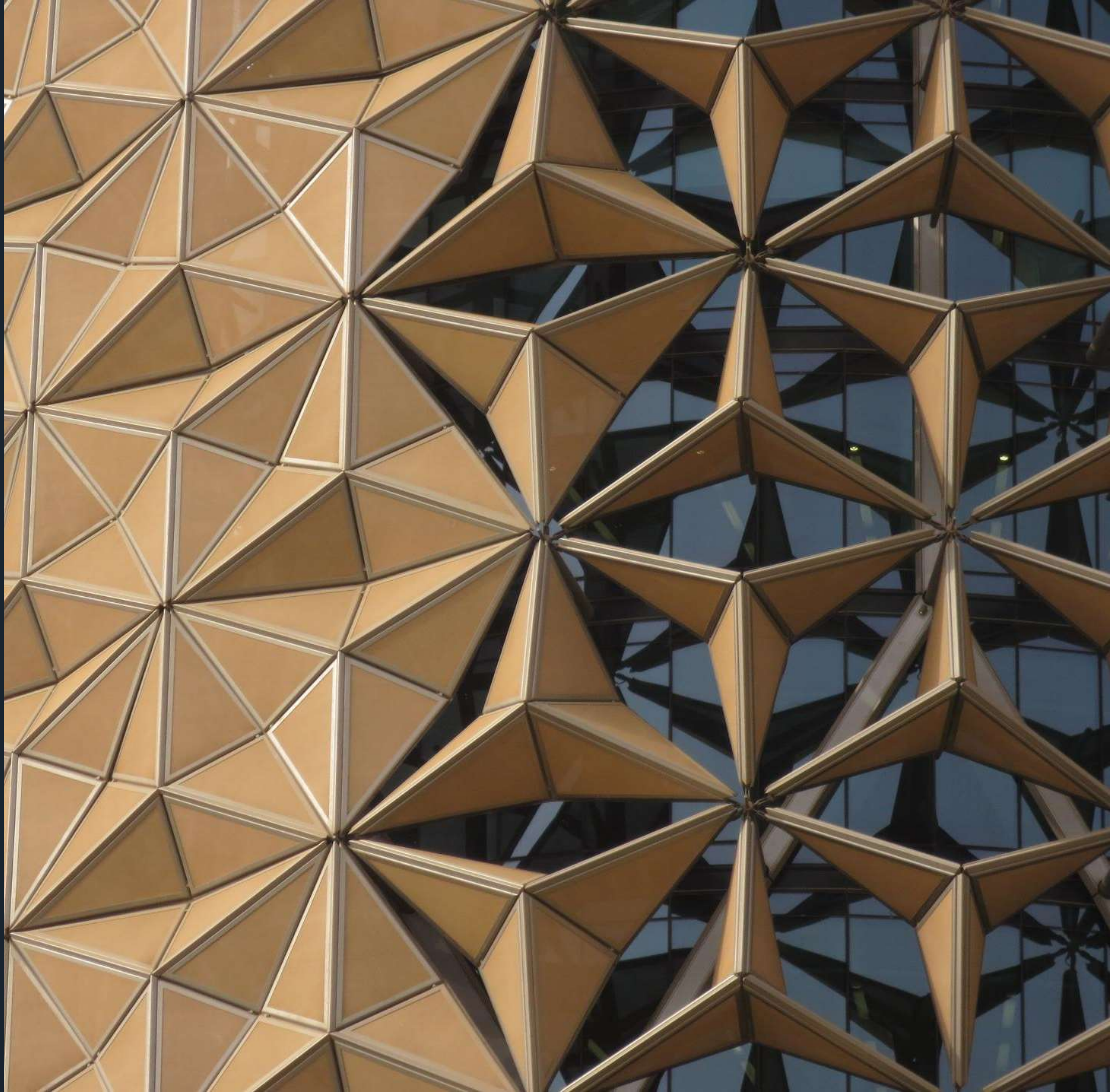
Most conventional devices exhibit performance deficiencies and demonstrate a need for adaptive building skins [shape shifting mechanisms] that respond to multiple variables including weather, context and space occupancy.

"Buildings and climate change: a summary for decision makers," United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris, 2009.

Why *Shape Shifting?*

The purpose of adaptive building skins is to actively moderate the influence of weather conditions on the interior environment of buildings.

Current adaptive skins rely on rigid body motions, complex hinges and actuation devices. These attributes are obstacles to their broader adoption in low-carbon buildings.



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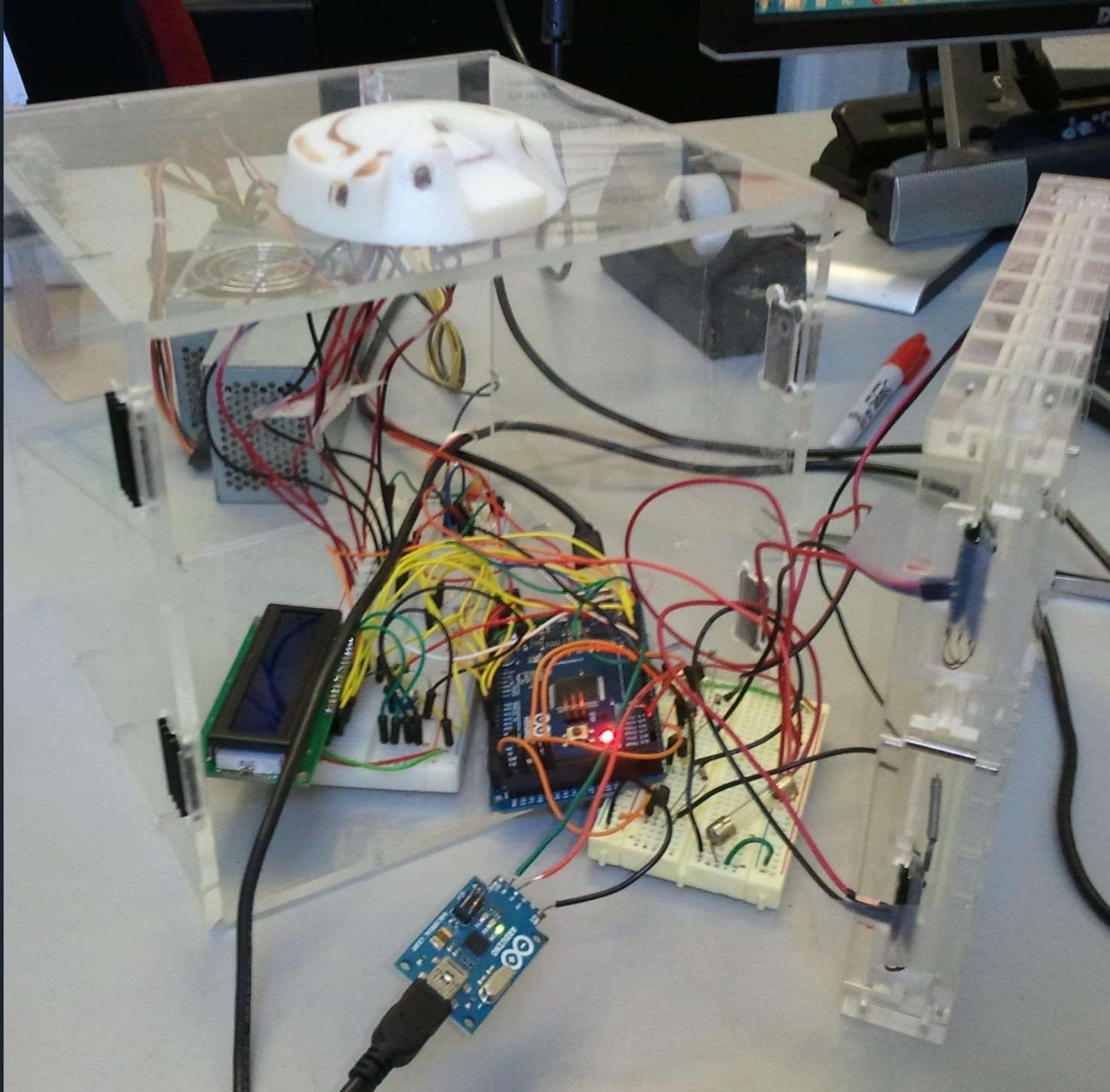


Why *Shape Shifting*?

The core idea of soft adaptive skins is that they exploit the systems’ elasticity to respond to stimuli.

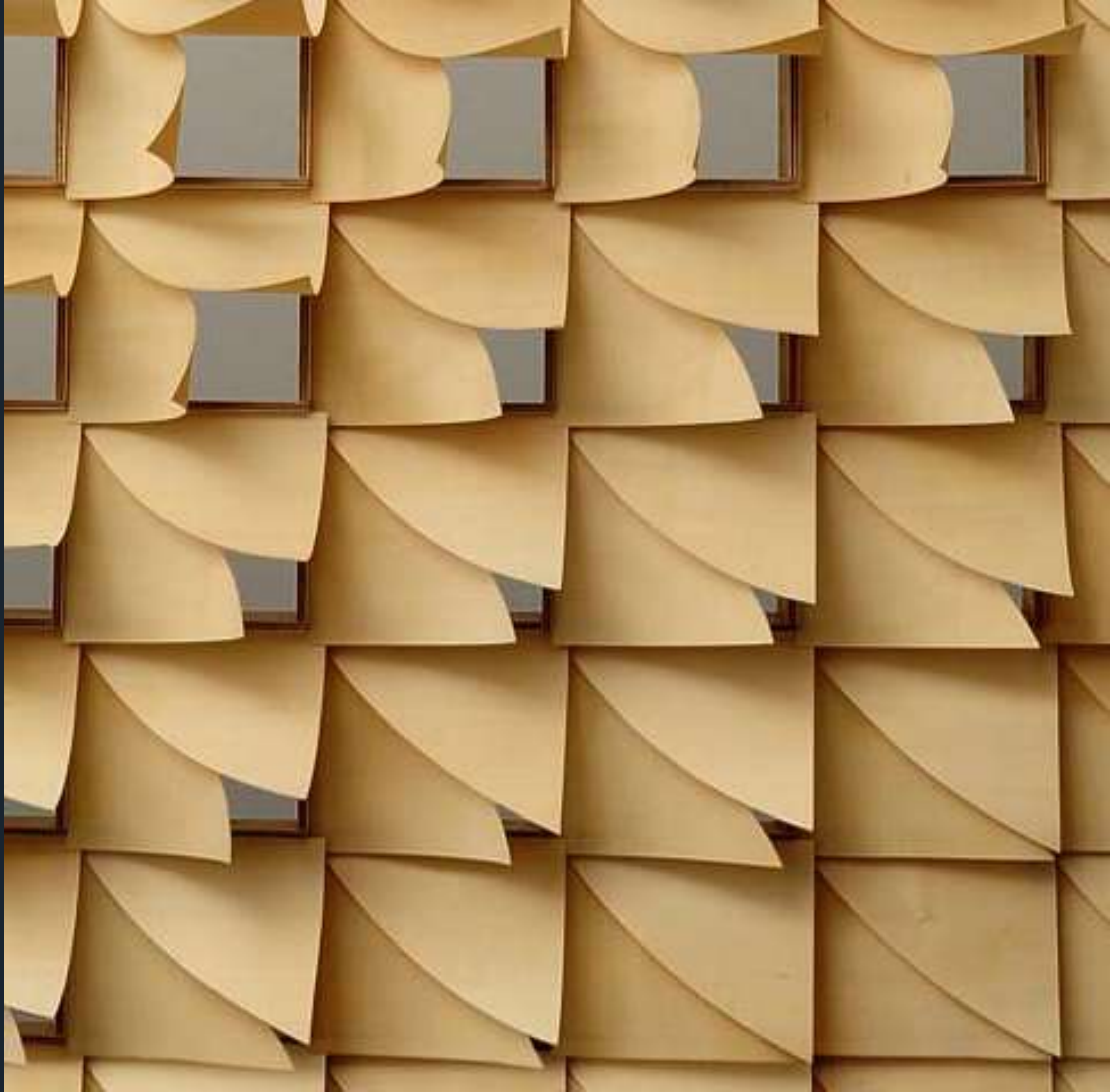
However, designing such a skin is a challenging task due to the interaction between geometry, elasticity and environmental performance.

If successful, these skins will reduce energy consumption in the construction industry.

Programmable matter is matter which has the ability to change its physical properties (shape, density, optical properties, moduli, conductivity, etc.) in a programmable fashion, based upon user input or autonomous sensing.

Moving to Hygroscopic

Wood tends to absorb moisture from the air when the relative humidity is high, and to lose it when the relative humidity is low. Moisture absorbed into the cell walls causes wood to shrink and swell as the moisture content changes with the relative humidity of the surrounding air.



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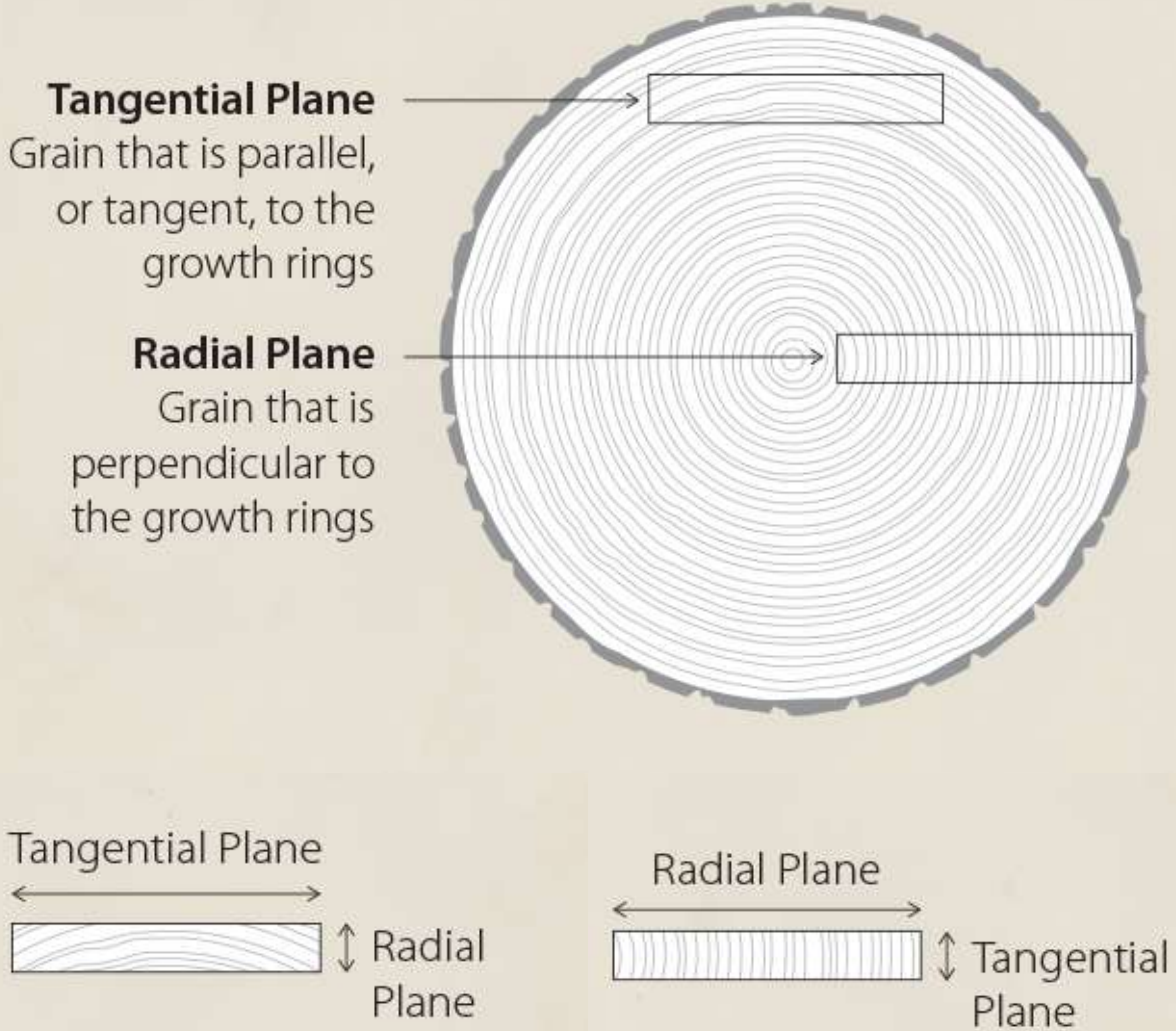
Moving to Hygroscopic

Once all the parameters related to moisture content, humidity, grain orientation, and the shrinking and swelling of wood are known and can be modeled, a regulated and adaptive scenario of controlled movement of wood, bilayers and laminated timber can be generated, leading to a soft responsive skin, without the use of complex hard mechanical procedures or equipment.



Moving to Hygroscopic

Physics Modeling

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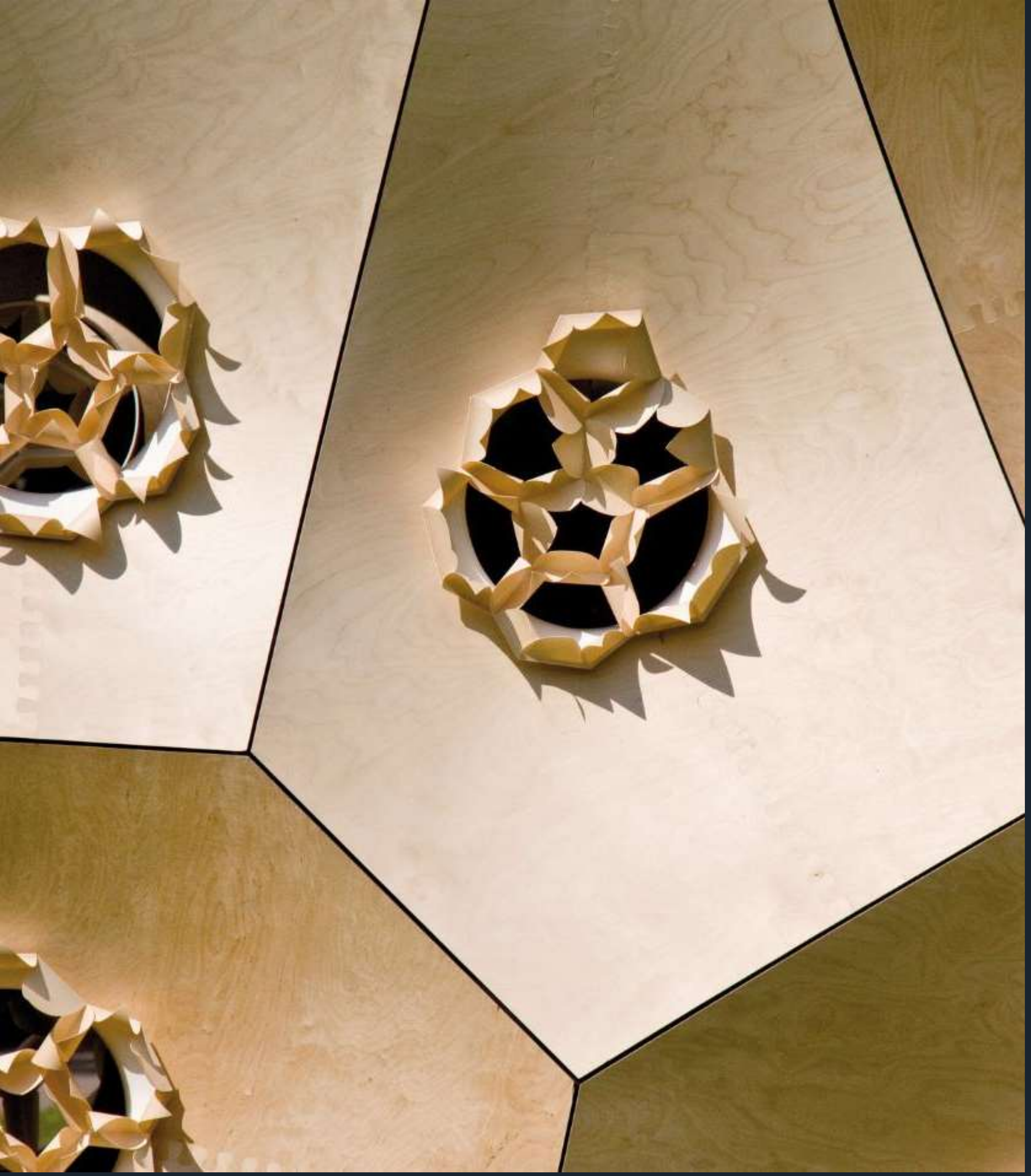
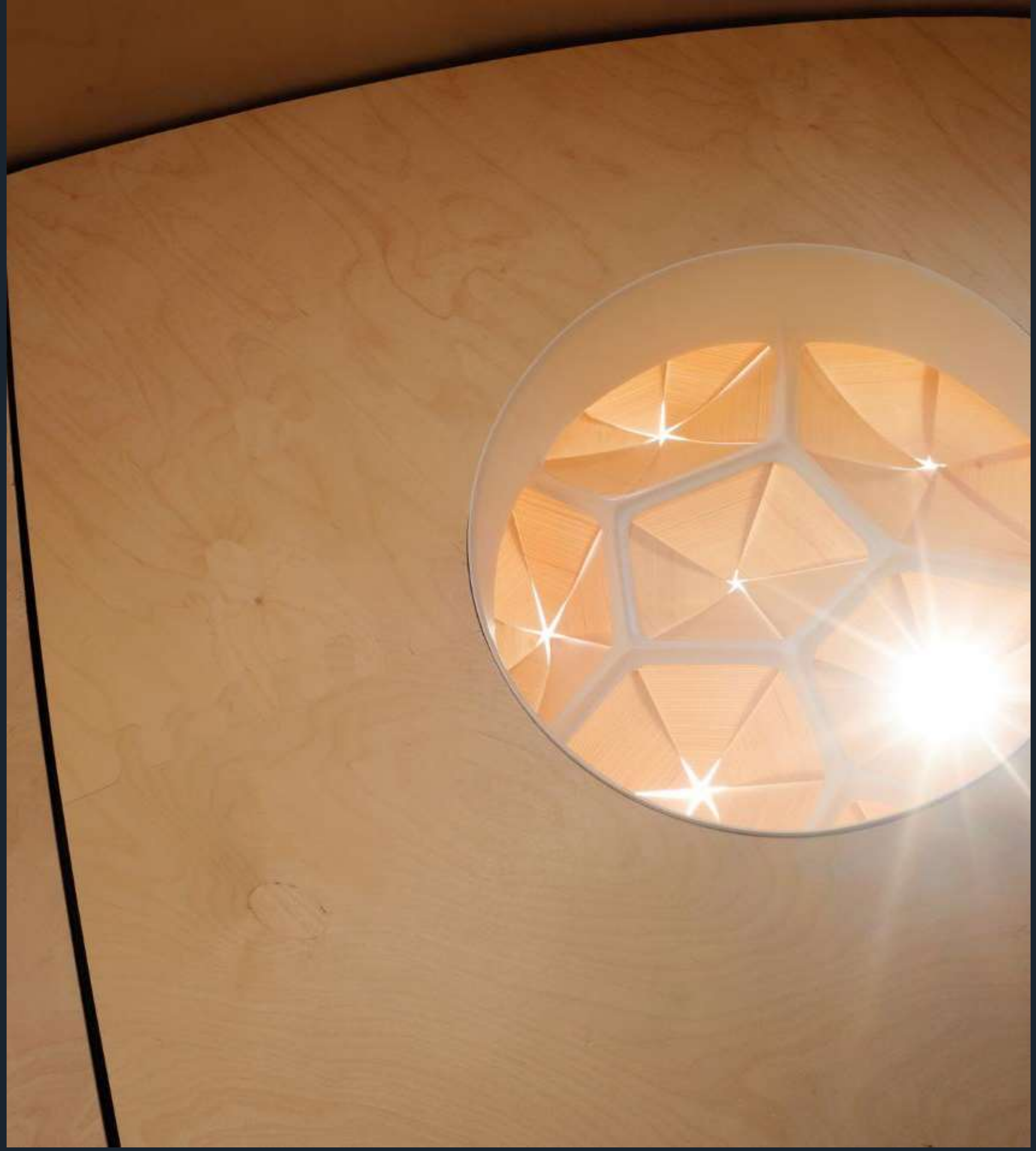
Inspirations

Hygroscopic behavior of wood

The behavior of different types of wood in reaction to varying levels of humidity in the surrounding environment at the interface between the exterior and interior of a space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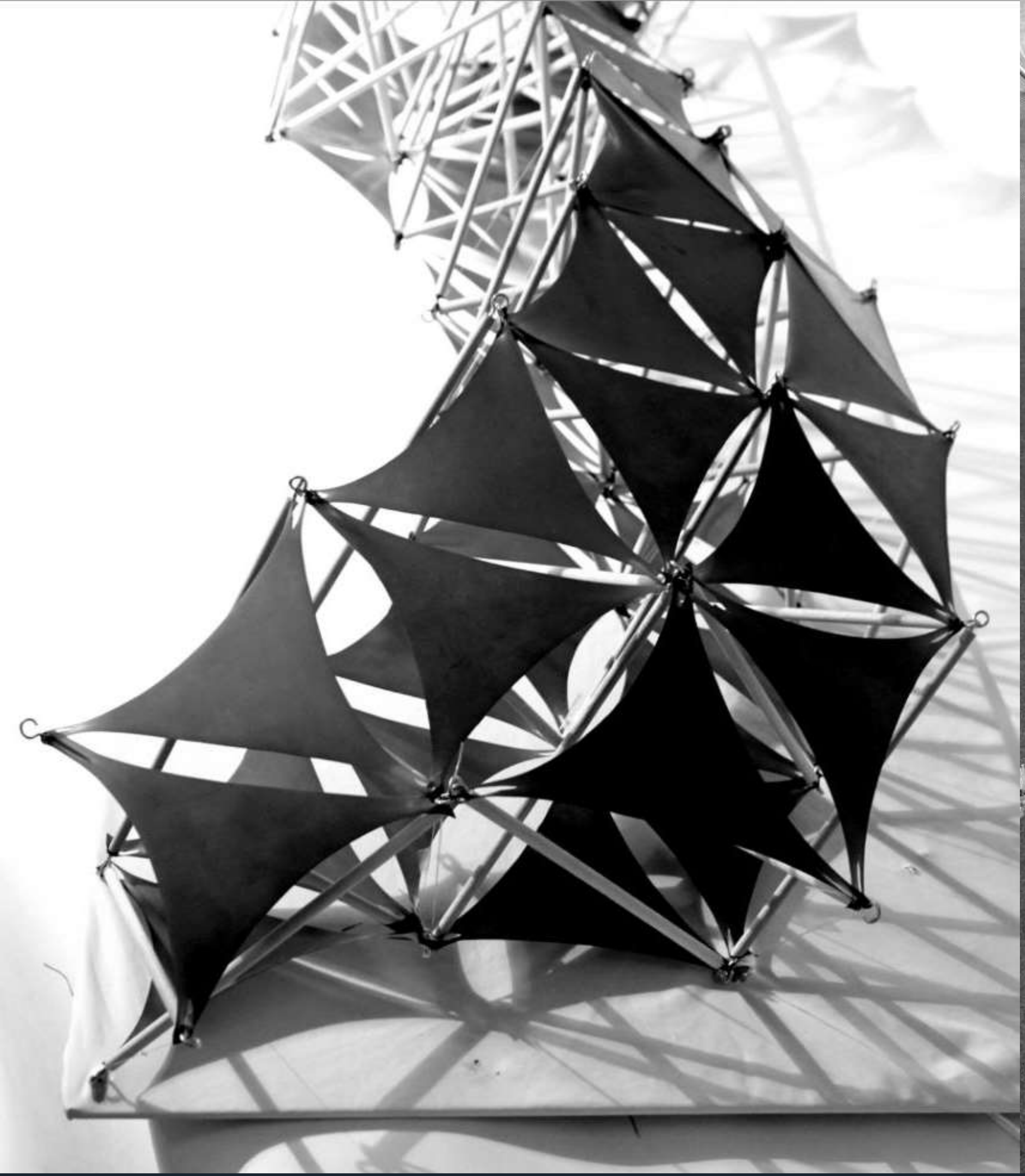
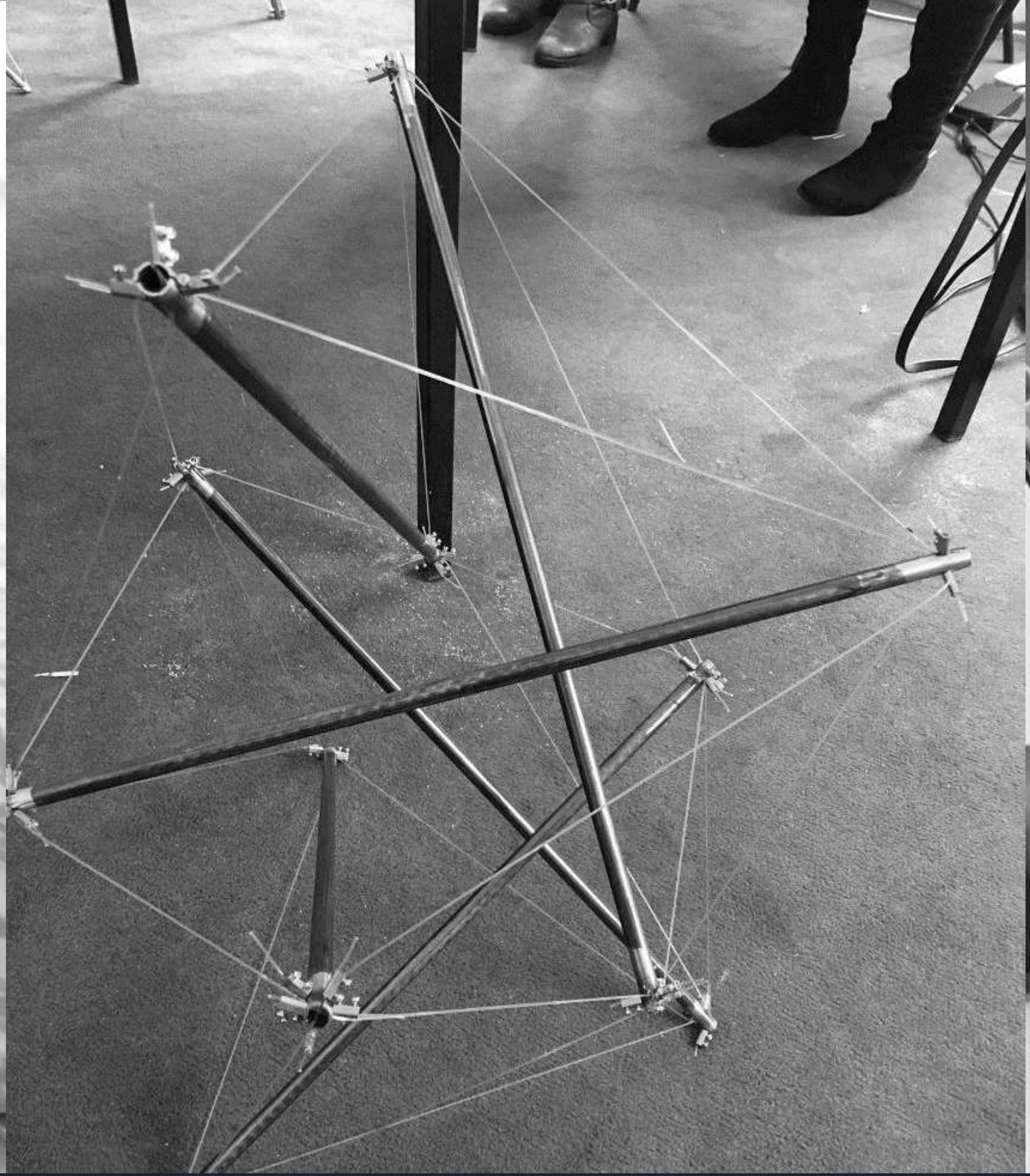
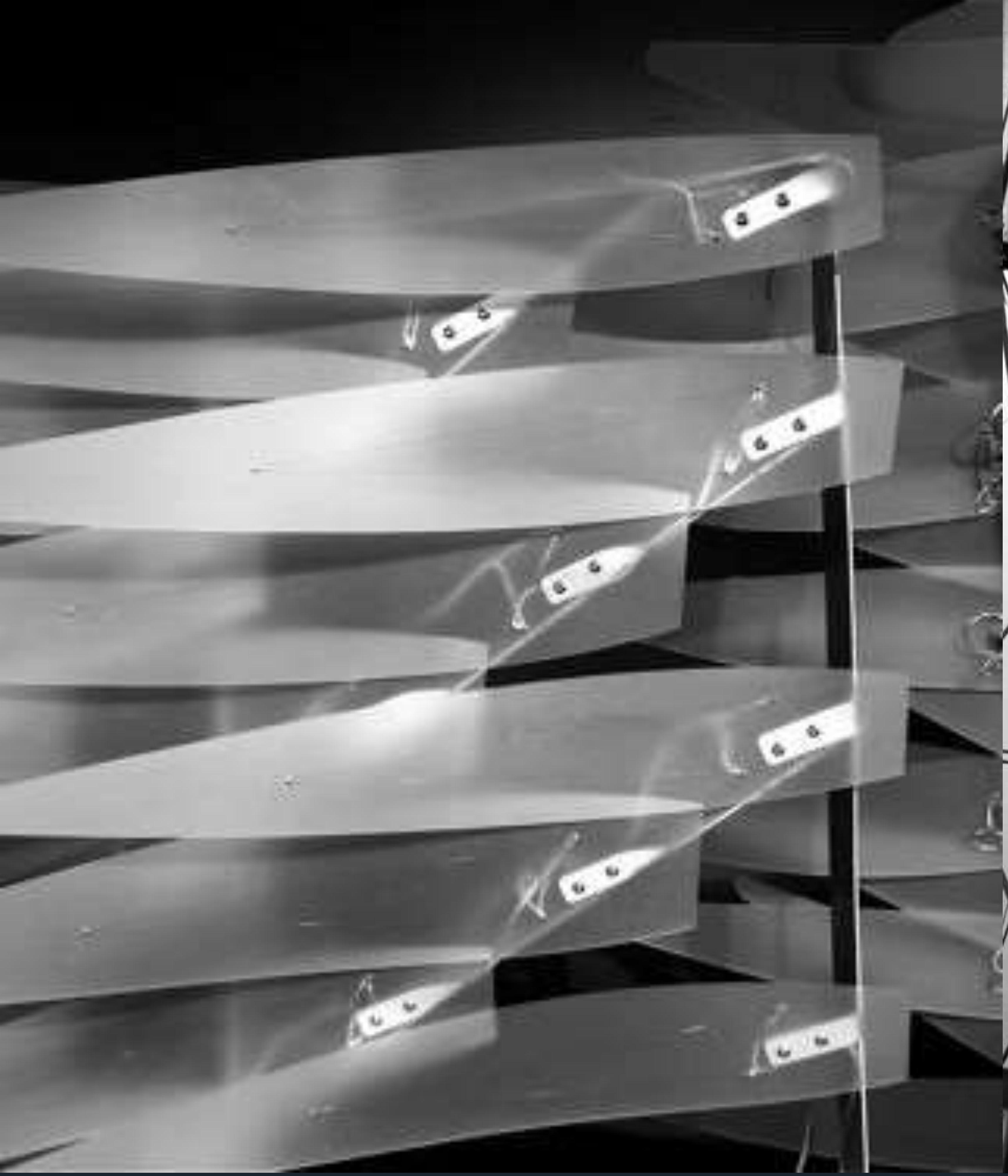
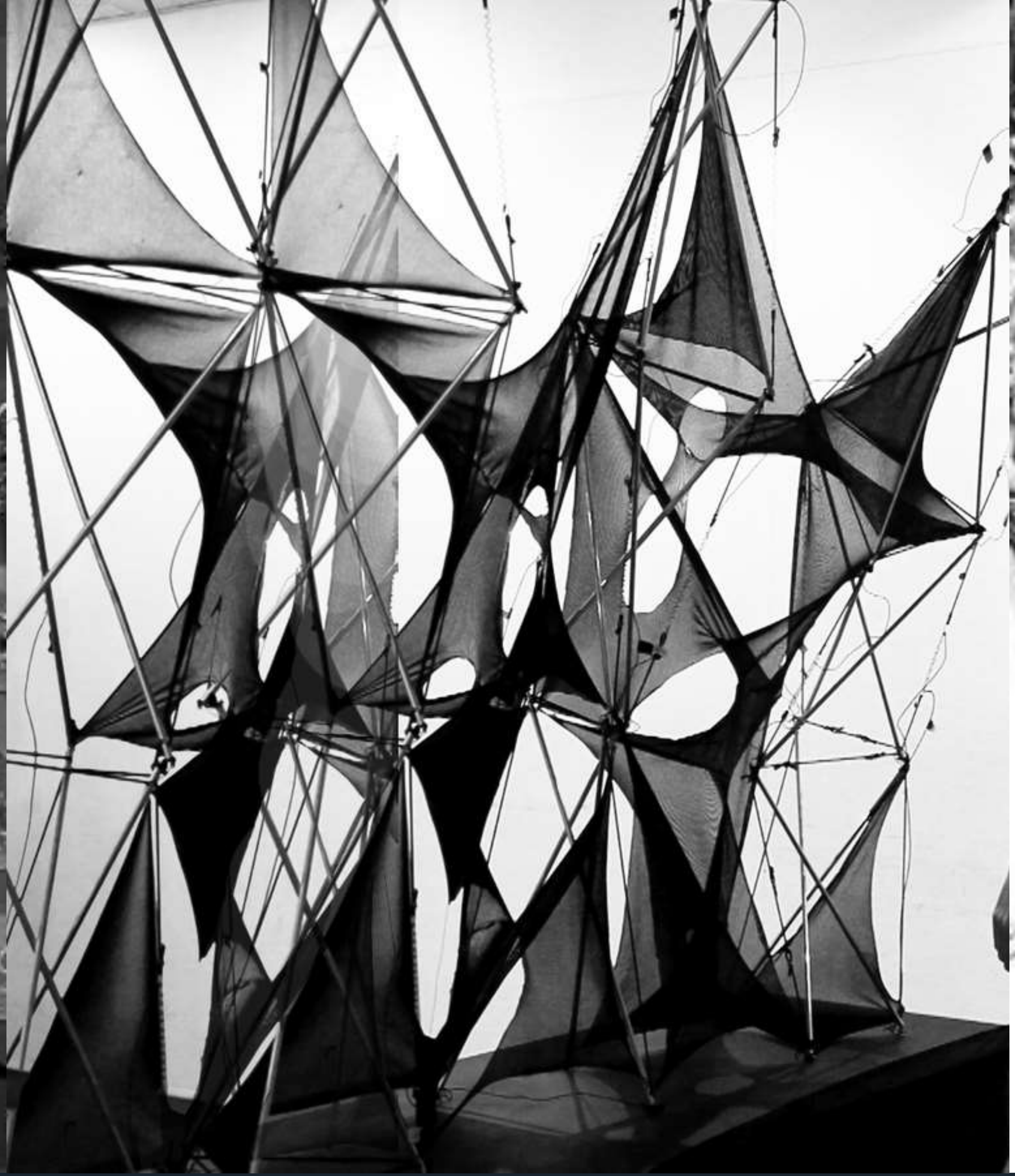




Inspirations

Lightweight and Tensegrity Structures

Tensegrity and lightweight structures with the core principle of isolated components in compression in a continuous network under tension


Inspirations

Shape Memory Alloys

Structures and materials that "remember" their original shape and when deformed return to their pre-deformed shape when heated

Early Experiments

Testing with different veneer samples

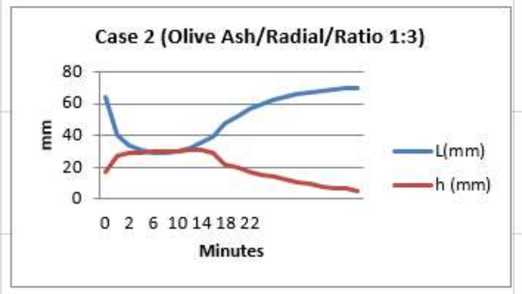
Samples

The behavior of several samples of ash and beech veneer with varying direction and orientation of grain was tested under the effect of wetting.

SAMPLE 1

Case 2: Olive Ash [Radial Cut/7cmX20cm]	L(mm)	h (mm)	θ	r (mm)	Temp. [C]	Humidity (%)	Time (min.)
	64.44	16.59	11.12	18.94062	23.2	37	12:23
	40.5	27.12	59	15.31269	23.4	37	12:34
	33.27	28.74	73.46	21.14455	23.6	39	12:35
	30.33	29.2	79.34	17.21115	23.7	40	12:36
	28.94	29.54	82.12	312.1002	23.8	40	12:37
	29.21	29.61	81.58	5763.518	23.8	41	12:38
	29.9	30.01	80.2	32.95153	23.8	40	12:39
	31.92	30.74	76.16	111.2201	23.9	40	12:40
	35.5	30.52	69	4617.512	23.9	40	12:41
	38.9	29.33	62.2	151.9173	23.9	40	12:42
	47.17	21.55	45.66	19.47225	23.9	40	12:43
	51.85	19.27	36.3	23.24045	24.1	40	12:44
	56.5	16.69	27	12.91657	24.1	40	12:45
	59.21	15.08	21.58	7.867844	24.1	40	12:46
	62.01	13.77	15.98	7.013967	24.1	40	12:47
	63.89	11.95	12.22	201.2158	24.2	40	12:48

Sample

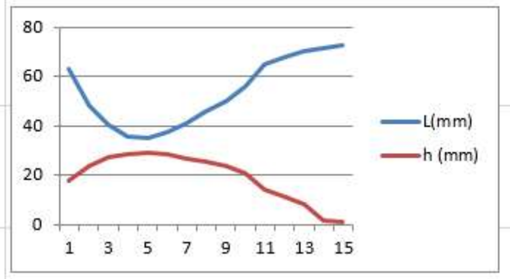


SAMPLE 2

	Case 2a: Olive Ash [Radial Cut/7cmX20cm]	L(mm)	h (mm)	θ	r (mm)	Temp. [C]	Humidity (%)	Time (min.)
		63.29	17.74	12.53061	27750.73	19.8	51	4:16
L initial	69.43	48.01	23.73	43.71429	664.6948	19.8	51	4:17
D	0.49	40.6	27.29	58.83673	16.46624	19.8	51	4:18
		35.92	28.82	68.38776	113.9055	19.8	51	4:19
		35.15	29.02	69.95918	86.46435	19.8	51	4:20
		37.48	28.65	65.20408	16.67294	19.7	51	4:22
		40.94	26.61	58.14286	26.00179	19.7	51	4:24
		45.62	25.5	48.59184	23.12572	19.8	51	4:25
		50.23	24.03	39.18367	26.29471	19.8	51	4:27
		55.87	20.9	27.67347	11.45301	19.7	51	4:29
		64.92	14.36	9.204082	7.268143	19.6	50	4:31
		67.9	11.14	3.122449	5.57051	19.6	50	4:33
		70.62	8.18	-2.42857	4.657282	19.5	50	4:35
		71.8	1.55	-4.83673	1.769458	19.6	50	4:37
		72.8	0.95	-6.87755	5.539483	19.6	50	4:39
		72.96		-7.20408	0	19.6	50	4:41

Sample

Graph



Early Experiments

Testing with different veneer samples

Samples

The behavior of several samples of ash and beech veneer with varying direction and orientation of grain was tested under the effect of wetting.

Early Experiments

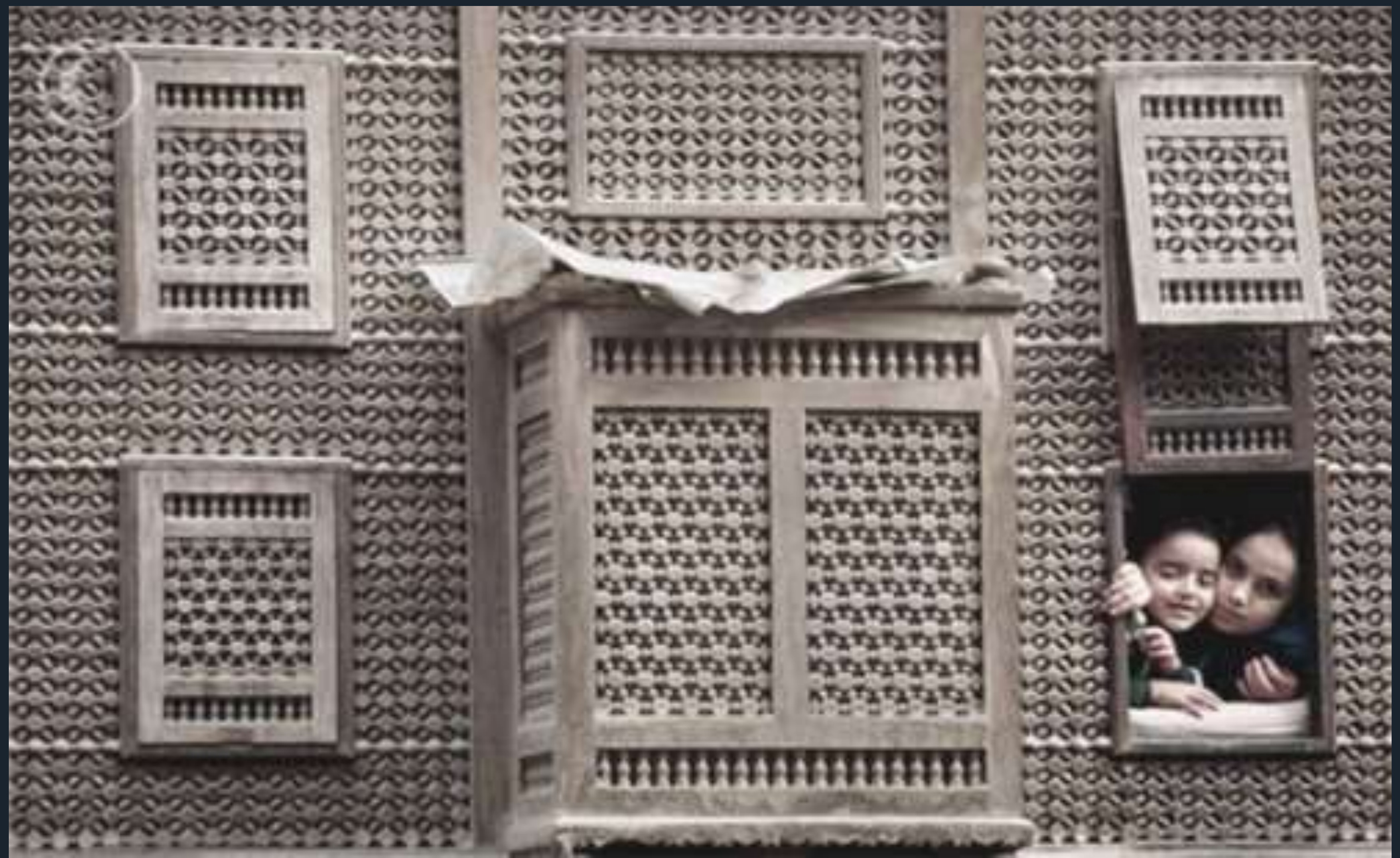
Experimenting with patterns on ash & beech veneer

Patterns

Several patterns and shapes were explored with different wood veneer samples and grain orientations

Precedents

The idea of the an adaptive shape shifting façade relied in its core on the parametric modeling of a prototype that mimics the behavior of the Islamic ***Mashrabiya*** in terms of *daylighting*, *ventilation*, and *visibility*, and features different behaviors of wood in different directions and orientations.



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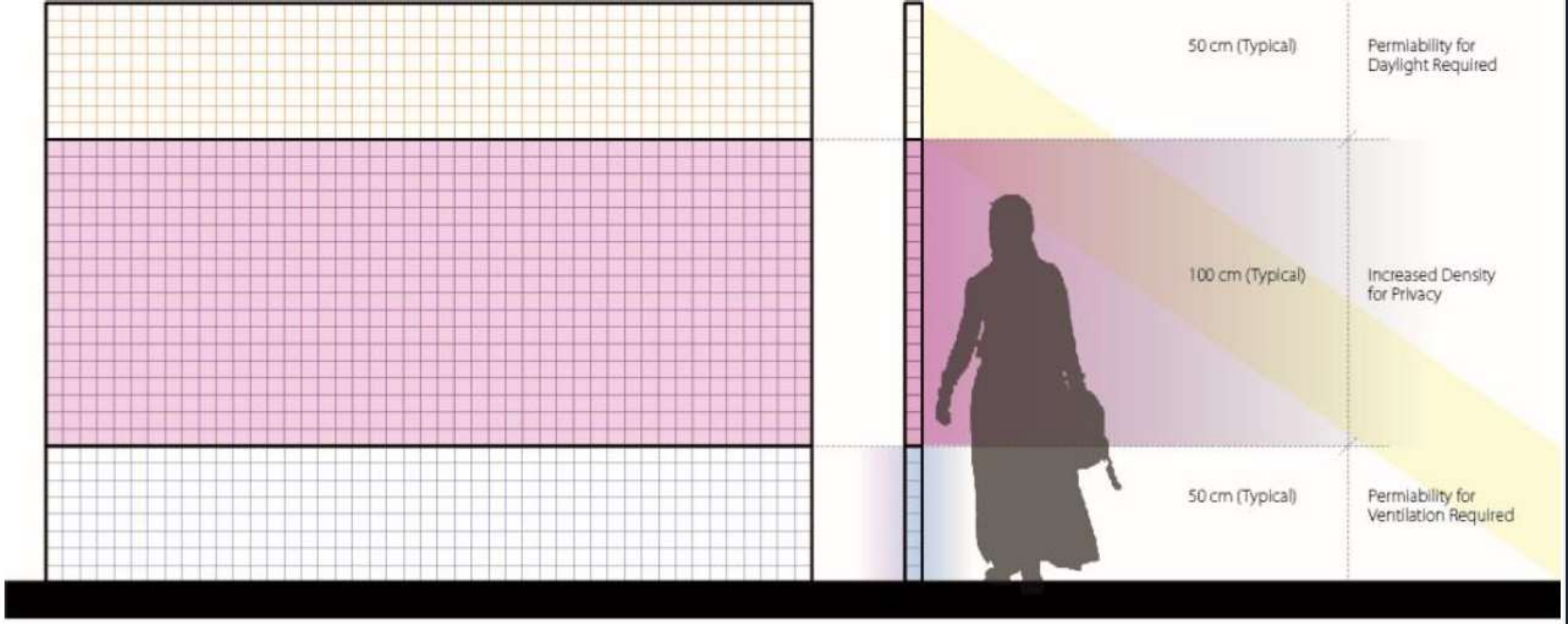

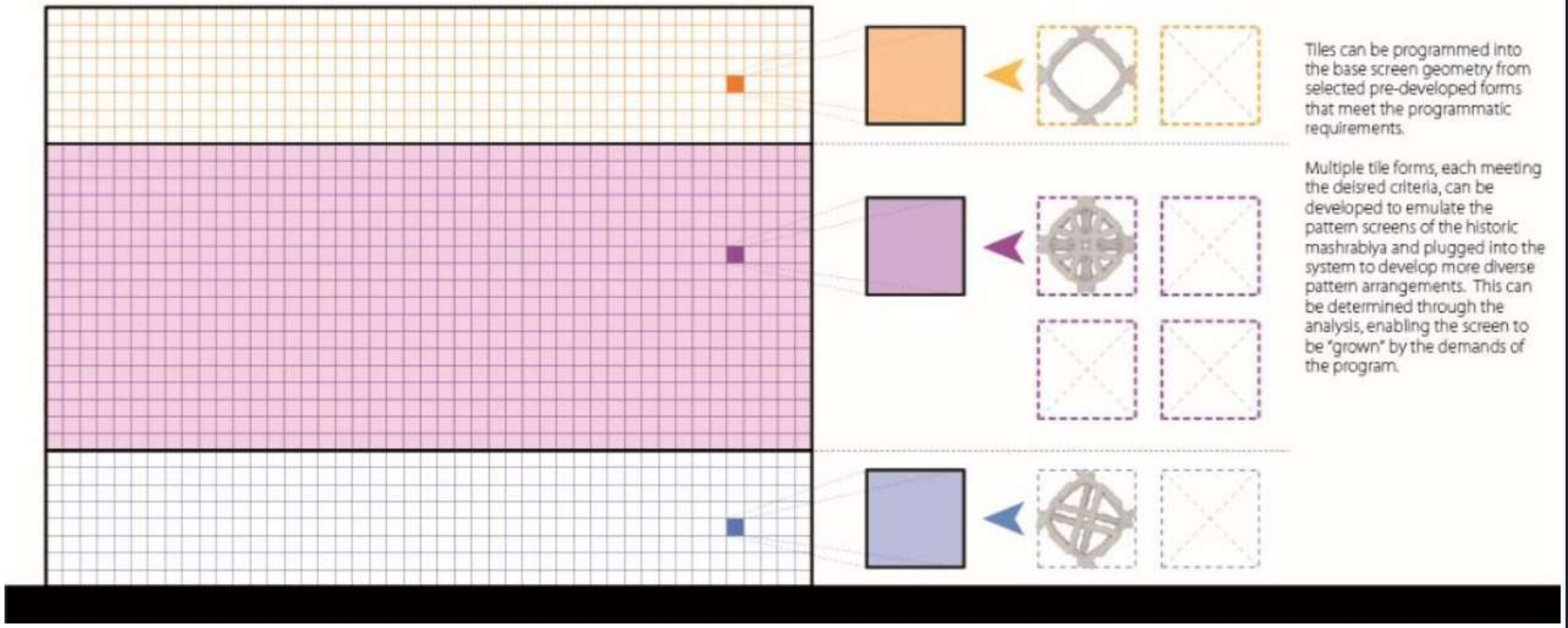

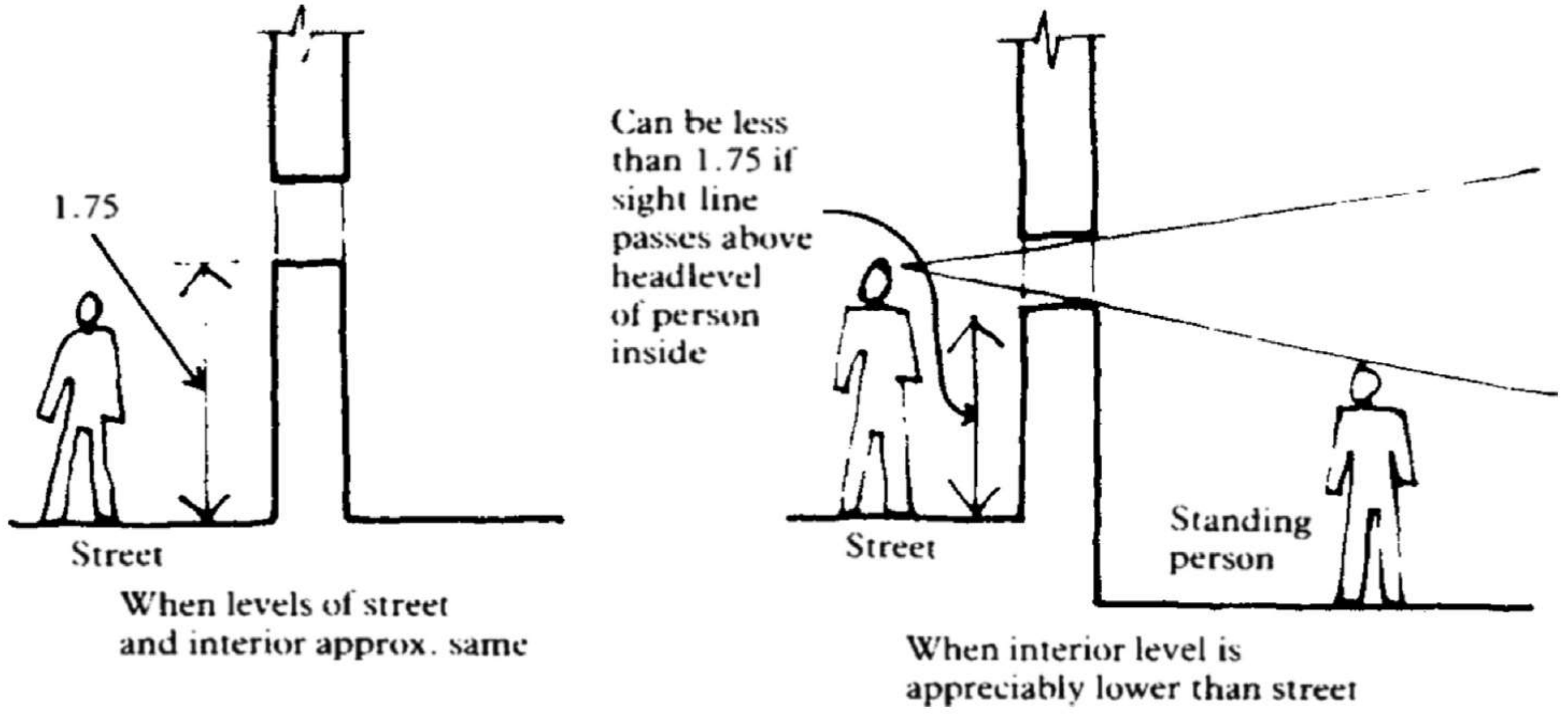

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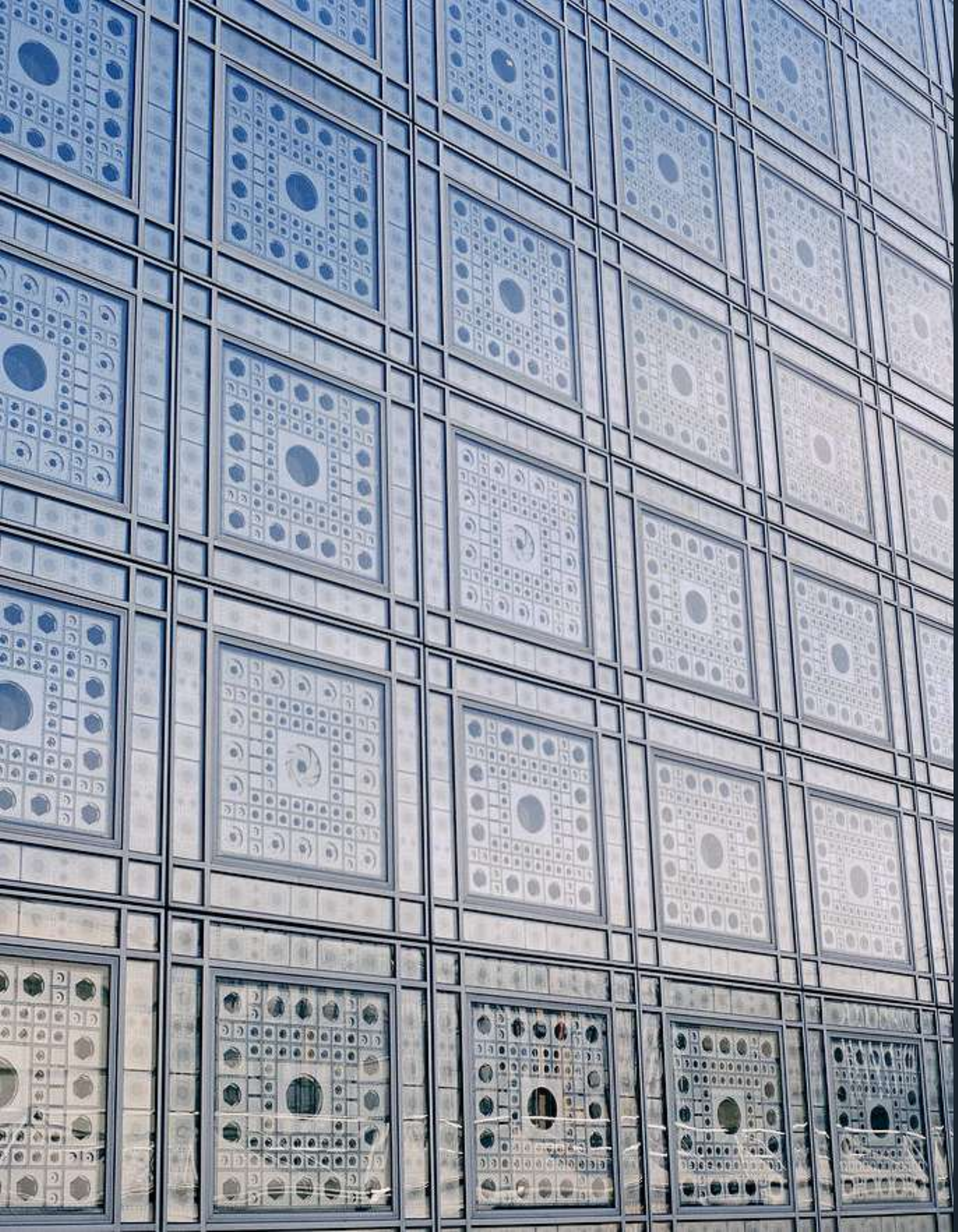

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L'Institut Du Monde Arabe | **JEAN NOUVEL**

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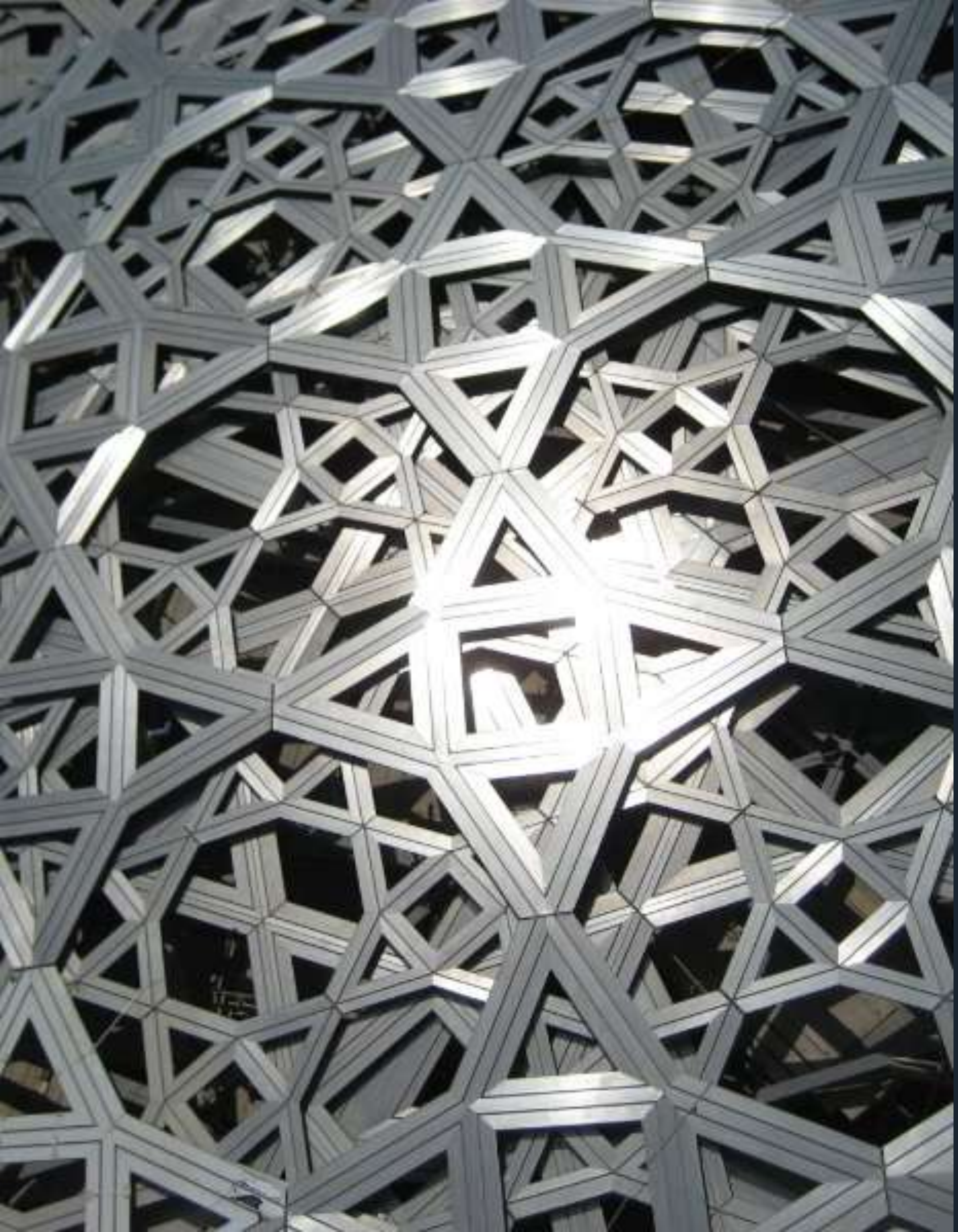
Abu Dhabi Louvre Museum | **JEAN NOUVEL**



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Programming wood initial configuration
Increasing moisture content
on single side of wood


Input Parameters
Identifying Hygroscopic Design Parameters
Types of wood (soft and hardwood)
Thickness of wood
Grain orientation
Moisture content in wood
Aspect ratio of sample
Form of wood sample
Multi layers fabrication Techniques
Analysis
Analytical Approaches
Physical Experimentations
Numerical Analysis
Methods for Evaluating the Response Motion
Tracking tangible Interface
Computational Interface
Computational Analysis
Output
Response Motion Parameters via Physical Experimentations
Speed response rate
Type of motion
Direction of motion
Architectural prototypes
Interactive skin prototypes
Full scale facades

Inputs (Hygroscopic Design Parameters)

Types of wood:
Softwood: Fir
Hardwood: Beech

Thickness of wood
Veneer (0.5 mm)

Grain orientation
Tangential

Moisture content in wood
Variable according to the humidity level in the chamber

Aspect ratio of sample
1:3 Length to width ratio

Form of wood sample
Rectangular form

Multi layers fabrication Techniques
Dry Lamination of two layers (Beech + Fir) using Polyurethane glue

Tracking / Analysis of Motion

1. Image Analysis System

2D Tracking Software

Angle of deflection in relation to variation in humidity levels through time

2. Sensing Motion mechanism

Smart Material Interface

Passive motion response of material to the external Stimuli

Tangible Interface

Setting of the experiment (sealed humidity chamber, Flex sensor, Arduino kit)

Digital Interface

Firefly Plugin to connect the Arduino processing unit to Grasshopper script.

Tools

1. Image Analysis

Video Camera

Kinovea Software

2. Physical Experiment setting

Sealed Humidity Chamber

Humidity / Temperature sensor

Flex sensors

Arduino kit

3. Grasshopper

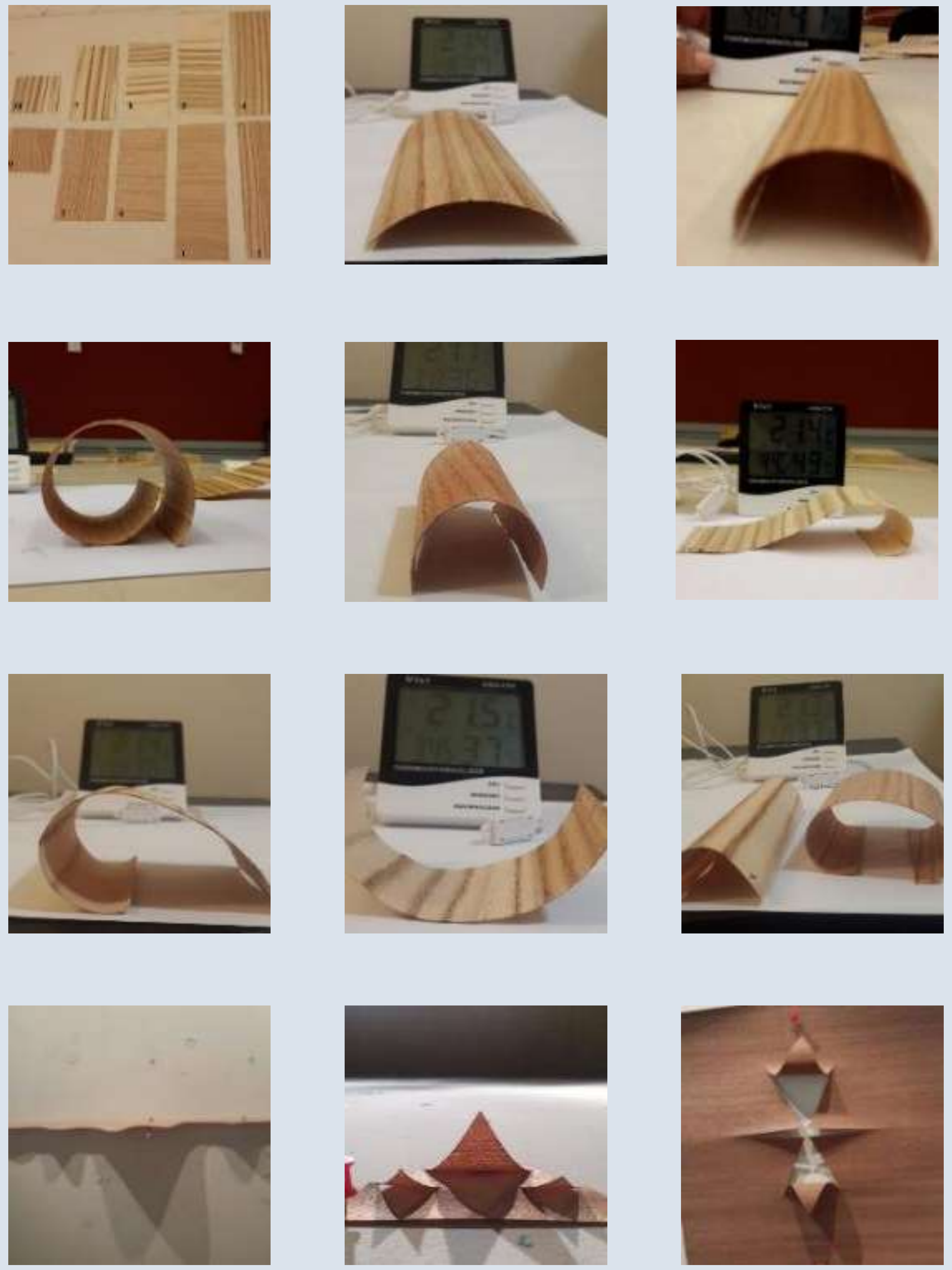
Firefly plugin

Firefly Plugin to connect the Arduino processing unit to Grasshopper script to measure and record the angle of deflection

Soft Adaptive Building Skins for Energy Efficient Architecture

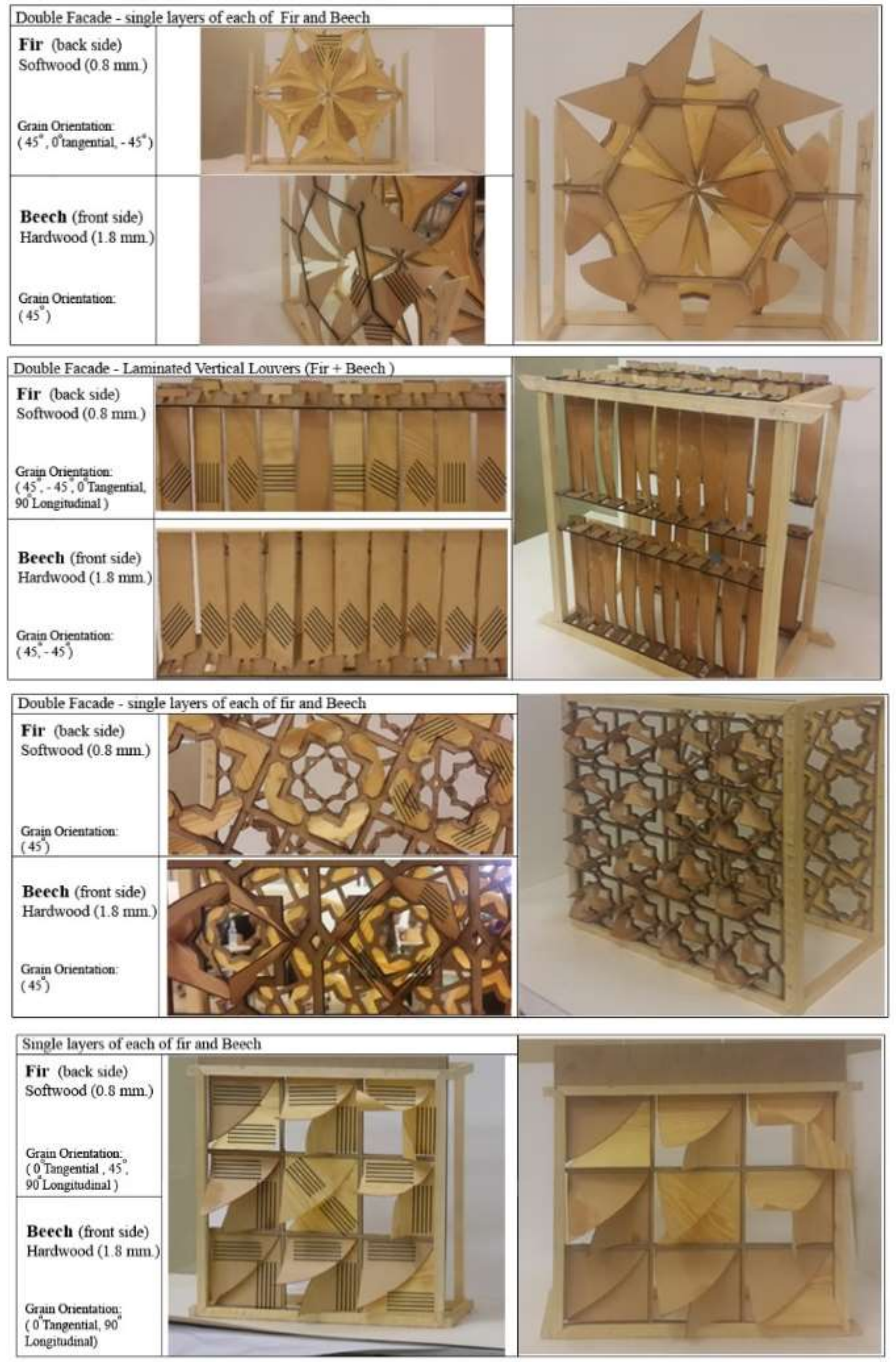
[AUC/Princeton – Bartlett Family Fund]

Sherif Abdelmohsen, Sigrid Adriaenssens, Stefano Gabriele



Hygromorphic behavior of wood veneer samples

Parametric exploration of shape shifting facades



Experimenting with grain orientation & lamination

Abdelmohsen, S., Adriaenssens, S., El-Dabaa, R., Gabriele, S., Olivieri, L. and Teresi, L. (2019), Programmable Matter: A Multi-Physics Modeling Approach for Low-Tech Architectural Adaptive Systems using Hygroscopic Properties of Wood, *Computer-Aided Design*, 106 (43-53).

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Wood is a natural engineering material that has traditionally been exploited in design for a wide variety of applications. The recent demand for sustainable material and construction processes in the construction industry has triggered a renewed interest and research in the inherent properties of wood and their derived applications, and specifically for developing low-tech architectural adaptive systems. This paper focuses on the physical and computational modeling of the morphing behavior of wood through hygroscopic expansion or contraction to a high degree of precision. This hygroscopic shrinking and swelling does not induce mechanical stresses in wood, and thus alleviates any fatigue challenges. This property is beneficial for any engineering application subjected to a repeated reversal of loading such as adaptive systems. Current calculation models do not simulate the actual water diffusion process that causes the swelling in all three wood grain orientations (i.e. the radial, longitudinal and transverse directions). Nor do they incorporate changes in mass density due to water absorption. In this paper, a multi-physics numerical model is presented with parameters that have a physical meaning. The control parameter in the model is the relative moisture change in wood, that determines the orthotropic swelling (shrinking) phenomenon and interacts with the elastic behavior of wood. This model is integrated into a programmable matter design approach that combines physical and computational exploration. The approach is illustrated for a hygromorphic building façade panel. The approaches and algorithms presented in this paper have further applications for computer-aided design of smart materials and systems with interchanging functionalities.

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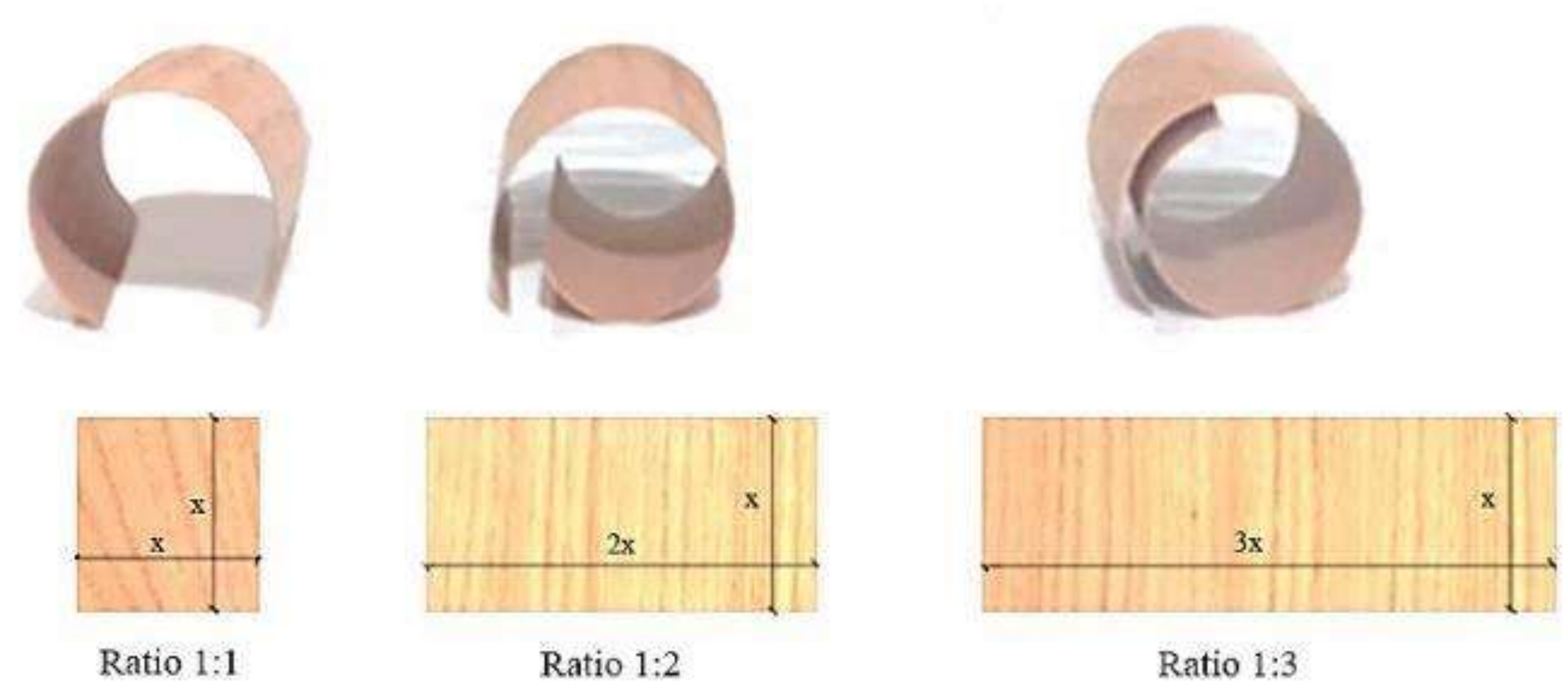
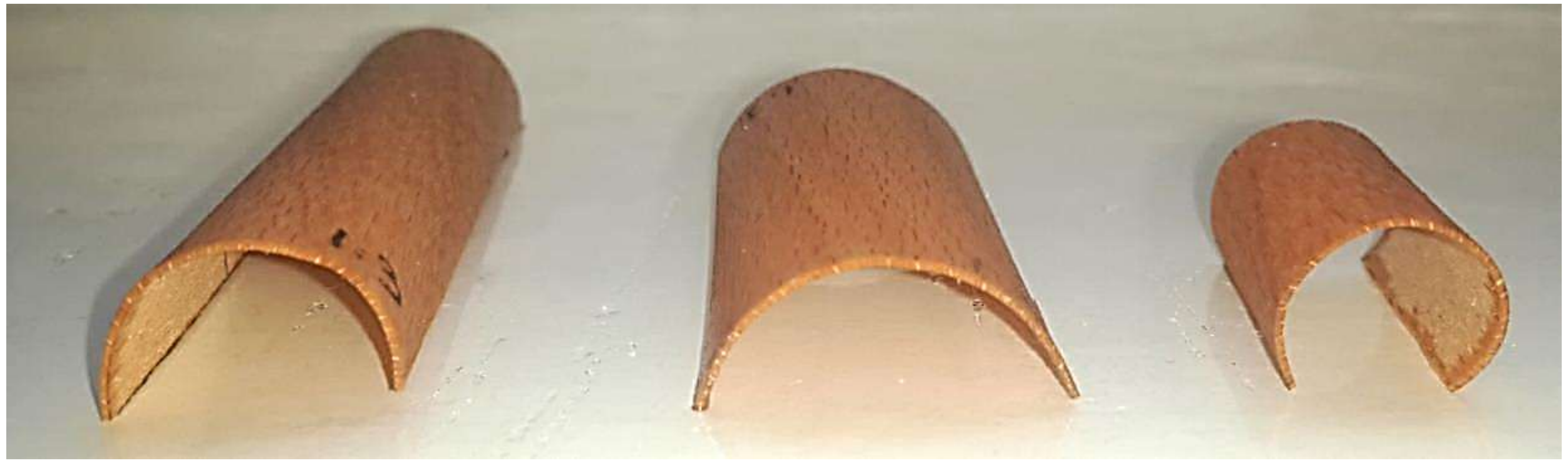
Time lapse for wood response during increase in moisture content



Maximum deflection values in three Tangential beech veneer samples with different aspect ratios



Maximum deflection values in three longitudinal beech veneer samples with different aspect ratios

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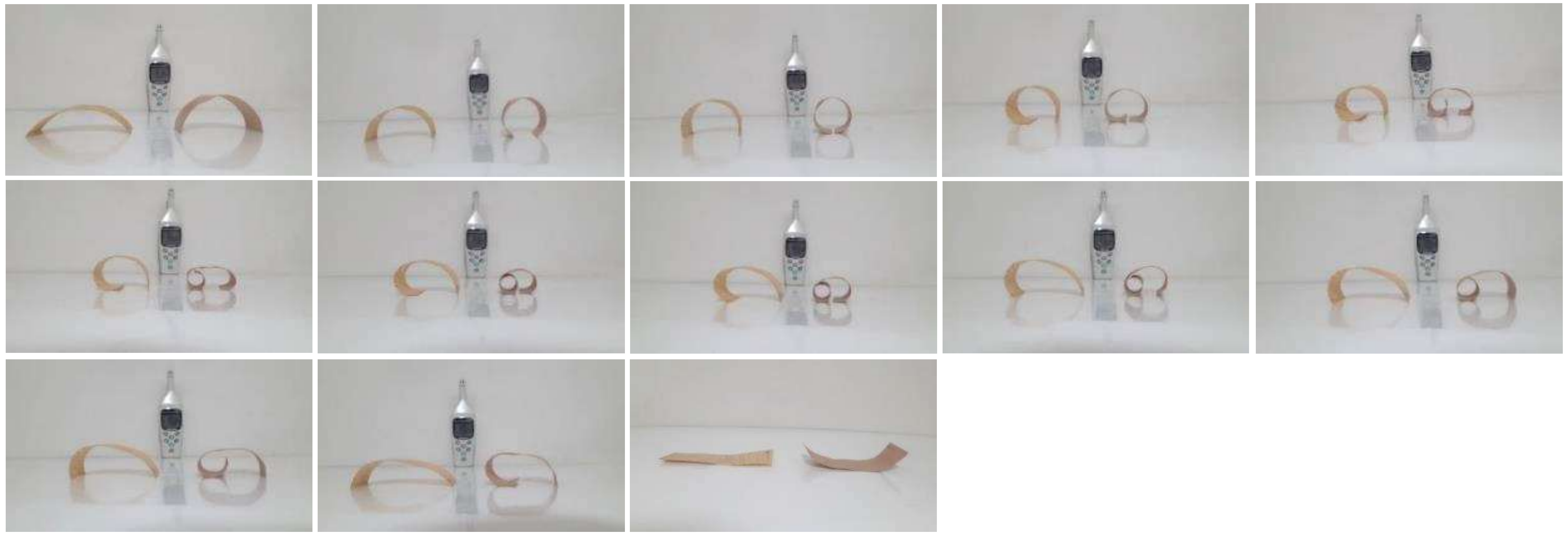
Sample used	**Beech veneer (right)**	**Fir veneer (left)**
Fiber orientation	Tangential	Tangential
Moisture content	6 %	6 %
Aspect ratio	1:3 (15*5 cm)	1:3 1:3 (15*5 cm)



Time-lapse images showing the response of a beech and fir veneer samples exposed to increase in humidity

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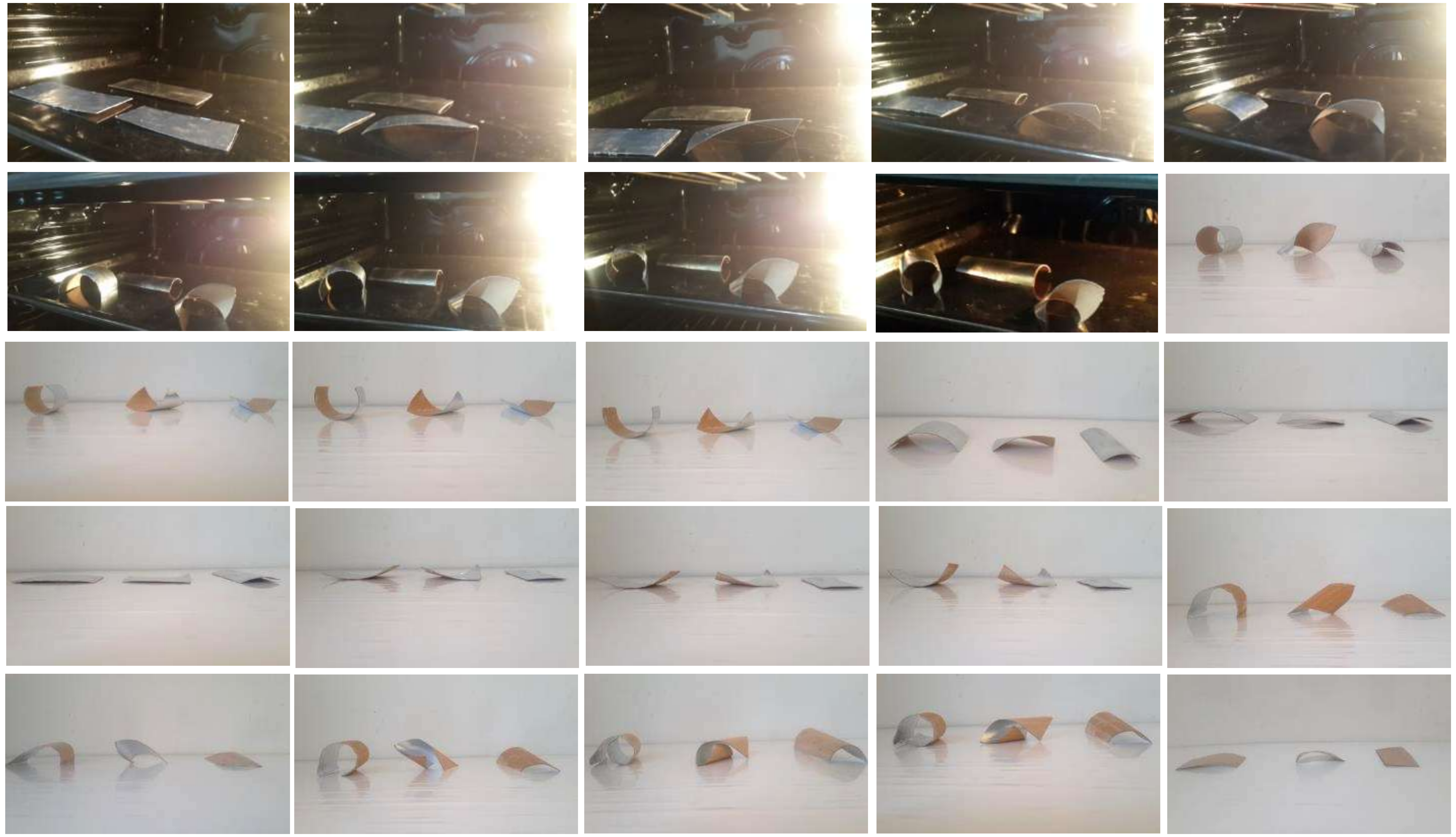
Sample used	**Beech veneer+ polyurethane Tidebond+ aluminum tape**
Fiber orientation	Tangential, 45, Longitudinal (left to right)
Aspect ratio	1:2 (10*5 cm) , while the 45 (8*4 cm)



Combining properties to achieve controlled motion (Beech veneer + aluminium sheet)

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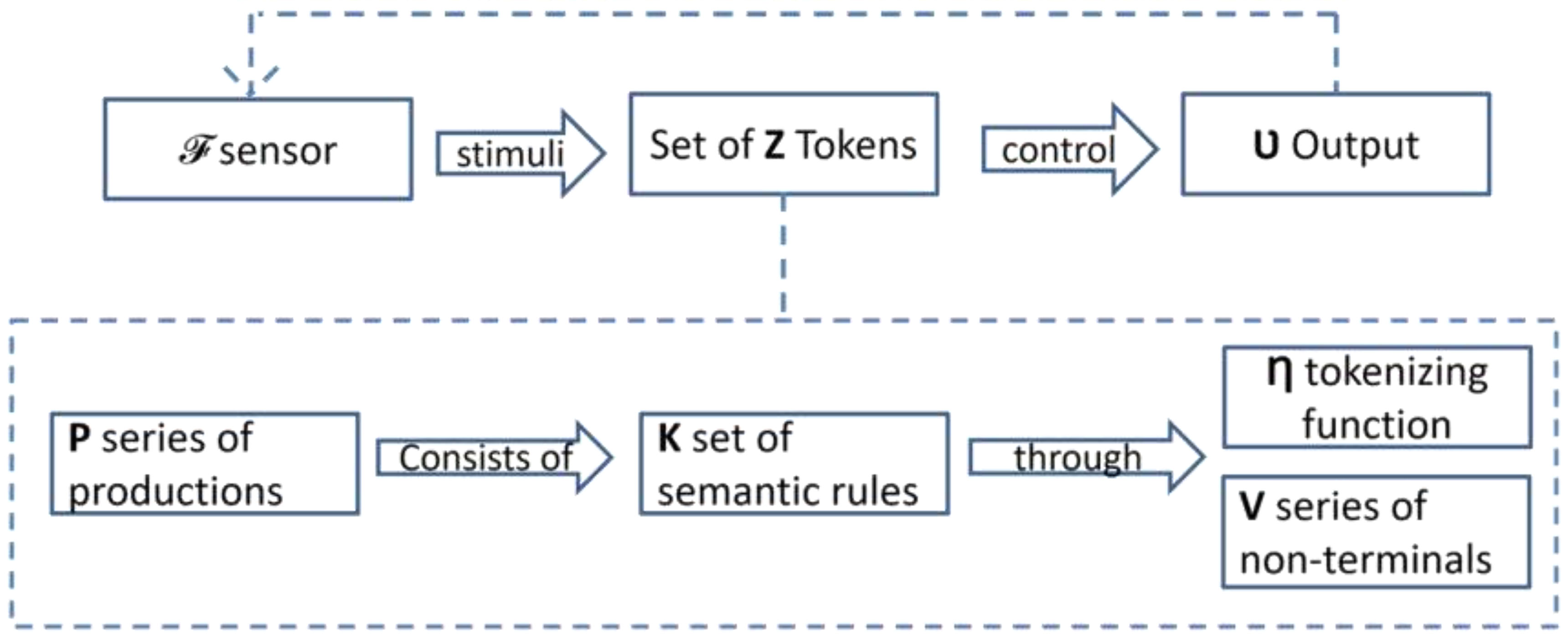
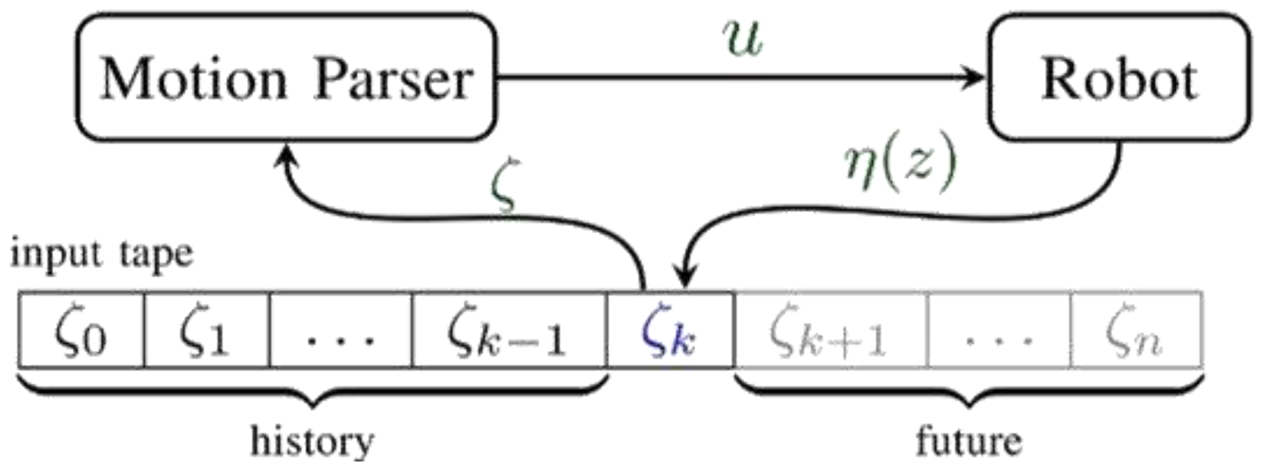
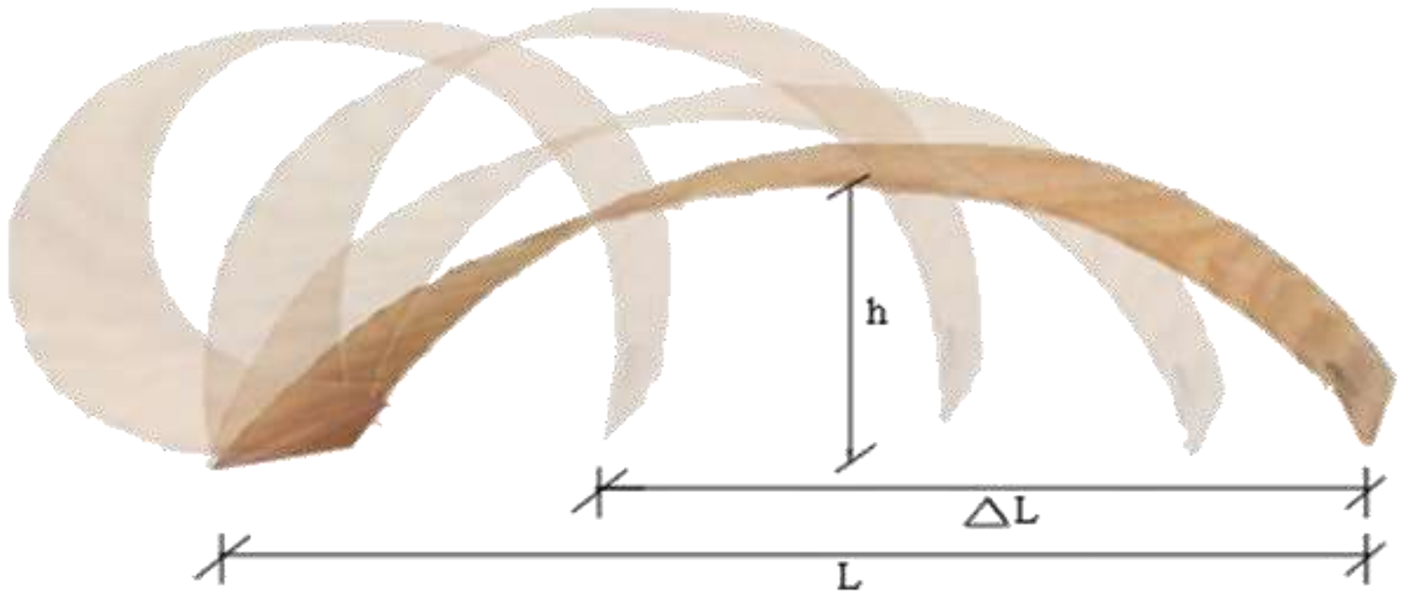




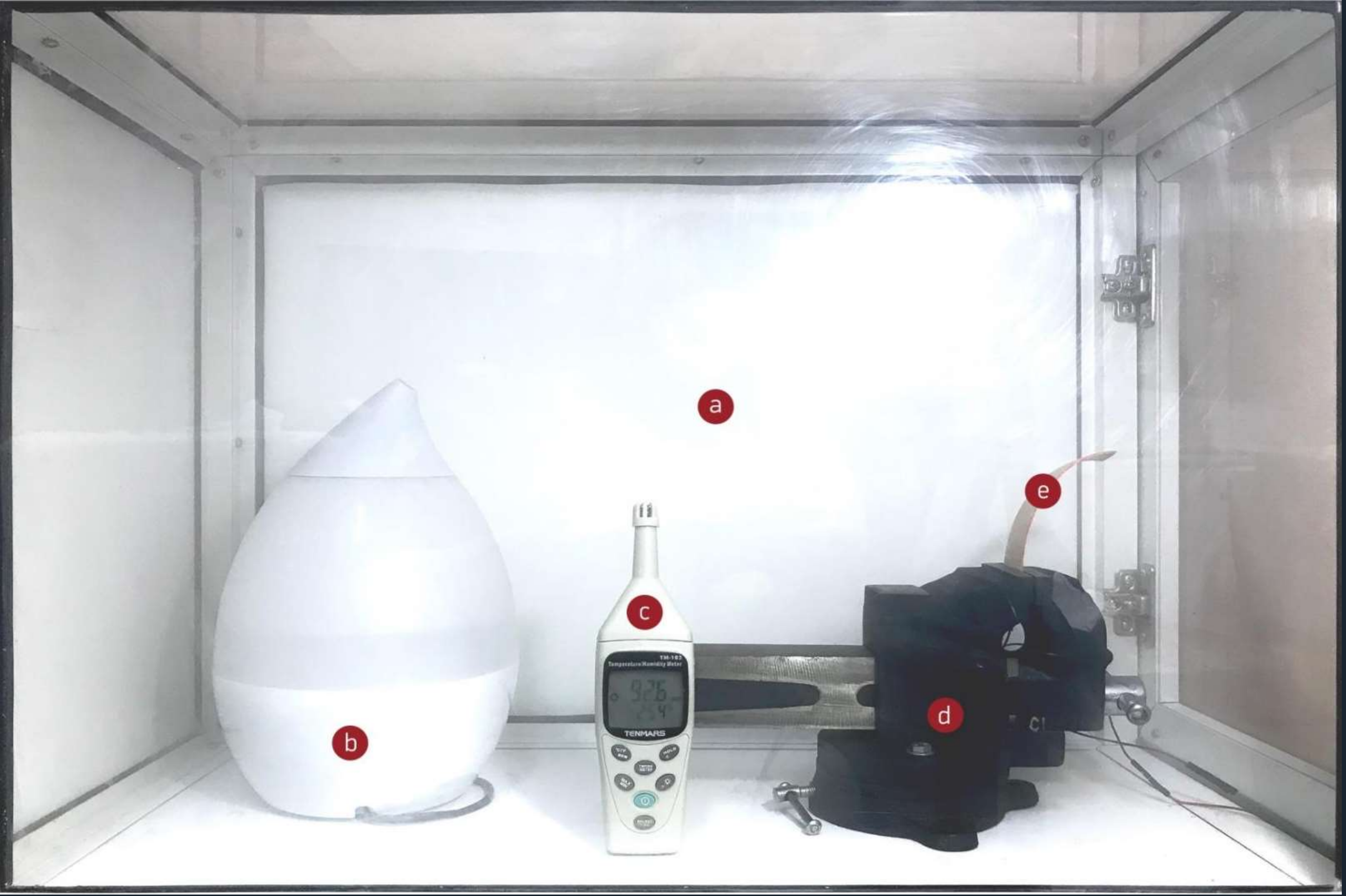
Motion grammar elements and process



Sequential response motion of wood upon increase in moisture content

Productions (**P**)	Semantic rules (**K**)	Robot (high-level) commands (**U**)
Production 1	Increase in MC	Bending the material
	Increase in r	
	Increase in Δh	
	Decrease in ΔL	
Production 2	Decrease in MC	Flattening the material
	Decrease in r	
	Decrease in Δh	
	Increase in ΔL	

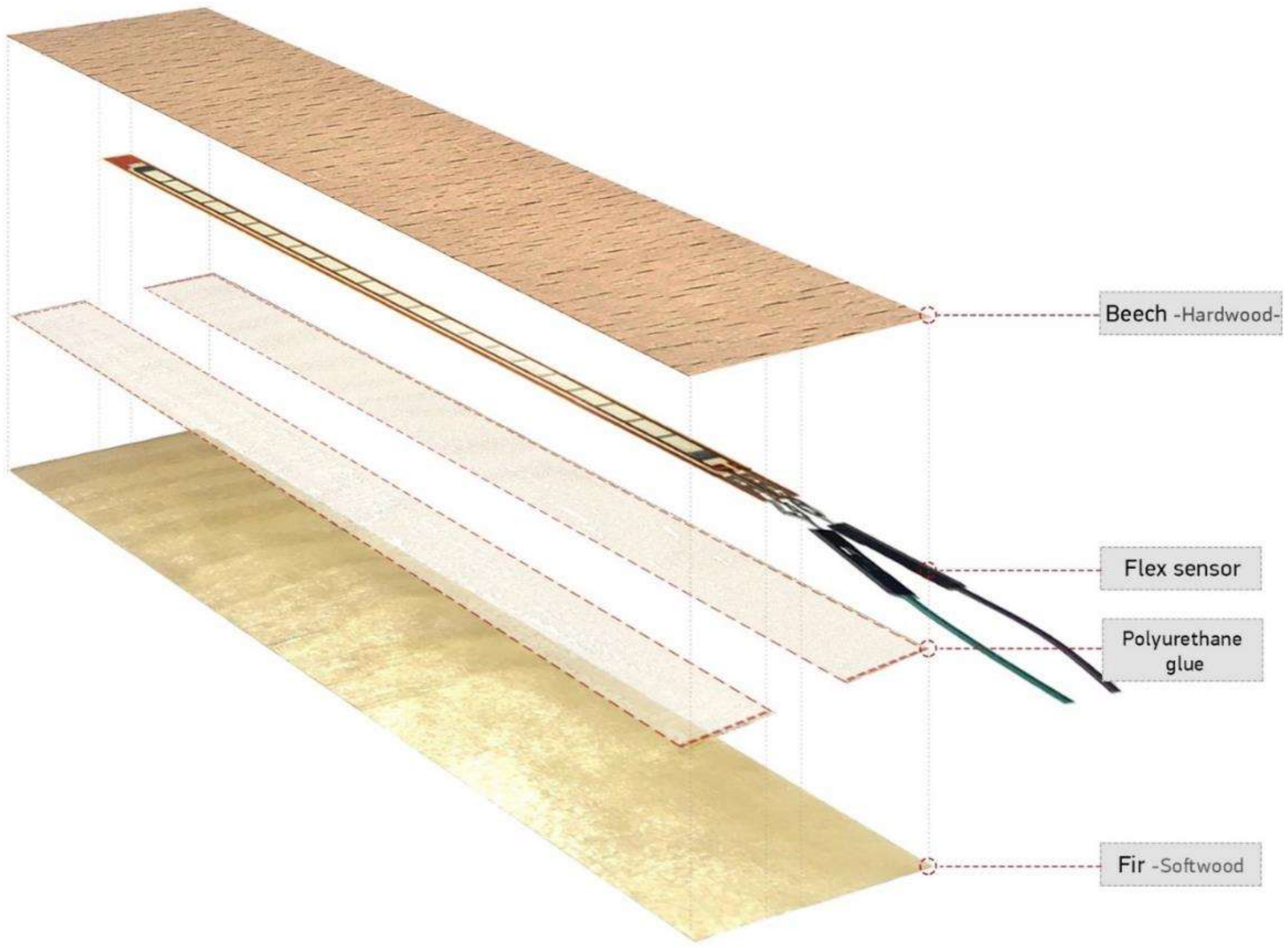
Defining productions, semantic rules and robot commands of wood motion in relation to motion grammar



Chamber Setup

Experiment setup inside humidity chamber:

(a) Sealed humidity chamber;
(b) Humidifier;
(c) Humidity and temperature sensor;
(d) Metal clamp;
(e) Bi-layer wood sample



Smart Material Interface

For the motion sensing experiment, the flex sensor was fixed on the wood veneer bi-layer sample and connected to the Arduino Uno kit to measure its bending. The motion response of the wood was captured by the Flex sensor, and then processed using the Arduino microcontroller.

Image Analysis

Kinovea software was used to analyse the wood sample motion by means of evaluating angles and distances on movable tracked markers in a frame by frame fashion.

a) Adjusting reference marker position

b) Taking angular measurements

c) Initiating frame tracking

d) Recording the output angles

Tracking the motion of wood through image analysis: (a) Humidifier;
(b) Temperature and humidity sensor;
(c) Metal clamp;
(d) Tracked angle;
(e) Fixed marker point;
(f) Variable point in sample
(g) Tracked frame

Motion Sensing

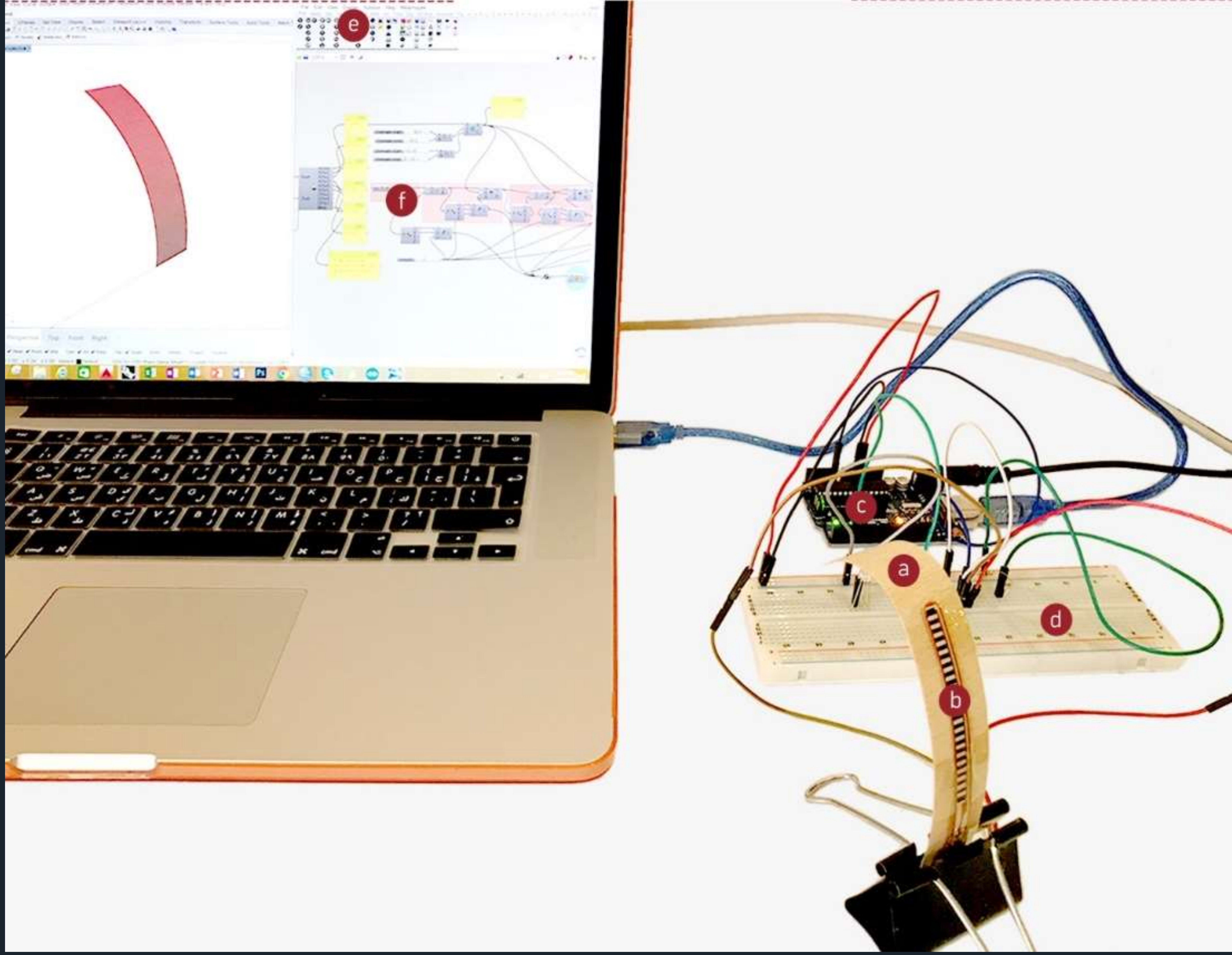
This loop relates the smart material interface (SMI) with a digital and a tangible interface

The smart material interface is represented in the hygroscopic properties of wood to shape shift as a response to moisture content

The **tangible interface** is composed of a circuit that consists of a Flex sensor and an Arduino microcontroller kit.

The digital interface is composed of the Grasshopper interface and Firefly plugin definition which are used to map and store the acquired angles and motion of the tested wood samples in relation to time.

a) Testing the effect of humidity of the sensor in the chamber,
b) Fixing the sensor to the bilayer wood sample,
c) Fixing the bilayer wood sample in the humidity chamber,
d) Recording and evaluating the motion of the bilayer wood sample using the digital interface.



Tracking the motion of wood through motion sensing:
(a) Wood sample;
(b) Flex sensor;
(c) Arduino Uno;
(d) Breadboard;
(e) Grasshopper interface;
(f) FireFly definition

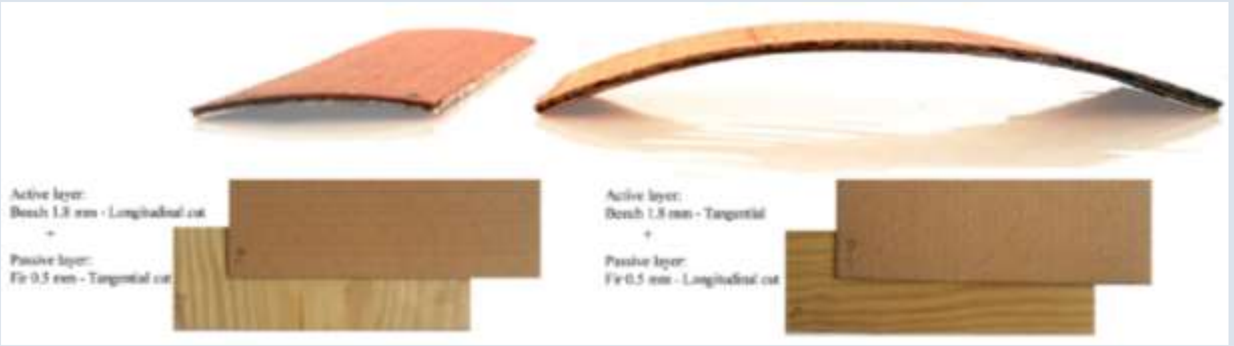
Script

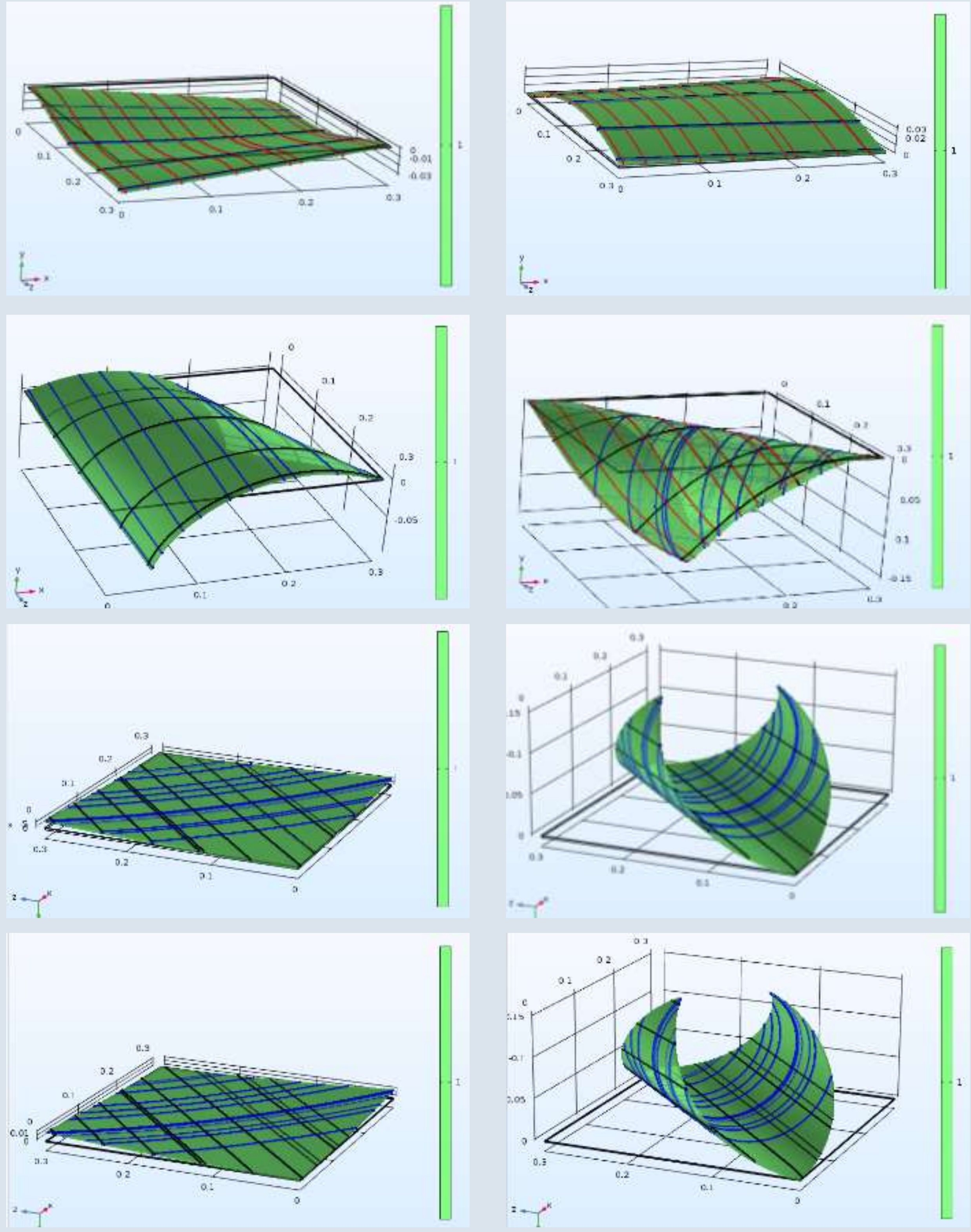
A Grasshopper script was used to store the variations of angles and tracking and analyzing the response behavior of wood. The digital interface was used to map, store and evaluate the motion of wood. The tangible interface was read by the Firefly plugin using Grasshopper. Firefly transmits the real-time motion response of wood to Grasshopper. A parametric Grasshopper script was generated to evaluate, analyze and store the sample motion.

Soft Adaptive Building Skins for Energy Efficient Architecture

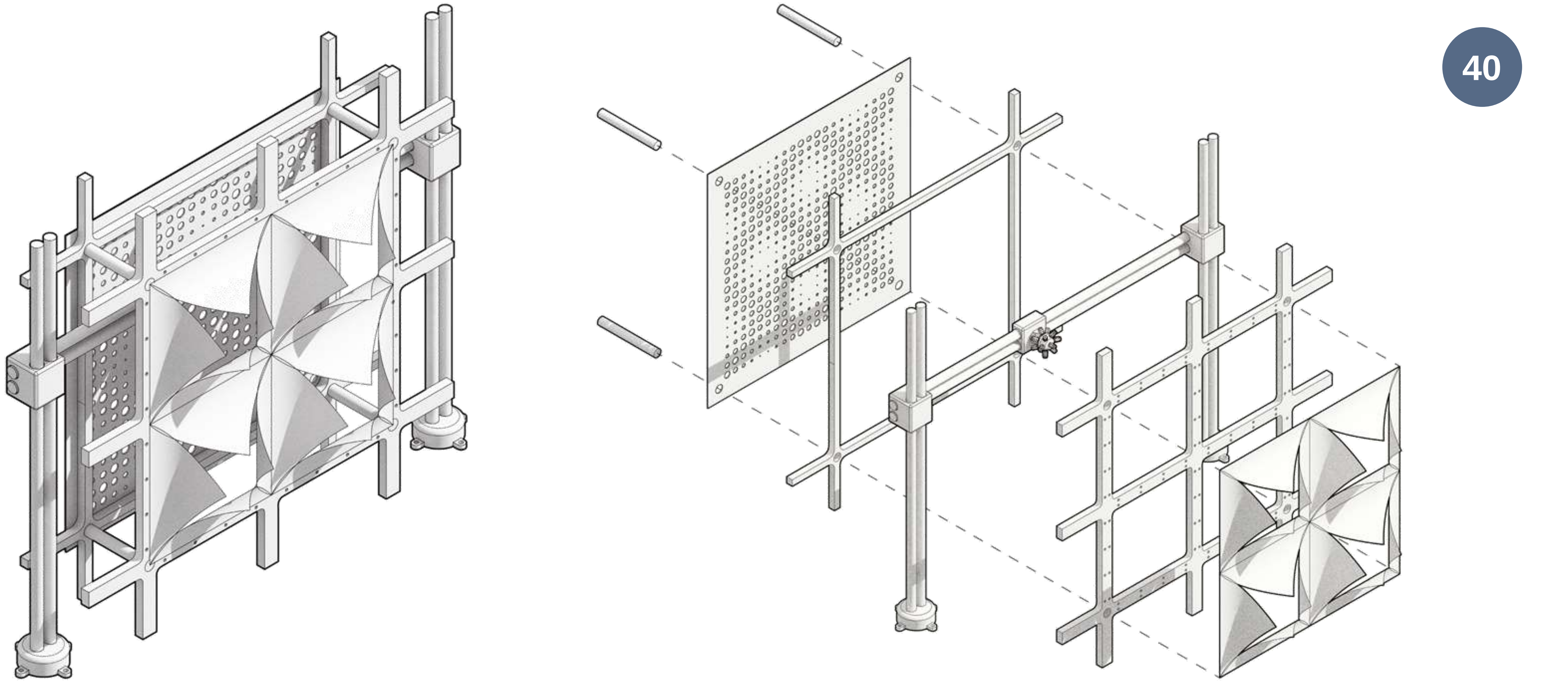
[AUC/Princeton – Bartlett Family Fund]

Sherif Abdelmohsen, Sigrid Adriaenssens, Stefano Gabriele





Numerical Modeling of Cross-Laminated Timber Samples



Shape-Shifting Façade Prototypes

Abdelmohsen, S., Adriaenssens, S., El-Dabaa, R., Gabriele, S., Olivieri, L. and Teresi, L. (2019), Programmable Matter: A Multi-Physics Modeling Approach for Low-Tech Architectural Adaptive Systems using Hygroscopic Properties of Wood, *Computer-Aided Design*, 106 (43-53).

Non-linear Modeling of Hygroscopic Behavior of Wood

(1) The congruence equations, relating the strain measure $\boldsymbol{E}$ (aka, Green–St.Venant strain tensor) to the displacement field $\boldsymbol{u}$

$$\boldsymbol{E} = \frac{1}{2}\left(\boldsymbol{F}^T\boldsymbol{F} - \boldsymbol{I}\right), \text{ in } \Omega, \qquad \boldsymbol{u} = \overline{\boldsymbol{u}} \text{ in } \partial_u\Omega, \tag{1}$$

with $\boldsymbol{F} = \nabla\boldsymbol{u} + \boldsymbol{I}$; here $\boldsymbol{F}$ is the deformation gradient, $\boldsymbol{I}$ the identity tensor, ∇ the gradient operator, and $\partial_u\Omega$ the portion of the boundary with kinematics constraints.

(2) The constitutive prescription, relating the elastic strain $\boldsymbol{E_e}$ to the elastic stress $\boldsymbol{S_e}$; here, we assume the response of wood in the range of interest to be well represented by the Kirchhoff–St.Venant relation:

$$\boldsymbol{S}_e = \mathbb{C}\boldsymbol{E_e}, \qquad \text{with } \boldsymbol{E}_e = \boldsymbol{E} - \boldsymbol{E}_o. \tag{2}$$

The mechanical behavior of the material is described through the elasticity tensor $\mathbb{C}$ (a fourth-order tensor) and the distortion $\boldsymbol{E}_0$; in such context, the distortion $\boldsymbol{E}_0$ is called hygroscopic strain and describes the swelling of the wood caused by a change in moisture content.

(3) The balance equations, relating the reference stress $\boldsymbol{S} = \boldsymbol{F}\boldsymbol{S}_e$ (aka, Piola–Kirchhoff stress) to the bulk load $\boldsymbol{f}$ and the boundary load $\boldsymbol{t}$

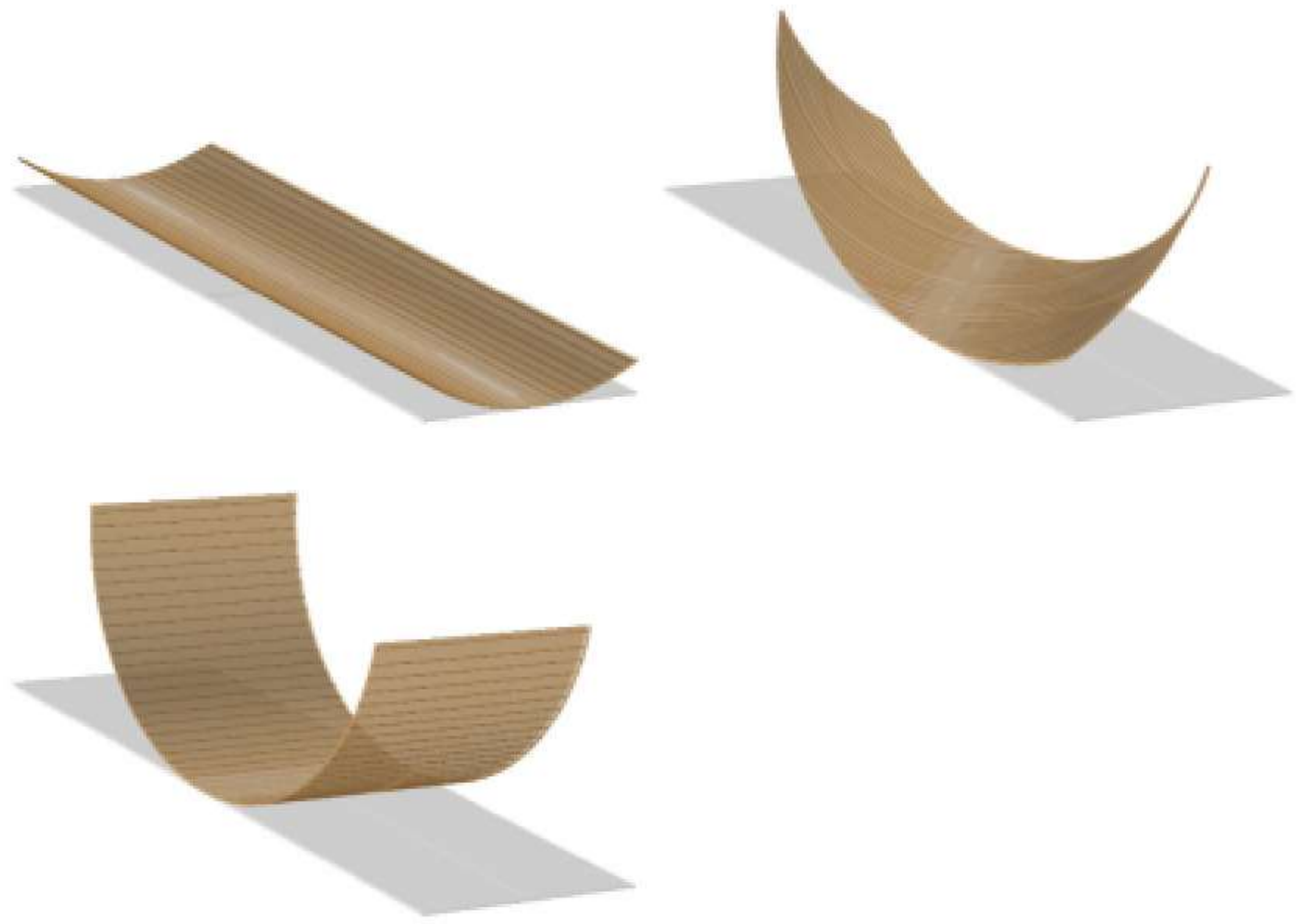
$$div\,(\boldsymbol{S}) + \boldsymbol{f} = \boldsymbol{0}, \text{ in } \Omega, \qquad \boldsymbol{S}\boldsymbol{n} = \boldsymbol{t} \text{ in } \partial_t\Omega, \tag{3}$$

The orthotropic swelling is described by $\boldsymbol{E}_0$; we assume the following form for the distortion tensor:

$$[\boldsymbol{E_o}]_\beta = \left(c - c_{ref}\right)[\boldsymbol{H}]_\beta, \quad [\boldsymbol{H}]_\beta = \begin{bmatrix} h_L & 0 & 0 \\ 0 & h_T & 0 \\ 0 & 0 & h_R \end{bmatrix}_\beta \tag{4}$$

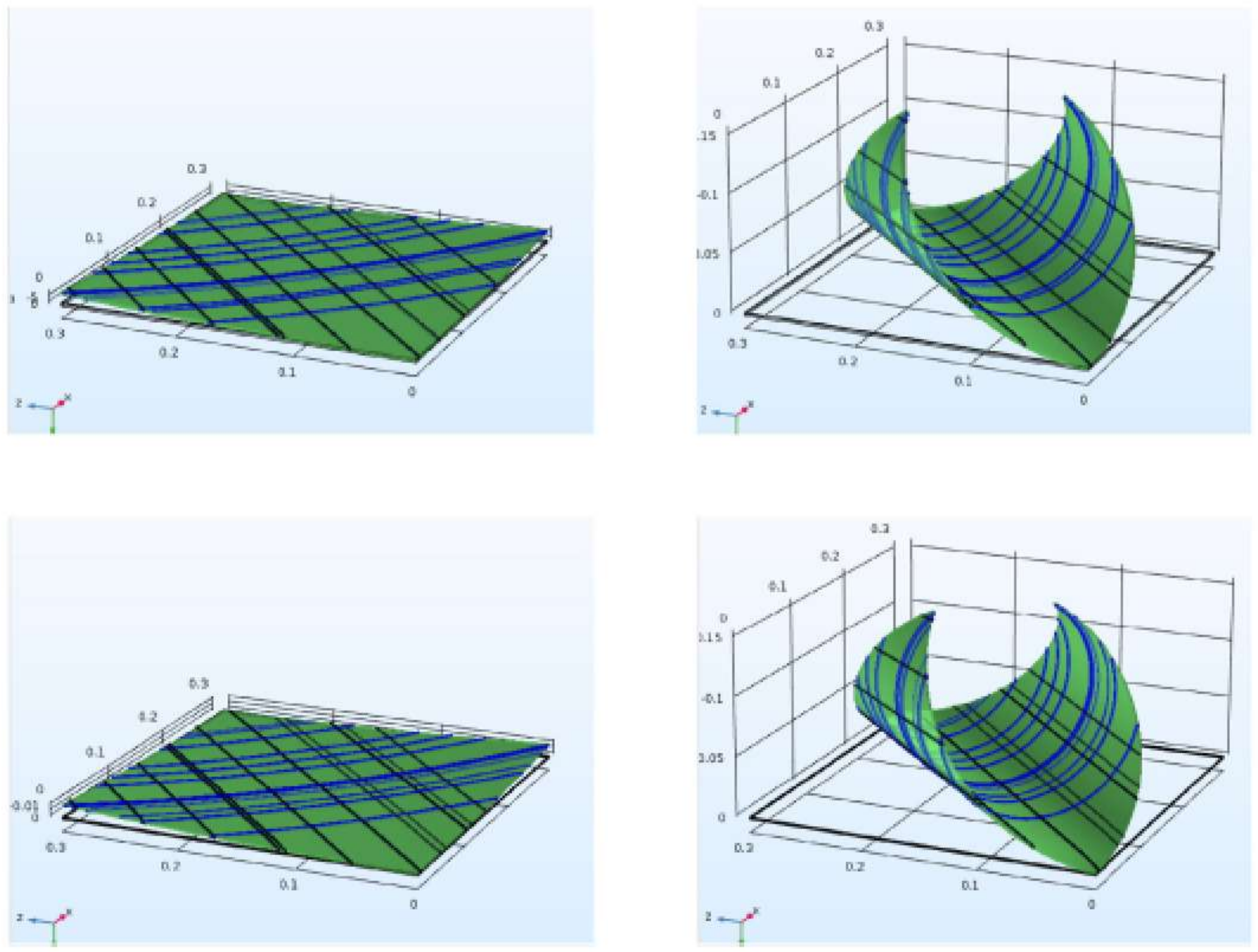
where c and c_{ref} are the actual and the reference moisture concentrations, respectively, and h_i with $i = L, R, T$ are the hygroscopic swelling coefficients in the LRT-directions.

Numerical Modeling in COMSOL Multi-physics software



(a) (b) (c)

Parametric numerical modeling for wood behavior with different grain orientations.



Cedar and ash parametric grain study. Top row: Cedar = 0.001 m and Ash = 0.001 m; bottom row: Cedar = 0.001 m and Ash = 0.002 m.

Non-linear Modeling of Hygroscopic Behavior of Wood

The orthotropic stiffness is described by $\mathbb{C}$, and its entries with respect to the local base are denoted by $[\mathbb{C}]_\beta$. Voigt's representation of $\mathbb{C}$ is used. This notation exploits the symmetries of the three tensors involved in Eq. (2): $\boldsymbol{S_e}$ and $\boldsymbol{E_e}$ are represented by 6×1 column vectors, and $\mathbb{C}$ by a 6×6 symmetric matrix, called stiffness matrix, denoted $[\boldsymbol{D}]_\beta$ as follows:

$$\begin{bmatrix} S_{e11} \\ S_{e22} \\ S_{e33} \\ S_{e12} \\ S_{e23} \\ S_{e13} \end{bmatrix}_\beta = \begin{bmatrix} D_{\beta 11} & D_{\beta 12} & D_{\beta 13} & 0 & 0 & 0 \\ D_{\beta 12} & D_{\beta 22} & D_{\beta 23} & 0 & 0 & 0 \\ D_{\beta 13} & D_{\beta 21} & D_{\beta 33} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{\beta 44} & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{\beta 55} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{\beta 66} \end{bmatrix}_\beta \times \begin{bmatrix} E_{e11} \\ E_{e22} \\ E_{e22} \\ 2E_{e12} \\ 2E_{e23} \\ 2E_{e13} \end{bmatrix}_\beta \qquad (5)$$

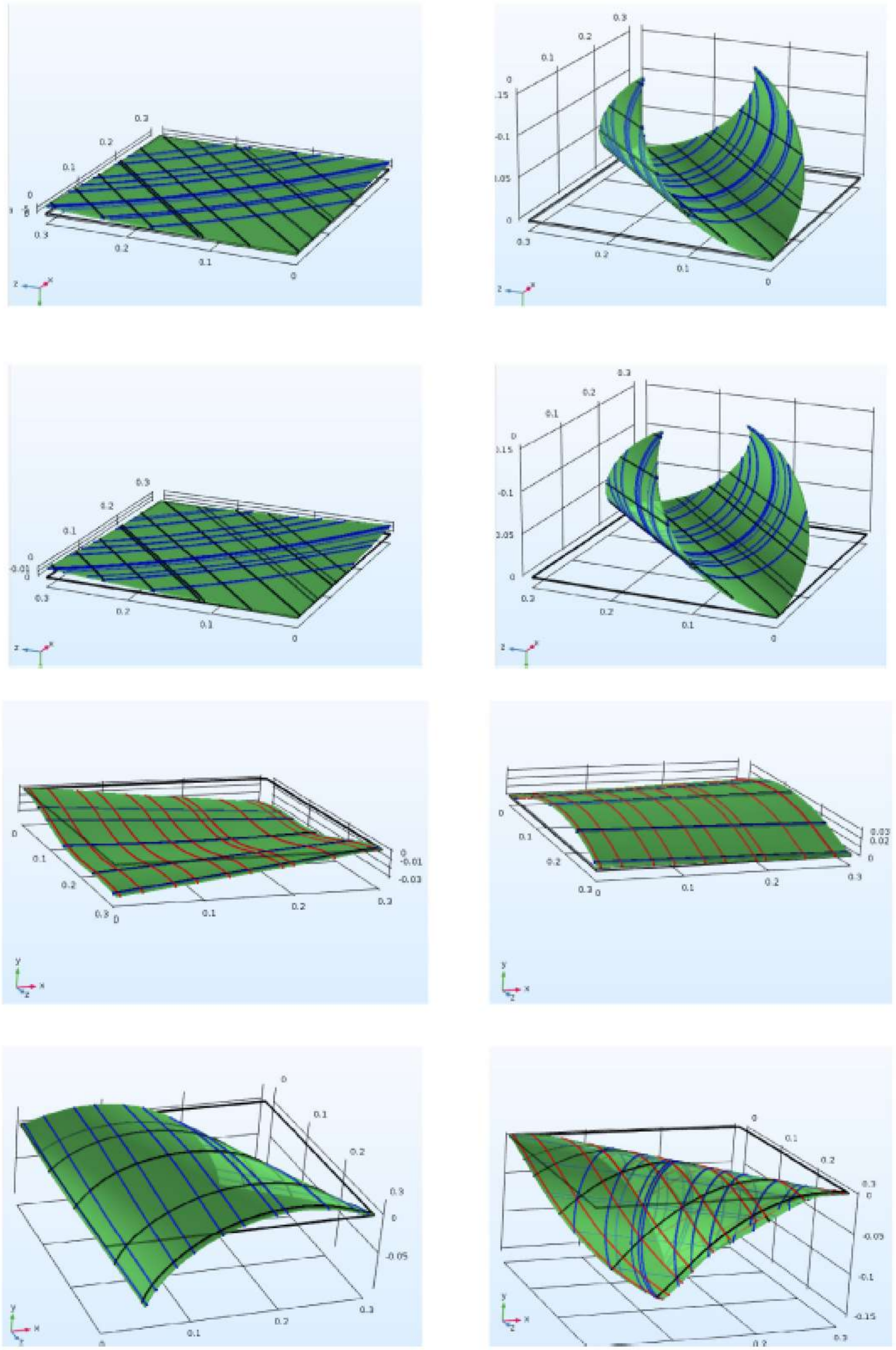
It is noted that, by using a base that accounts for the symmetry axes of the material LRT, the matrix $[\boldsymbol{D}]_\beta$ has a simple block structure, with S_{eii} coupled only with E_{eii}, and S_{eij} only with E_{eij}. As aforementioned, the response of such materials is completely characterized by nine parameters: three Young moduli Y_L, Y_R, Y_T, three Poisson moduli $\nu_{LR}, \nu_{LT}, \nu_{RT}$, and three shear moduli $\mu_{LR}, \mu_{LT}, \mu_{RT}$. While the stiffness matrix $[\boldsymbol{D}]_\beta$ has a cumbersome representation in terms of these nine parameters, the representation of the flexibility matrix $[\boldsymbol{G}]_\beta = \left[\boldsymbol{D}^{-1}\right]_\beta$ is straightforward.

$$[\boldsymbol{G}]_\beta = \begin{bmatrix} 1/Y_L & -\nu_{LR}/Y_L & -\nu_{LT}/Y_L & 0 & 0 & 0 \\ -\nu_{LR}/Y_L & 1/Y_R & -\nu_{RT}/Y_R & 0 & 0 & 0 \\ -\nu_{LT}/Y_T & -\nu_{RT}/Y_R & 1/Y_T & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\mu_{LR} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/\mu_{LT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/\mu_{RT} \end{bmatrix}_\beta = \begin{bmatrix} G_Y & 0 \\ 0 & G_\mu \end{bmatrix}_\beta \qquad (6)$$

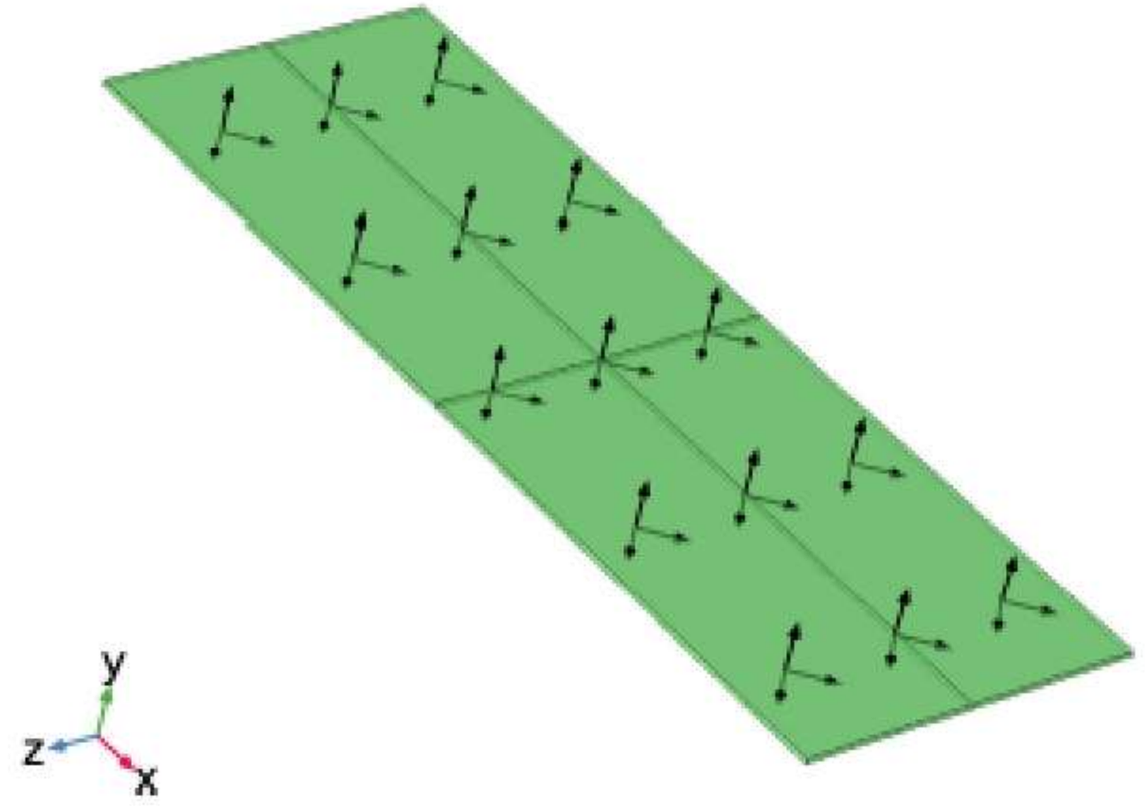
Given $[\boldsymbol{G}]_\beta$, the stiffness matrix can be obtained by inverting the non-zero blocks of the compliance matrix:

$$[\boldsymbol{D}]_\beta = \begin{bmatrix} G_Y^{-1} & 0 \\ 0 & G_\mu^{-1} \end{bmatrix}_\beta \qquad (7)$$

Numerical Modeling in COMSOL Multi-physics software



Non-linear Modeling of Hygroscopic Behavior of Wood



Representation of the local basis.

This transformation is done by means of the rotation tensor $\boldsymbol{Q}$, representing the change of base $\boldsymbol{\alpha} \rightarrow \boldsymbol{\beta}$. Let $\boldsymbol{b}_i = (b_1, b_2, b_3)_i$ be the components of the vector $\boldsymbol{b}_i$ with respect to the base $\boldsymbol{\alpha}$; the rotation tensor $\mathbf{Q}$ (see Fig. 7) is represented by the following matrix:

$$[Q] = \left[\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}_1 \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}_2 \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}_3 \right], \tag{8}$$

Thus, given a constitutive relation $[\boldsymbol{S}_e]_\beta = [\mathbb{C}]_\beta [\boldsymbol{E}_e]_\beta$, in the local base $\boldsymbol{\beta}$, the corresponding relation represented with respect to the base $\boldsymbol{\alpha}$ can be computed by the formulas:

$$[\boldsymbol{S}_e]_\alpha = [\mathbf{Q}]\,[\boldsymbol{S}_e]_\beta \left[\mathbf{Q}^T\right], \; [\boldsymbol{E}_e]_\beta = \left[\mathbf{Q}^T\right][\boldsymbol{E}_e]_\alpha\,[\mathbf{Q}] \tag{9}$$

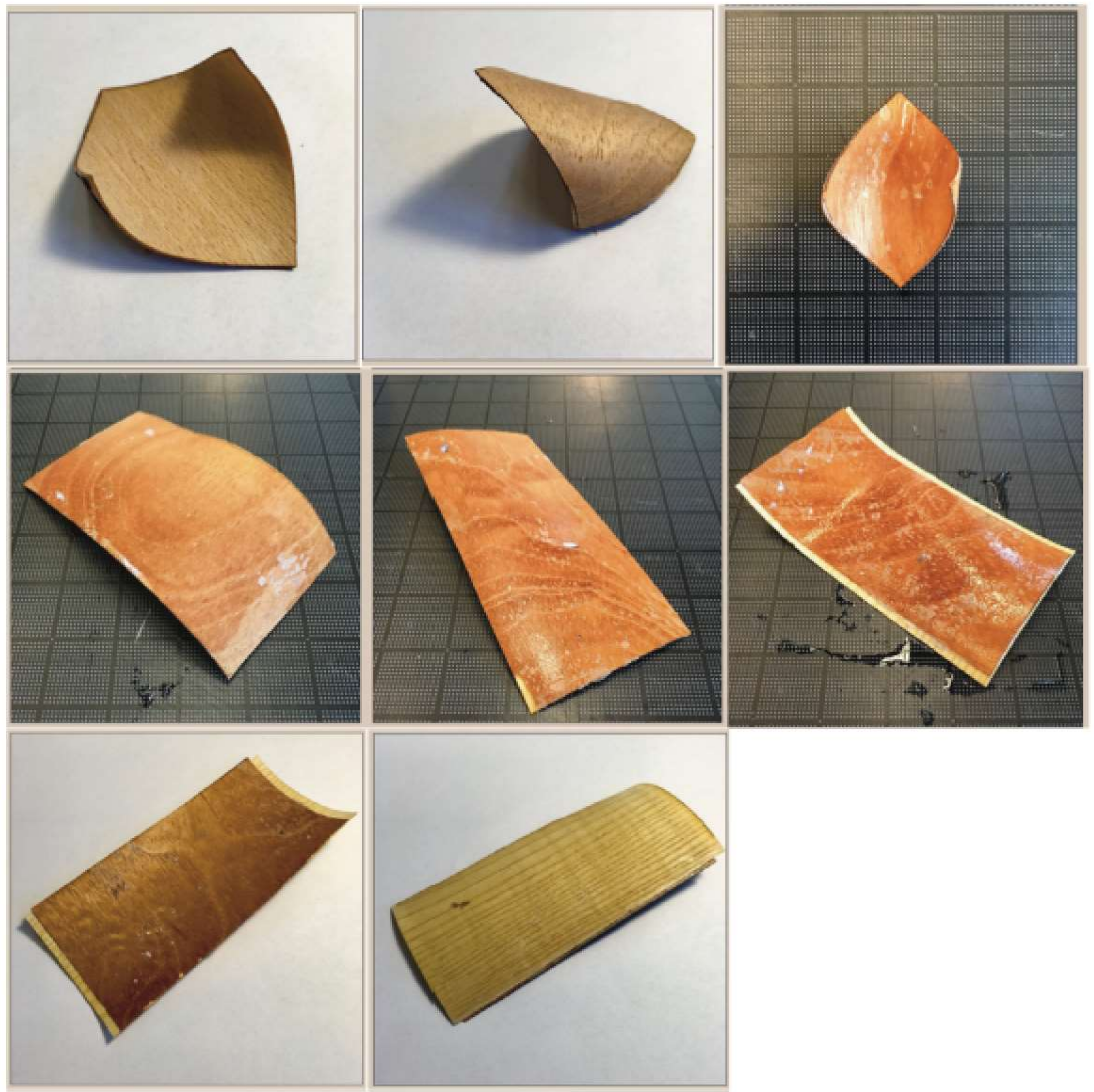
that yields $[\boldsymbol{S}_e]_\alpha$ in terms of $[\boldsymbol{E}_e]_\alpha$

$$[\boldsymbol{S}_e]_\alpha = [\mathbf{Q}]\left([\mathbb{C}]_\beta \left(\left[\mathbf{Q}^T\right][\boldsymbol{E}_e]_\alpha\,[\mathbf{Q}]\right)\right)\left[\mathbf{Q}^T\right] = [\mathbb{C}]_\alpha [\boldsymbol{E}_e]_\alpha. \tag{10}$$

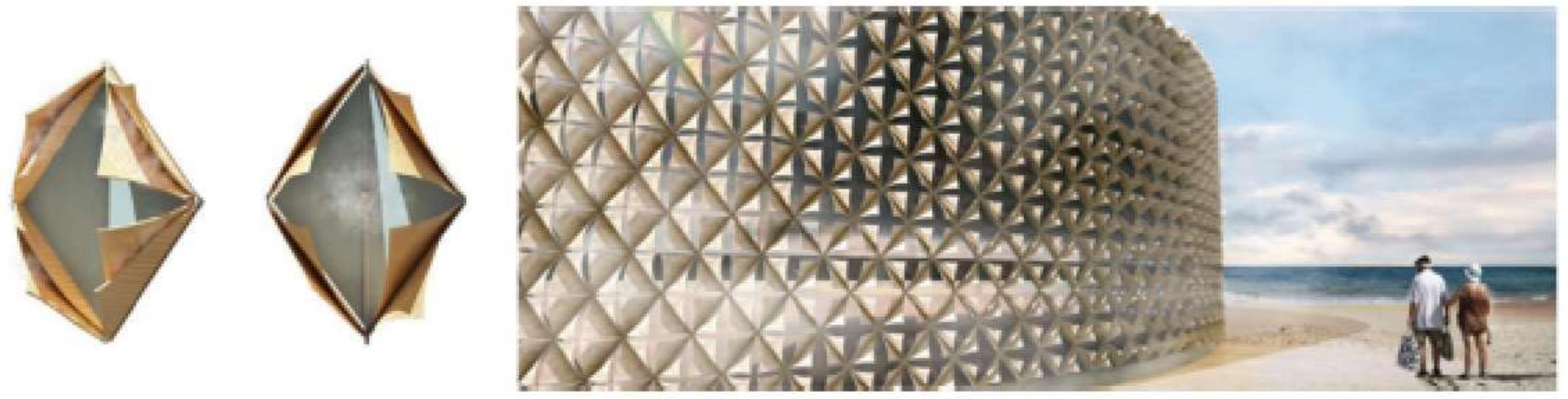
We note that the change of base for the strain and stress tensors involves the product of $[\mathbf{Q}]$ square, while that for the stiffness tensor involves $[\mathbf{Q}]$ to the power of four. Similarly, the change of base for the distortion tensor $[\boldsymbol{H}]_\beta$ is given by

$$[\boldsymbol{H}]_\alpha = [\mathbf{Q}]\,[\boldsymbol{H}]_\beta \left[\mathbf{Q}^T\right]. \tag{11}$$

Physically Modeled Shape Shifting Prototype

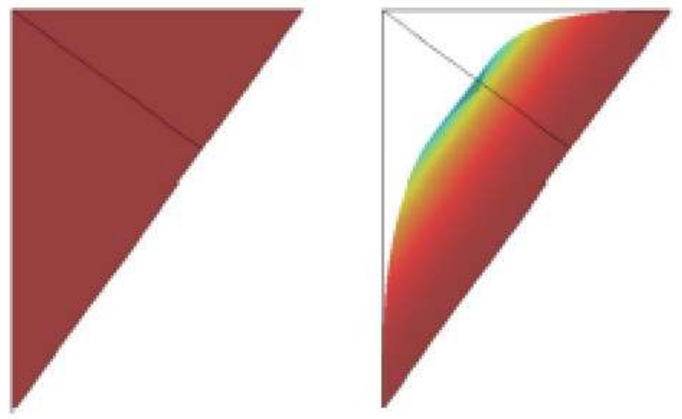


Physically modeled shape shifting from cedar and ash bilayers, with different fiber orientations.

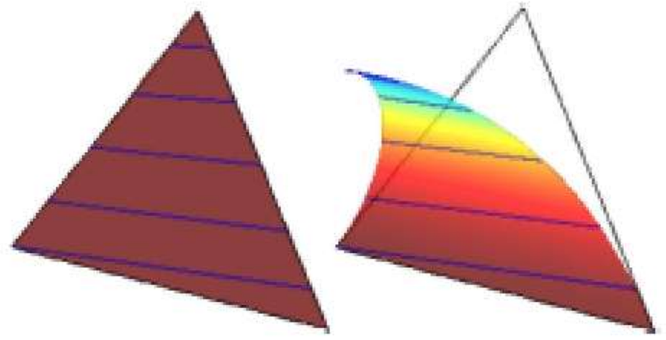


Diamond module (left) – Simulation of the entire façade (right)

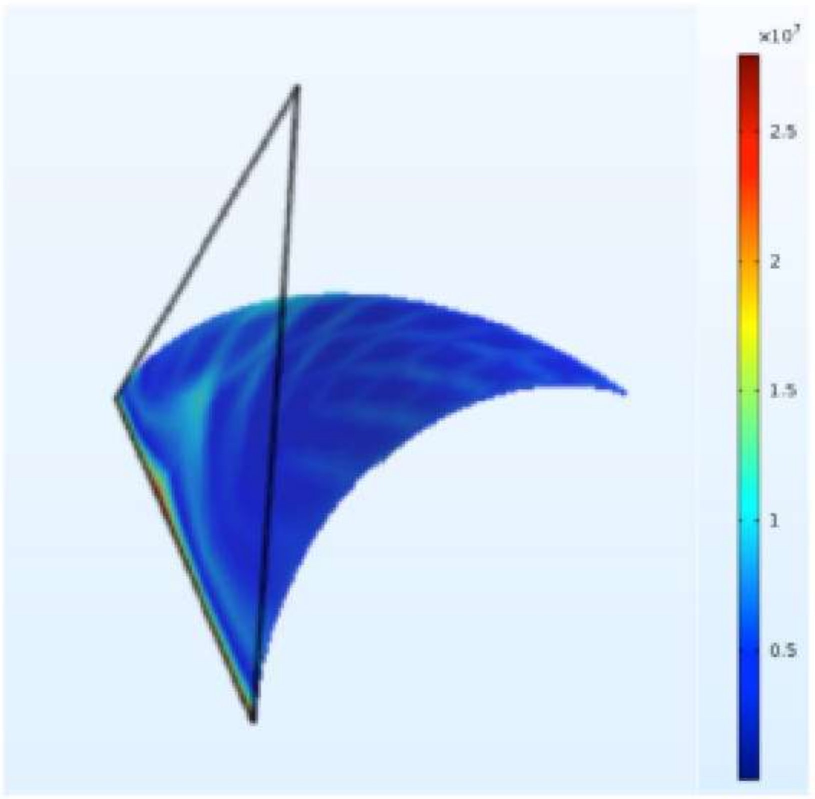
Numerical Modeling in COMSOL Multi-physics software



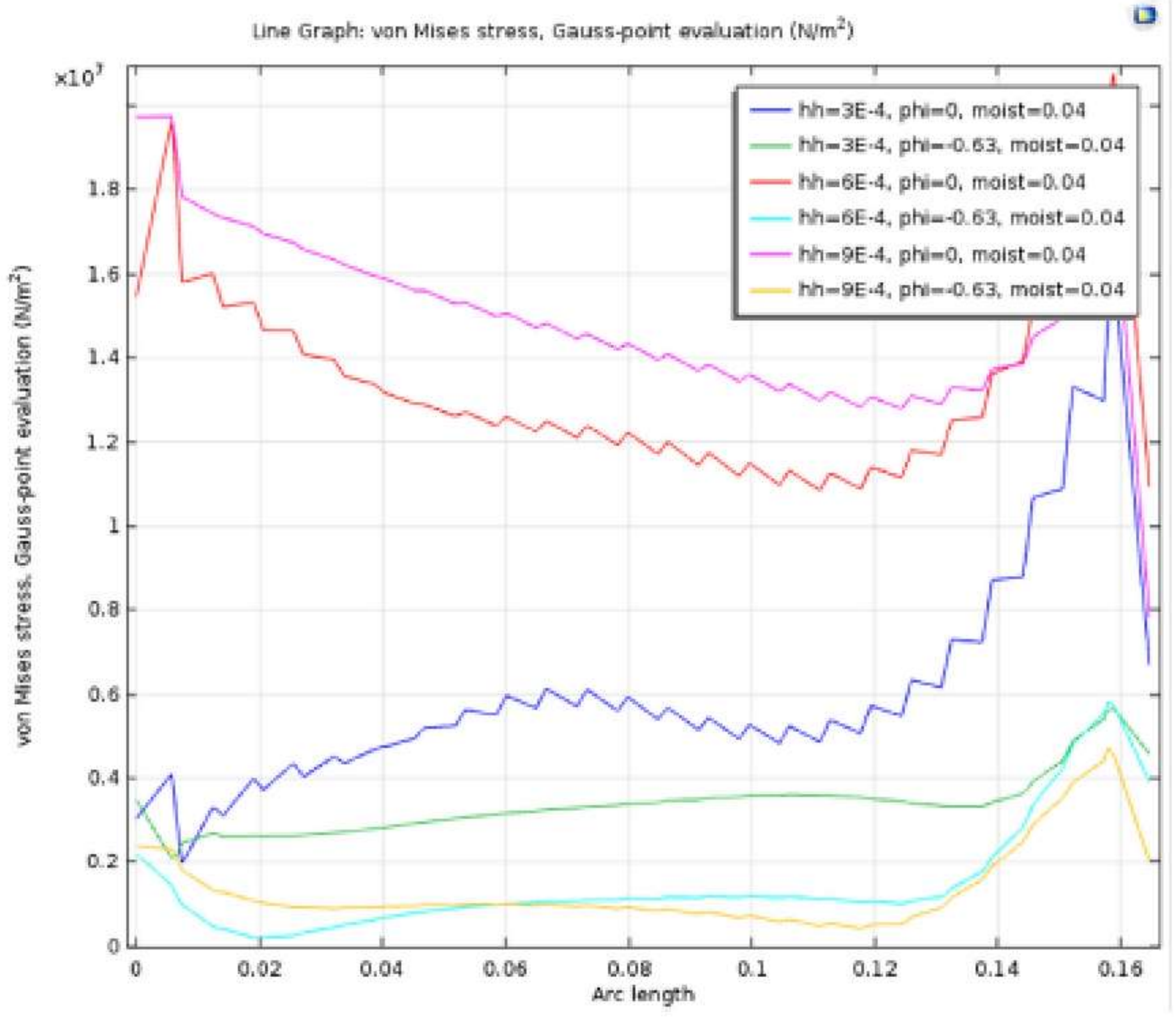
Asymmetric basic triangle. Initial (left) and deformed (right) configurations.



. Inclination of the fibers given to the active layer – initial (left) and deformed (right) configuration.



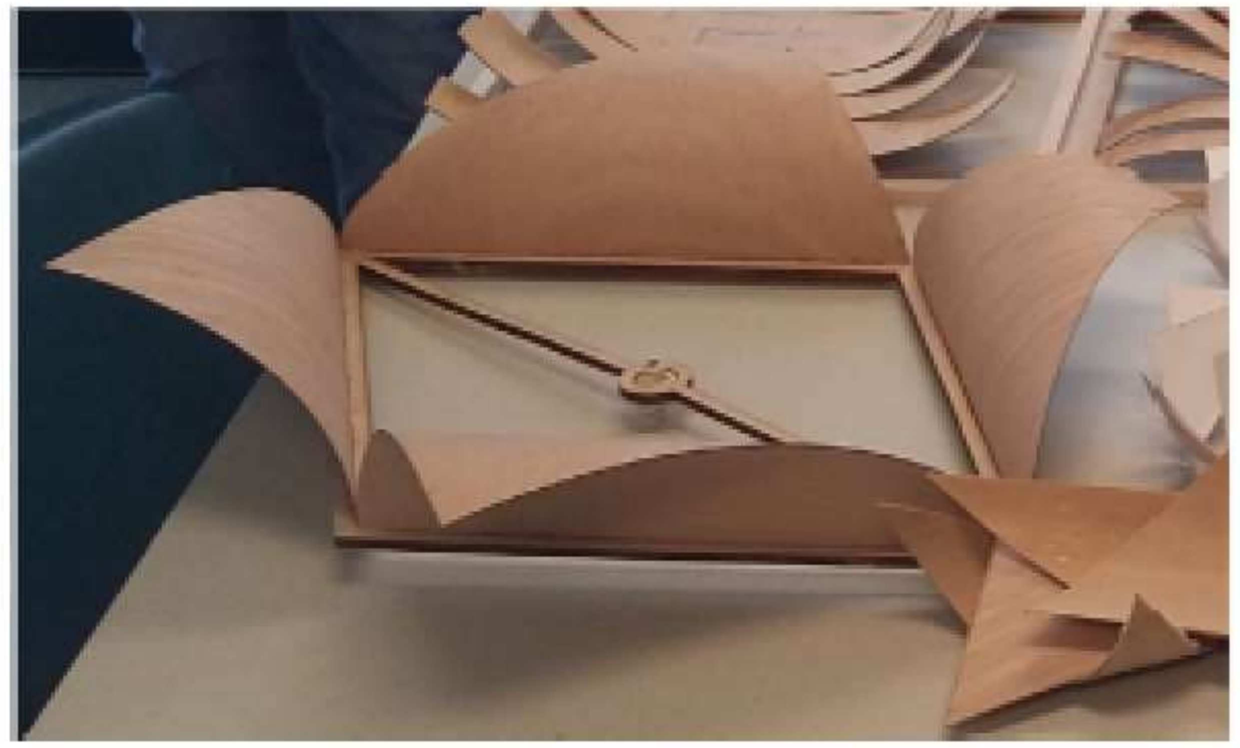
Von Mises stress level for the final configuration – stress values in N/m^2.



Reduction of stress levels due to change in grain orientation – stress values in N/m^2.

Physically Modeled Shape Shifting Prototype

Physical implementation of the diamond module – simulation of the closure.



Physical implementation of the diamond module – complete opening.

Conclusions

We exploit the potential of the inherent hygroscopic properties of wood to drive the design of morphing strategies for adaptive architectural systems by proposing a multi-physics modeling approach.

This approach is augmented with physical explorations on the effect of grain orientation, moisture content, wood types, and lamination on the deformation of wood.

Hygroscopy induces strains but no, or low, stresses in wood upon water sorption. As a result, fatigue is not an issue, and wood becomes a preferred low-cost material candidate for adaptive systems that undergo cyclic deformations.

To predict the behavior and deformation of these systems, designers traditionally resorted to analytical beam models and geometric digital models. What we introduce is a step forward in modeling and numerical simulations, where we present a generalized orthotropic model for both elastic and hygroscopic behavior, where it is possible to model single or multi-layered wood, each layer having his own fiber orientation.

This model allows for design exploration of many different layered setups, and can capture complex material deformations and quantitative design parameters like maximum displacements and stress levels. We combined numerical simulations with physical explorations into a schematic design approach exemplified by a proof of concept for an adaptive diamond module hygromorphing façade panel.

Beyond this research, advanced foreseen versions of responsive systems exhibit cognitive and biological models, the anticipation of desirable preferences, and educating both buildings and their users.

Thank You

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