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Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness

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HIGHLIGHTS

- Access and instrumentalisation of computational capacities within organic systems.
- Formal complexity through singular parametric differentiation in material behaviour.
- Environment cognisant architectural systems with climate dependent formal behaviour.
- Embedded biomimetic intelligence through material programming.

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ABSTRACT

In this paper, the authors present research into autonomously responsive architectural systems that adapt to environmental changes using hygroscopic material properties. Instead of using superimposed layers of singular purpose mechanisms – for sensing, actuation, control and power – in the form of high-tech electronic equipment as is emblematic for current approaches to climate responsiveness in architecture, the presented research follows an integrative, no-tech strategy that can be considered to follow biological rather than mechanical principles. In nature plants employ different systems to respond to environmental changes. One particularly promising way is hygroscopic actuation, as it allows for metabolically independent movement and thus provides an interesting model for autonomous, passive and materially embedded responsiveness. The paper presents a comprehensive overview of the parameters, variables and syntactic elements that enable the development of such meteorosensitive architectural systems based on the biomimetic transfer of the hygroscopic actuation of plant cones. It provides a summary of five years of research by the authors on architectural systems which utilize the hygroscopic qualities of wooden veneer as a naturally produced constituent within weather responsive composite systems, which is presented through an extensive analysis of research samples, prototypes at various scales, and two comprehensive case studies of full scale constructions.

1. Introduction and background

1.1. Responsiveness in architecture

With the increased reliance and interdependence of computation through our everyday life, our environments are becoming progressively more cognisant. Through embedded sensory, more and more data about our environment is continuously exchanged, processed, stored and distributed to seamlessly adapt and respond to our actions and signals. In architecture, responsiveness has been of particular interest when dealing with climatic adaptation. Although this has progressively moved towards adapting ever more distributed and localized mechanisms to affect and respond to climatic conditions, this research moves the investigations further, into the possibility of directly embedding sensing, control and actuation within the material itself; that is, the *material as a machine*. The presented work directly engages in environmental mediation and the morphological implications of such material embedded capacity while exploring the deviceful potential of biomimetic constructional effectiveness.

Within this context, two subsets of applications within the field of architecture are of particular interest for this discussion—opening roofs for semi-interior spaces, such as sports stadiums, and adaptive facades for fully enclosed buildings. Adaptive facades try to achieve responsiveness through rather localized permeability control, while most convertible roofs employ the movement of larger building components. Both systems usually possess a high

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degree of mechanical complexity and require at least one external energy source, a series of actuators and sensors, as well as a logical control unit. Examples have been implemented as adaptive textile building envelopes with global adaptation [1] and local adaptation [2], adaptive pneumatic envelope constructions [3] or adaptive tensegrity envelopes [4]. Such complex electromechanical systems have the disadvantage that they are complex to build and difficult to maintain and tend to frequently mal-function. Material embedded actuation provides a new perspective to these challenges as it intrinsically engages weather conditions.

It must be noted that other construction systems without complex mechanics have been approached by other researchers [5]. Here, principles of material deformation are used to simplify the mechanical actuation, while the independence from mechanical systems is mostly achieved through the usage of electro-active polymers [6]. Such active material deformation has the disadvantage of requiring high energy consumption and demonstrates a lack of physical strength; the latter is also the drawback of passive responsive systems [7], where the utilized bimetal material is used as a thin laminate composite to autonomously respond to temperature changes [8]. In the following article, the authors present an alternative perspective on responsiveness, which through material embedded actuation, respond to many of the issues discussed. This approach intends to directly engage atmospheric conditions for both control and actuation by intrinsically depending on them for its operational efficacy.

1.2. Natural responsiveness

In nature there are various examples of climate responsive, dynamic movements. Of special interest is the hygroscopic shape changing adaptation that can be observed in a variety of plants as it provides particularly interesting potential for architectural applications. Moisture driven plant motion can be categorized in two major groups: (a) active cell turgor pressure movement as seen in e.g. *Dionaea muscipula* (Venus fly trap) [9] or (b) passive movement triggered through differentiated elongation of material e.g. the hygroscopic movements of fruit awns [10–15] or the opening of the seed capsules of ice plants [16]. While active cell pressure movement is connected to the metabolism of plants, the passive alternative is a result of the material's hygroscopic behaviour and its anisotropic composition, in response to environmental changes. For instance, the *Pinophyta* (conifers) possess cones to protect internal seeds (Fig. 1)—the plants reproductive structures [12,17,18]. Once the cone becomes mature, the scales dry out and open up to release the seeds. At that point, the materiality of the cone is already dead and has no direct connection to the tree. However, since the motion is triggered by external stimuli and does not plastically alter the molecular structure of the material, it is fully reversible for a large number of opening and closing cycles. The geometric deformation of the scale is achieved through two different fibre layers; the outer layer consists of parallel, long and densely packed thick-walled cells while the inner layer of the seed scale possesses differentiated sclerenchyma fibres with cellulose fibrils at a higher angle (upper part) and lower angle (lower part) in relation to the longitudinal axis [12,17]. Through swelling and shrinking, the material performs the passive autonomous deformation. The instrumentalization of the hygroscopic material [18–22] behaviour is particularly promising for architecture, since it does not require any type of external actuation, electrical or otherwise.

1.3. Wood—a natural composite

Wood is one of the oldest and most widely used construction materials [23]. Wood as a fully renewable material not only holds a very low level of embodied energy [24] but it also provides a positive carbon footprint [25], even when considering today's heavily industrial wood processing practices [26]. As a natural fibrous composite, wood possesses a variety of complex properties that still allows it to compete with high-tech contemporary materials. However, the hygroscopic behaviour of the material and its related anisotropic dimensional changes have been considered to be a challenge – to be controlled and mitigated – largely for the wood craftsman, and more recently it has also been dealt with as a deficiency in standardized industrial applications [27,28]. As a result, various chemical and physical techniques have been developed to homogenize and restrict this unwanted behaviour with various degrees of success. It is worth noting that if we consider the total energy consumption of wood processing, heat-drying treatment for moisture content stabilization requires the most energy—about 70% [29]. Although there is a small subset of ancient applications that made use of the movement in wood, such as employing the huge forces resulting from swelling during an increase in moisture content (to break stone in preindustrial quarries, or the self-sealing capacity of traditional wooden casks), it is difficult to find examples in industrial applications, where the movement of wood is actively utilized to perform a functional task.

1.4. Composites and anisotropy

Wood's properties are realized through the constitution of its cell walls; its natural composite tissue possesses similar constituents to synthetic fibre reinforced polymer materials—for example a glass fibre composite. In both cases, composites are assembled out of a fibrous and a matrix component. While for the matrix of a synthetic composite, a polyester or epoxy resin is commonly used in combination with carbon, glass or aramid fibres, wood consists of cellulose fibrils, as well as hemicelluloses and lignin as the matrix [30]. Since the wood cells are mainly oriented along the stem axis of a tree, there is a dominant directional component to the material property—a material characteristic also known as anisotropy.

1.5. Hygroscopy

Hygroscopy describes the ability of a material to absorb (absorption) and release (desorption) moisture from the surrounding atmosphere to constantly maintain a relative equilibrium with its surrounding environment [31–33]. In wood, water molecules are primarily absorbed in the cellulose and hemicelluloses tissues (bound water). The moisture content of wood, calculated as a function of weight of water and wood substance, finds its fibre saturation point (FSP) at around 27%–30%. In this state, the maximum of bound water has been absorbed while any additional water is merely stored as so-called 'free water' in the cell cavities. In comparison to bound water, free water has only minor influence in the overall mechanical properties of wood. However, a decrease of bound water reduces the distance between the micro-fibrils of the cell tissue resulting in a significant dimensional change and an increase of mechanical strength due to interfibrillar bonding. Therefore, the physical change of the anisotropic material possesses three different coefficients: (1) longitudinal shrinkage (or parallel to grain), which is considered negligible (2) tangential to the growth rings, which is significant shrinking (i.e. 8.0%–8.9% for maple) and (3) radial shrinking, which extends from the stem centre towards the bark (i.e. 3.0%–4.4% for maple) [34,35] (Fig. 2).

Fig. 1. Cone of conifers (*Pinophyta*) in (A) high moisture content (MC) and (B) low moisture content (dry condition). Even after the cone has fallen off the tree, the material's intrinsic performance within the cones' scales remains. The moisture content in the scales changes as it finds equilibrium with the surrounding humidity level ((C)–(J)).
Source: Images courtesy of Iva Kremsa, Kenzo Nakakoji and Etien Santiago.

1.6. Earlier work

Prior work by the authors includes the development of physical prototypes that show similar performance characteristics to that of conifer cones. In the authors' *Responsive Surface Structures* (RSS1) (Fig. 3(c)) the hygroscopic behaviour of wood in relation to differentiated geometry is explored through a large physical mock-up [20,21]. Computational methods and computer-controlled fabrication machines enabled the design and production of the uncoated wood veneer structure consisting of 1800 individually unique pieces forming 600 folding elements and its corresponding reactive top layer veneer (Fig. 3(a), (b)). The geometric arrangement of the folding elements follows the normal vectors of the underlying surface (a Non-Uniform Rational *B*-Spline (NURBS) surface in this case), while the curling deformation is enabled by local moisture increase on one side of the reactive top layer veneer. The authors expand the work further in *Responsive Surface Structure* 2 (RSS2) (Fig. 3(d)–(f)) by incorporating the use of generative algorithmic design methods based on other biological principles like heterogeneity, hierarchy and anisotropy [36]. The system is developed around cells formed by concentrically arranged responsive elements—forming polygonal apertures. Unlike RSS1, the overall geometric arrangement is independent from a high level topological surface; instead, it follows a unidirectional heterogeneous cell structure of controlled variation by positioning each cell next to each other in a spiral sequence. Although visually similar to a Voronoi-based tessellation [37], this distribution system refers more to a growth algorithm as each new cell is successively constructed aside its neighbours. Moreover, the cells are not connected to a structural understructure. The additional thickness increases the structural strength and drastically decreases the responsiveness of the material—a suitable condition for the understructure. In this case, to further enable the hygroscopic deformation, a synthetic coating is applied on one side of the responsive veneer to increase the differential expansion between the two layers. A major drawback in this earlier research was the need for direct wetting of the veneer (through water spray) to activate the curling deformation. Although effective, this method leads to plastic deformation and increased material decay (*see* 4.2 *Material Limitations*). The presented research presents a more robust and highly

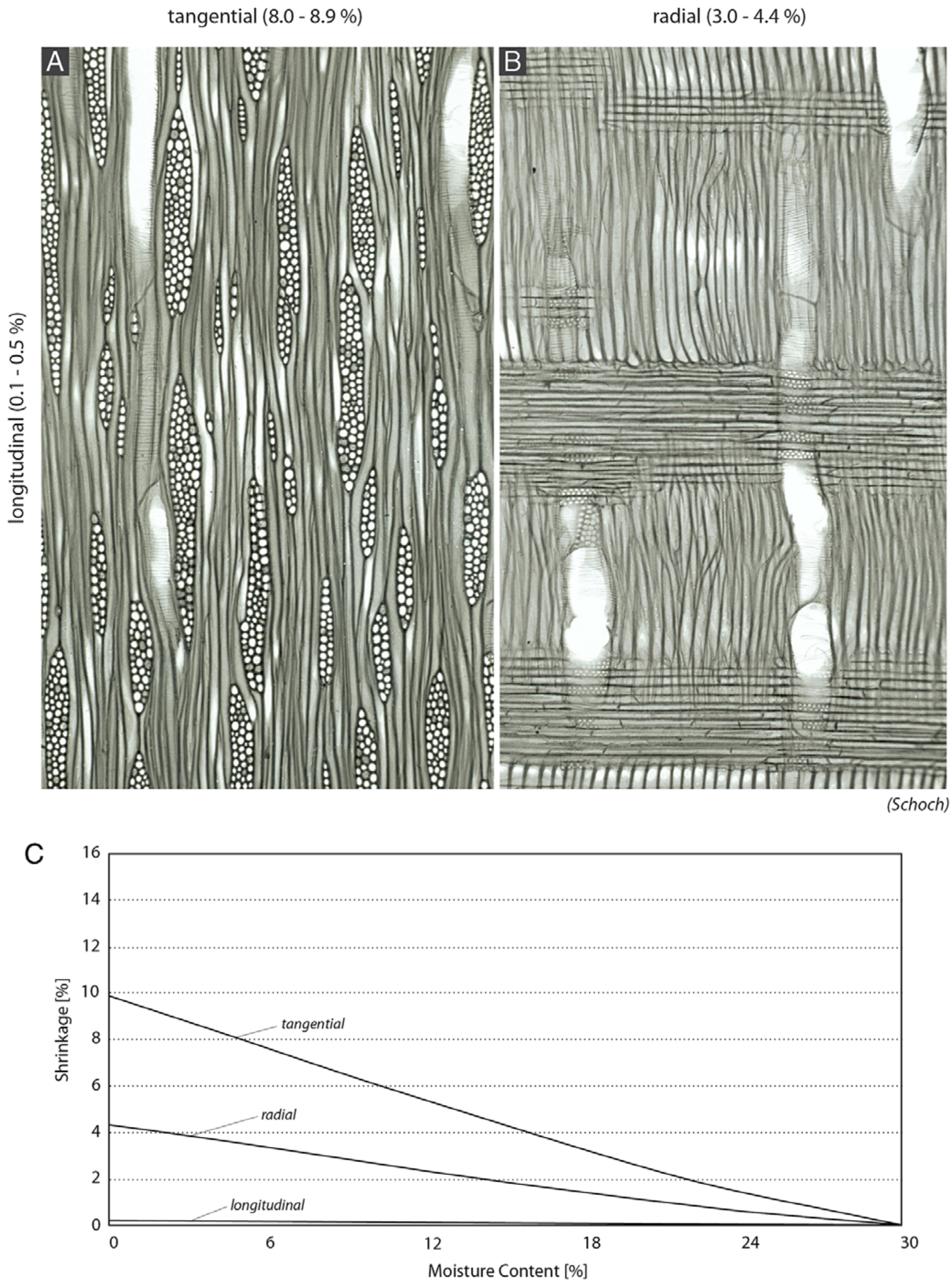

Fig. 2. The fibrous, anisotropic material composition leads to differentiated swelling and shrinkage behaviour (A + B). The graph (C) shows the relation between the shrinkage and moisture content of maple.
Source: Images courtesy of Werner H. Schoch.

programmable system, which enables a wider range of applications.

2. Materials and experiments

2.1. Development of a semi-synthetic, biomimetic responsive material system

Through the understanding of the microstructural principles that facilitate hygroscopic actuation in the pine cone, suitable analogues can be developed to produce a similar responsive motion to that of the presented cone. The research also presents an opportunity to utilize the actuation principle of the pine cone at larger scales. In this way, the cone's principle of transferring an anisotropic dimensional change into a shape change can be utilized in developing a humidity responsive, integrated technical system. A suitable starting point for doing so is employing the anisotropic dimensional change of wood as the actual responsive layer within a technical composite element. Wood (from the stem) can be considered to be the most effective and closely related material to the specialized woody scales of the cone as it has similar material make up and hygroscopic behaviour. Although the vascular tissue of the stem does not present the specialized microstructural arrangement required to achieve the same motion, it does possess hygroscopic properties that create dimensional changes in the material, namely, shrinking and swelling. These are

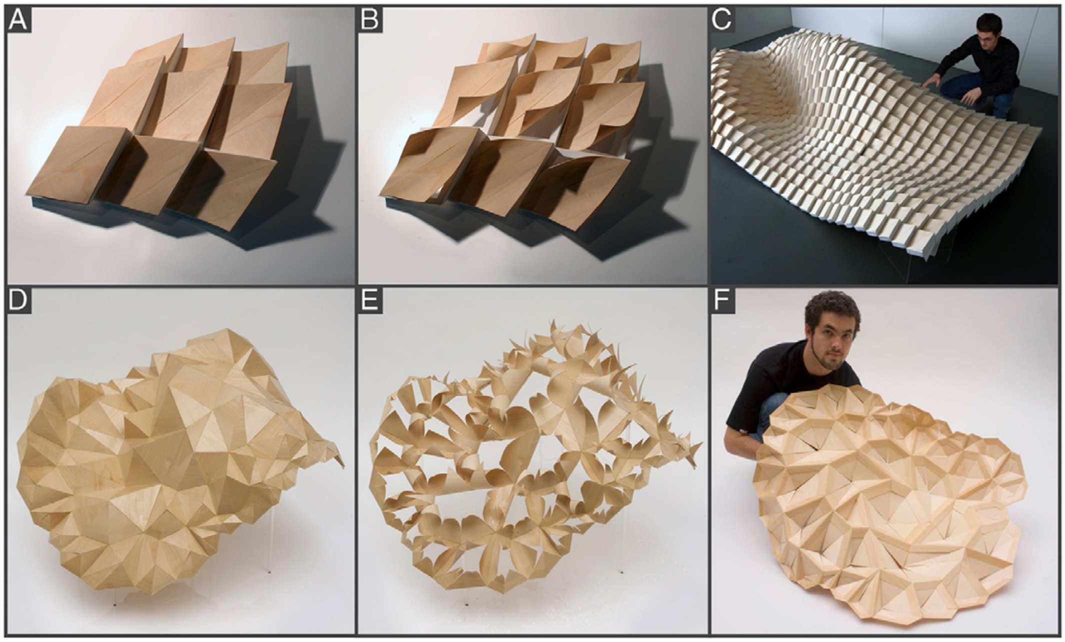

Fig. 3. Responsive Surface Structure 1 (RSS1); Array of nine cell components with hygroscopic veneer top layer in (A) closed state, (B) open state and (C) overall display configuration. Responsive Surface Structure 2 (RSS2); (D) closed and (E) open condition; (F) rear view.

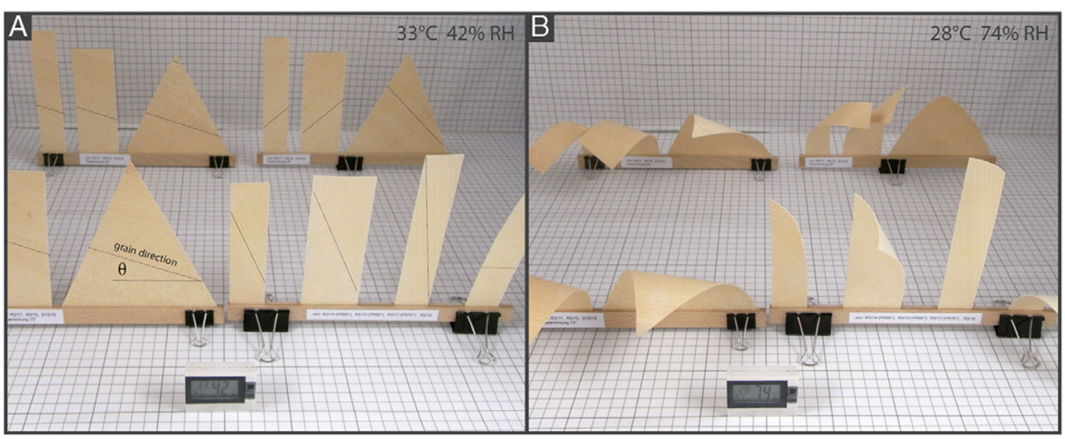

Fig. 4. Demonstrating dependencies between direction of grain (A) and direction of deformation (B). The greater θ, the smaller the deformation.

important functional properties, as they are dependent upon the relative humidity level of its surrounding environment; a specific increase in moisture content will consistently induce the same amount of swelling. In the simplest case, a control experiment exposing one layer of the material to a different humidity level than the other can easily induce differential expansion between the two layers. If the sample is thin enough, the material responds by dissipating the stress through an elastic deformation of the overall shape—that is, a curling of the material. This behaviour is not only predictable and reproducible but also highly reversible. The authors have conducted an extensive series of experiments to explore, analyse, manipulate and calibrate the various parameters affecting the behaviour of wood (Fig. 4).

The following are the critical influencing parameters of the developed programmable veneer–composite system:

(a) *Wood type and sample selection*—The molecular constitutions of various wood types show significantly different hygroscopic and structural properties (Fig. 2). To find the most suitable species for the presented application it was necessary to research and test a substantial range of wood species. Given the environmental exposure of the material and the cyclical nature of its actuation, the most suitable wood also needs to address a number of other performance parameters beyond hygroscopy. Some of these key parameters included: homogeneity of grain directionality, brittleness, density, commercial availability and fungus resistance. Through this empirical research, it has been identified that although beech (*Fagus sylvatica*) shows superior hygroscopic behaviour (tangential shrinkage of ca. 11.8% for beech vs. ca. 8.0%–8.5% for maple [35]), European maple (*Acer pseudoplatanus*) demonstrates better overall performance due to a number of other key parameters, such as a lower modulus of elasticity (9400–11 400 N/mm^2 vs. 14 000–16 000 N/mm^2 for beech) [35], marginally better resistance to decay and greater homogeneity in grain [35]. As a result, for all presented experiments, only quarter cut veneer (German: Schnittfurnier) of maple was used. Moreover, consistency in the sample selection and the type of wood used for all the experiments allows for a more rigorous understanding of the material behaviour and the parameter effects on the samples.

(b) *Fibre directionality*—As previously established (see Section 1.3), the hygroscopic behaviour of wood is directly related to the cellular structure and the micro-fibrils angle in relation to

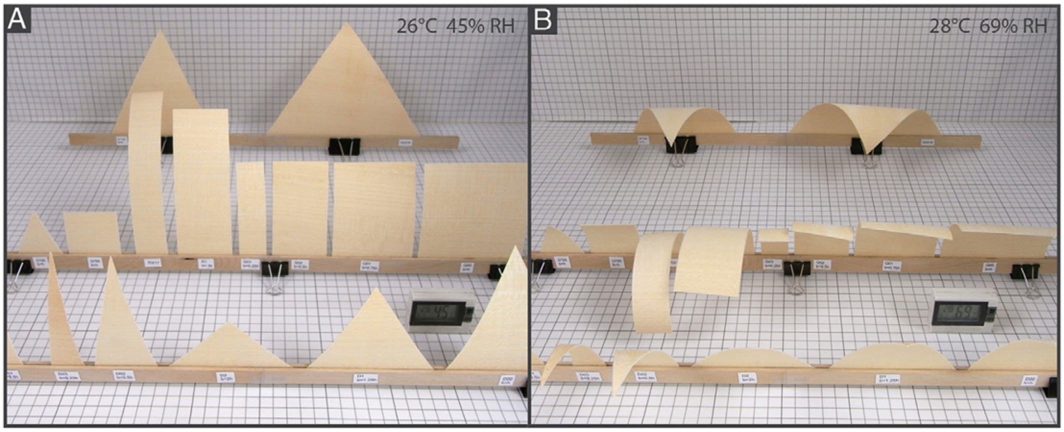

Fig. 5. Empirical tests show that the shape of elements influences the degree of deformation. Given the same conditions, narrow-long pieces appear to produce a smaller curvature than wide short specimens.

the cells axial direction. Therefore, the hygroscopic elongation appears perpendicular to the fibre direction. The grain pattern can consequently function as a visual indicator for the curling motion while enabling prediction and steering of the veneer's movement (Fig. 4).

(c) *Composite behaviour, layout of the natural and synthetic composite*—A semi-synthetic material system is developed through the combination of a climate responsive and a climate independent layer on each component. The composite mechanism allows the steering of the hygroscopic motion and the ability to achieve constant linear actuation in homogeneously surrounded but time-dependent variable conditions. Various tests employing different climate independent layers for the veneer pieces have been performed ranging from silicones, polyurethanes, polyester resins, epoxy resins and various composites. Such tests have led to the development of a specific synthetic composite mixture of glass fibre and an epoxy bonding, which allows for the application of a consistent material thickness and the ability to maintain constant material quality.

(d) *Dimensional considerations, relation between size, shape and material thickness*—The speed of the curling motion is related to the ratio between thickness and size as well as the overall geometric shape of the piece. Thicker material samples require more time to balance their moisture level with the external environment and therefore will withstand the intrinsic deforming forces for a longer period, while conversely; thinner samples will react more quickly. Moreover, in longer pieces (cut across the grain) the change of curvature results in greater travel of motion (Fig. 5).

(e) *Environmental control*—As established earlier, wood presents very specific behaviour in response to changes in environmental conditions. These conditions are dictated by a range of variables, parameters and functions that are deeply interrelated to each other. The presented experiments show that shrinkage and movement (expansion) of wood take place in direct response to the surrounding relative humidity. Since relative humidity is calculated as a function of absolute moisture and air temperature, warm air is able to contain a higher amount of water than cold air. Thus, within a given absolute humidity (physical amount of water within the air) the relative humidity of warm air is lower than that of cold air. By manipulating the reciprocal relationship between air, moisture and temperature, it is possible to influence the climatic conditions within the test chamber. Therefore, relative humidity can be manipulated through the following four methods: by increasing (i) or reducing (ii) moisture content in the air and by increasing (iii) or decreasing (iv) air temperature. To increase moisture content (i), two types of humidifiers were tested. An ultrasonic humidifier, which uses ultrasonic frequency waves to saturate the air with fine mist droplet, and a vaporizer, which boils water, increasing humidity through steam. The latter can increase the moisture content in the air more rapidly but it also increases the air temperature. Alternatively, it is also feasible to (ii) decrease the absolute humidity level through the use of commercial dehumidifiers, which have shown reliable results in reducing moisture content but may in some cases have a tendency to increase air temperature. As a critical parameter, temperature needed to be controlled and accounted for during the experiments as it can directly or indirectly affect relative humidity. Increase of temperature (iii) can be achieved by either heating the air (convection) or through thermal radiation. While thermal radiation can locally trigger the reactive behaviour by affecting the relative humidity level on the interface layer between the element and the air, temperature changes through air convection provide a more global yet stratified alteration (Fig. 6). Finally, air temperature can be lowered (iv) through air-conditioning equipment; in this case, the environment's relative humidity can be raised without the contribution of additional moisture. As a result, the presented experiments were executed under a climate-controlled environment using a custom designed, sealed climate chamber. The climate conditioning was provided by a separate commercial humidifier and a dehumidifier with their respective hygrometer control units. The climate conditioning system can be programmed to maintain either, a constant humidity level or to generate specific scheduled variation. The climate controlled set-up allowed for the material test to undergo sufficient cycles under consistent conditions ensuring accuracy in the results. During the experiments, humidity levels were simultaneously measured by several hygrometers to detect and eliminate measuring errors.

(f) *Material calibration through fabrication:* The same level of environmental control carried through the testing must also be maintained during the fabrication process. Careful control of the environmental conditions enables the linking of a specific curvature state to a determined humidity level. As shown in (Fig. 7), this method not only allows for the fine tuning of the range in which the hygroscopic behaviour occurs, but it also allows for the opening process to be even inverted through an antithetical parameter calibration during the fabrication process.

(g) Reaction time: The designed material is in constant feedback to its environment trying to equalize moisture content. The

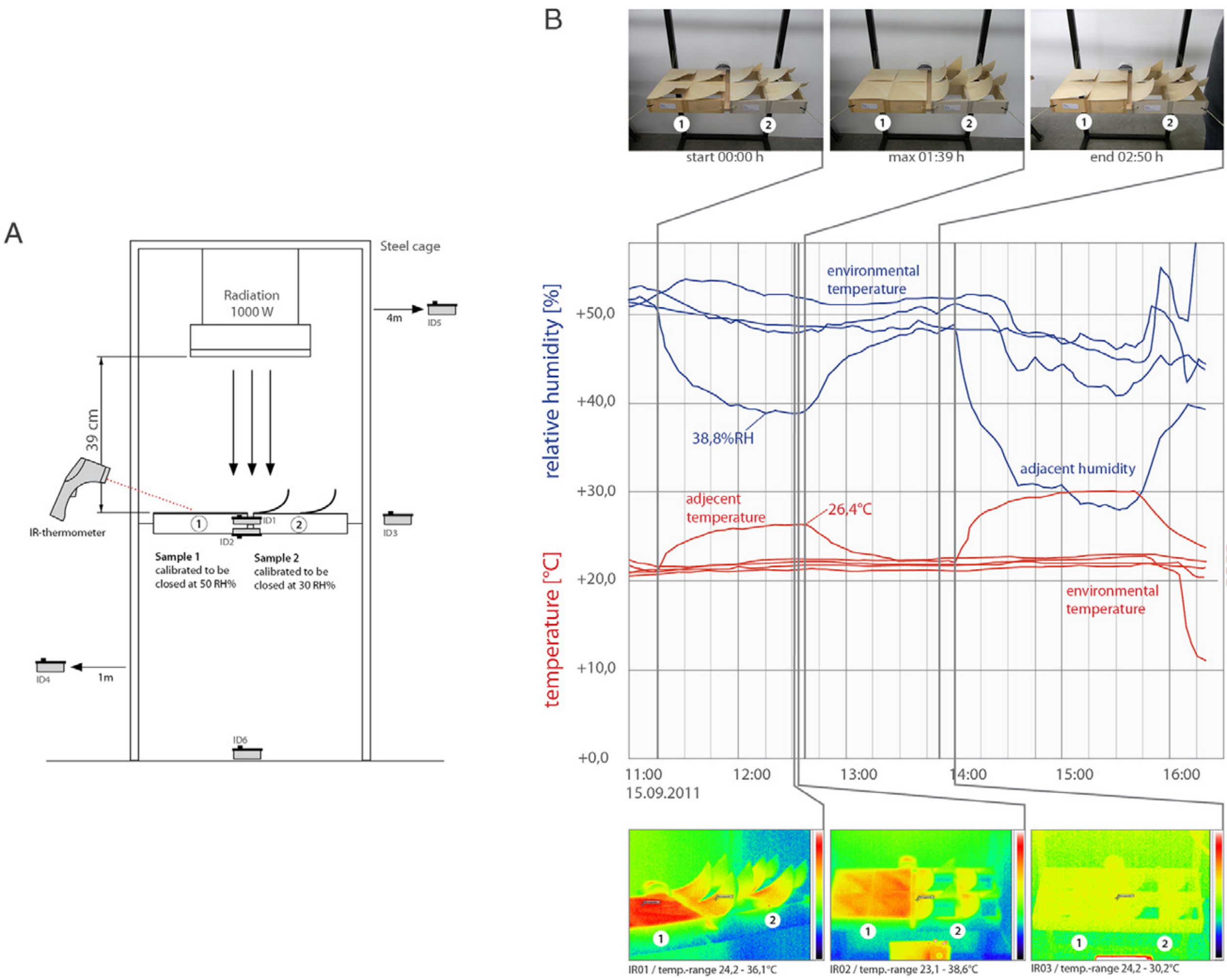

Fig. 6. (A) Experimental setup for thermal radiation test. A radiation source was positioned at 39 cm from the specimens. Specimen 1 (left) was calibrated to be flat at 40 RH% and specimen 2 at 70 RH%. (B) The experiment was monitored by an array of wireless humidity and temperature sensors, while an infrared camera was used to capture the heat distribution triggered through the radiation source.

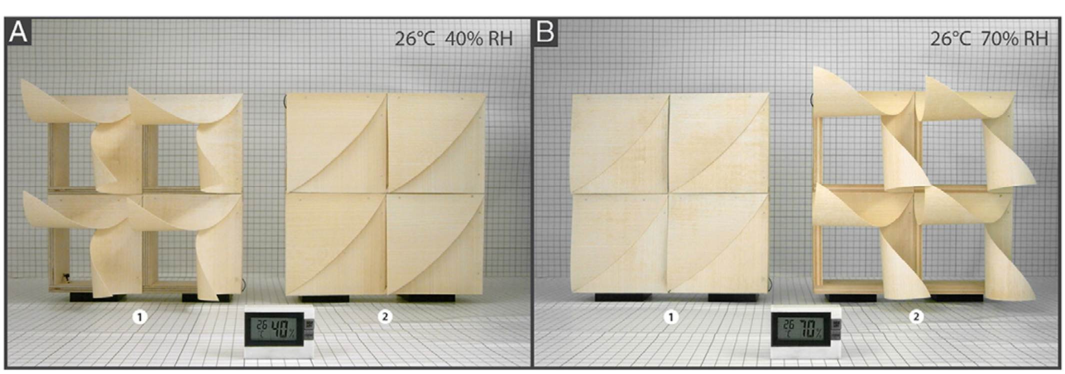

Fig. 7. Through the manipulation of the fabrication parameters for the reactive veneer–composite, it is possible to calibrate the material to react within a specific humidity range. Here, with an increasing relative humidity level, specimen 1 (left) closes while specimen 2 (right) opens.

speed of the reaction time results from all previously presented variables. The authors have performed various experiments (Figs. 3–9) to receive an understanding of the relationship between the material and environmental changes as discussed (see Section 2.1(e)). The fastest opening process of only 4 min and closing process of only 17 min (Fig. 8) were achieved utilizing a steam-based humidifier in series with a 1000 W thermal radiation source; both were positioned at approximately 0.75 m away from the specimen.

2.2. Geometric arrangement

In addition to manipulating the behaviour of the responsive material system on a material level or on the level of an

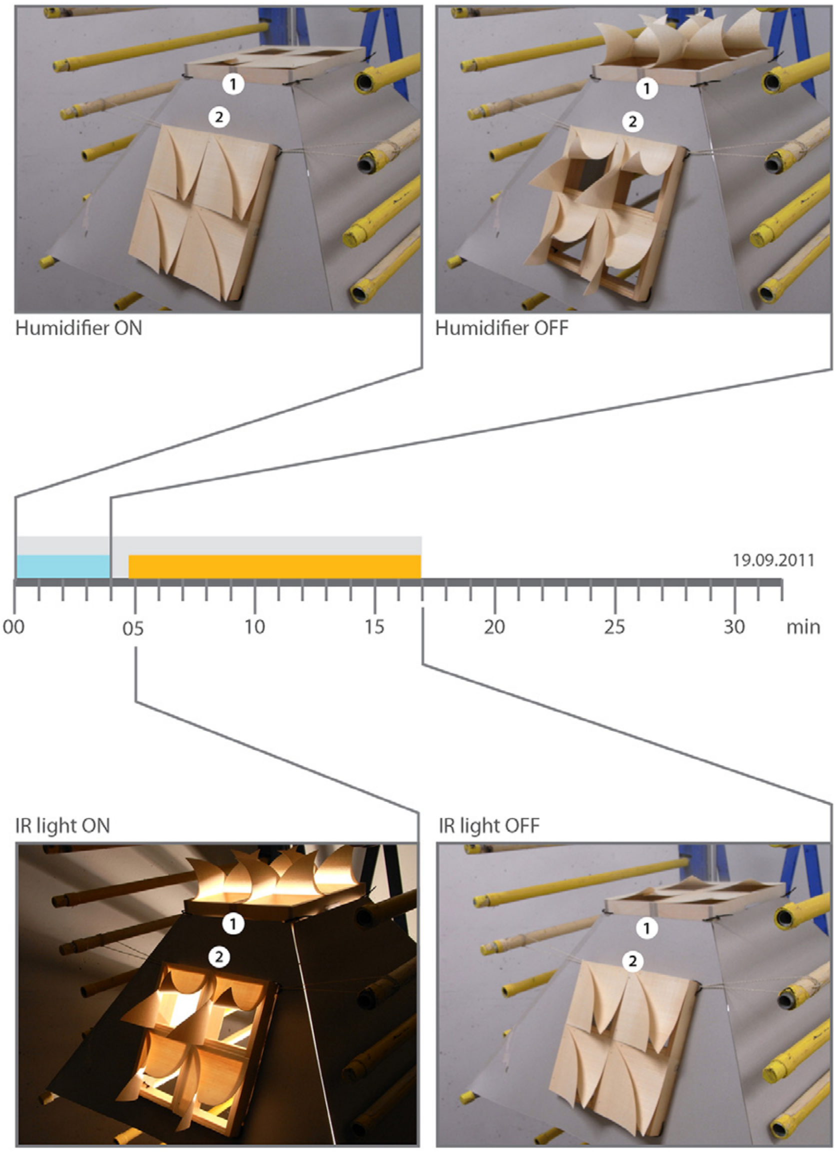

Fig. 8. Using a steam-based humidifier and a radiation source, the responsive reaction time can be accelerated. With this configuration it was possible to achieve full opening of the mechanism in under 3 min while the closing process time was reduced to only 12 min.

individual veneer piece, the geometric arrangement can also have a major influence in the overall performance of the responsive system. Different geometric opening mechanisms (components) (Fig. 9) demonstrate very diverse behaviour in terms of topological distribution, degree of openness (porosity), directionality and behaviour consistency. For instance, types 1–3 (Fig. 9(a)–(f)) encompass and all planar articulations where the elements are arranged tangential to the reference surface but through different orientation of the reactive veneer elements perform very different opening patterns: type 1 with centred, type 2 with alternate and type 3 with adjacent configuration. Through rotating the reactive elements out of the reference surface into a perpendicular configuration of type 4 (Fig. 9(g)–(h)) that geometrical articulation inverts the behaviour of the system. In contrast to types 1–3 where porosity increases through curling, in type 4 the system closes through an increase in curvature. In addition to rectangular tessellations, type 1–4 (Fig. 9(a)–(h)), reactive elements can be also oriented in linear (Fig. 9(i)–(j)) or polygonal (Fig. 9(k)–(l)) groups to produce very different appearances. For the presented prototypes, the latter polygonal articulation (Fig. 9(k)–(l)) was of particular interest; being independent of a grid based subdivision method, it allows for geometric freedom for tessellation while also having angled oriented reactive elements that display a very high degree of porosity.

2.3. Performance characteristics of material system

To further understand the performance characteristics of the material a long-term test was set up using a 5 × 5 array of reactive components. An initial laboratory testing phase provided verification on the expected responsive behaviour and curling deformation under the pre-determined operational atmospheric range—Stuttgart (Germany) conditions. The outdoor long-term performance test was actively monitored over a two-year period.

(a) *Laboratory testing:* The specimen was initially set up in a homogeneous climate chamber and conditioned to 80 ± 5% relative humidity. The controlled laboratory conditions provided an ideal set up to verify a homogeneous opening and closing motion across the array (Fig. 10). However, an additional set up was performed to generate a differentiated gradient of moisture content across the chamber. By a controlled increase in humidity through a localized emitter, it was possible to visualize

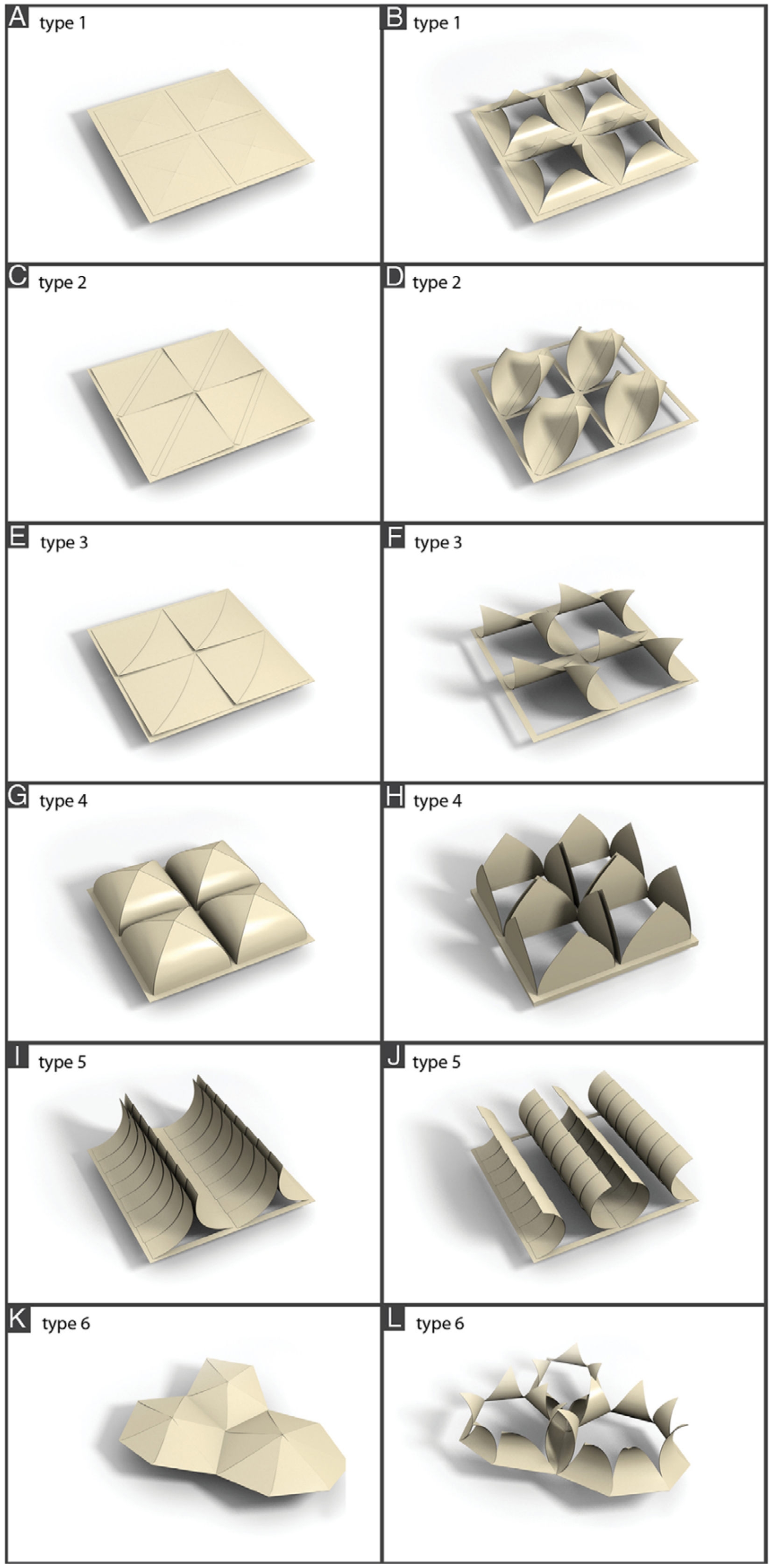

Fig. 9. Different geometric arrangements of the reactive material allow for different degrees of porosity and operational functionality. Type 4 (G–H) closes with smaller curvature while e.g. type 1–3 opens.

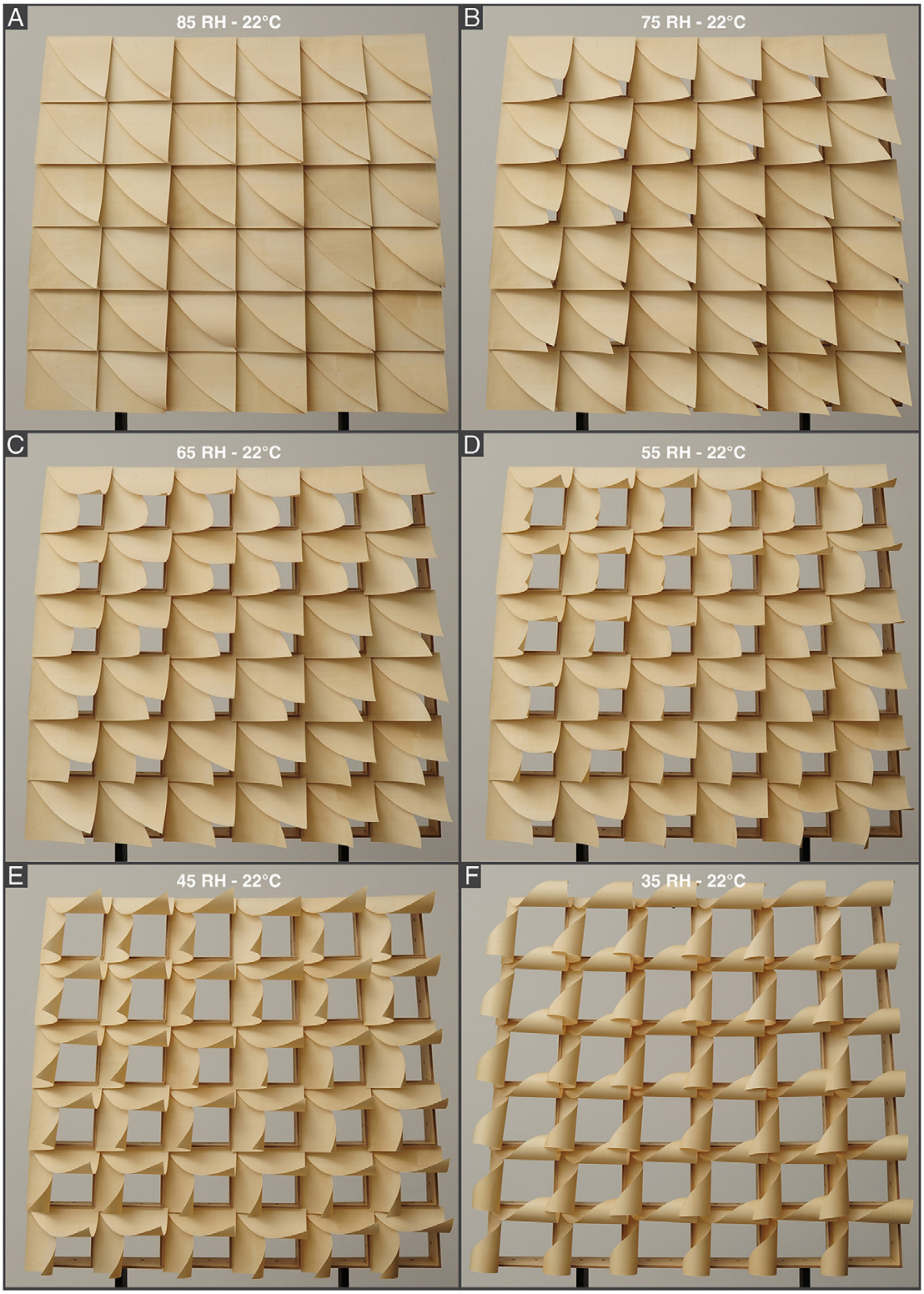

Fig. 10. Laboratory test of a 6 × 6 array of elements under controlled climatic conditions. Global changes in humidity levels coupled with appropriate material quality controls during fabrication enable a homogeneous opening and closing motion across the array. From fully closed (A) to fully open (F), the veneer performs various formal states as moisture is removed from the air.

the system's autonomous decentralized adaptiveness (Fig. 11). Since sensor and actuation is immanent in the material itself, such complex localized behaviour is natural to the system. It significantly enhances the functional robustness and constructional simplicity of the system as compared to mechanically and/or electronically driven systems.

(b) *Outdoor long-term testing*—The two-year test period provided the opportunity to monitor and record the long-term behaviour of the material (Fig. 12). Both daily and seasonal cycles were evaluated providing valuable insight into the long-term behaviour of the system. The test showed a surprisingly consistent hygroscopic behaviour over the two years, maintaining substantial responsive behaviour (range of motion and actuation) while continuously performing thousands of cycles. As indicated in Fig. 10, the setup was calibrated to fully open at

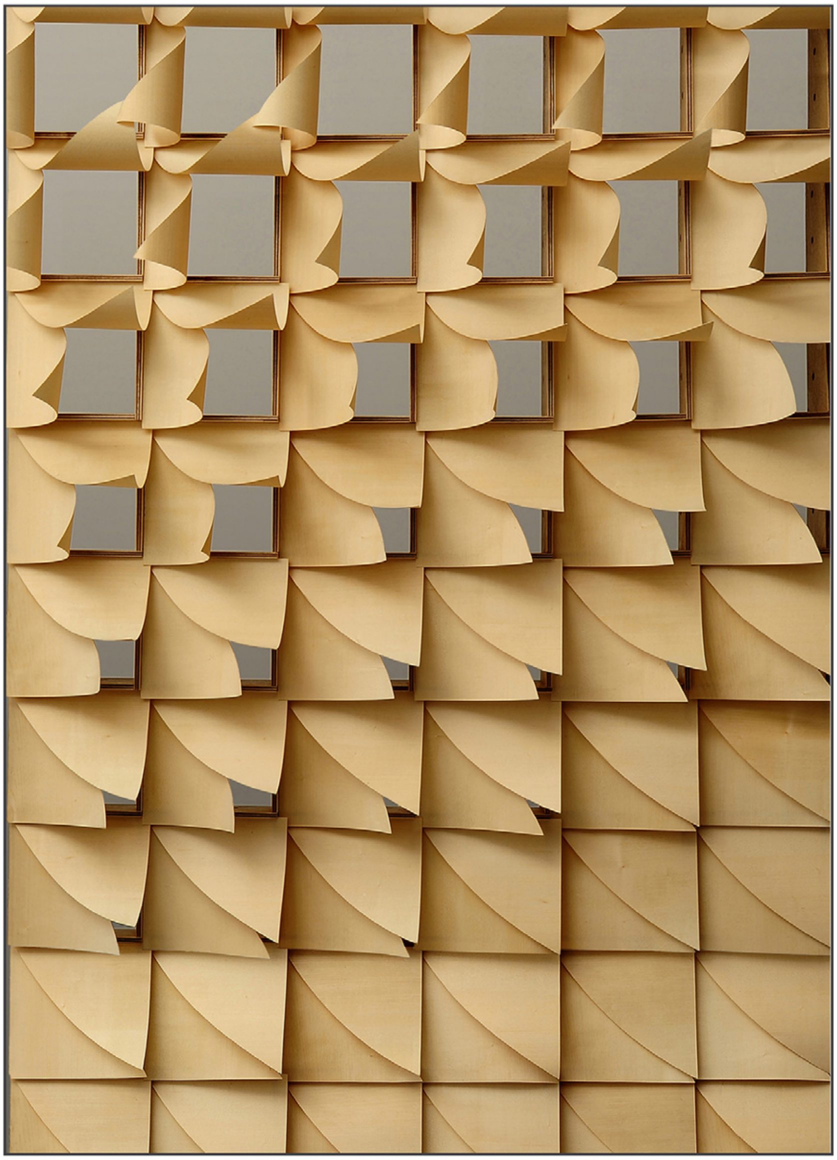

Fig. 11. Decentralized control and responsive behaviour. Local changes in relative humidity results in localized changes in porosity.

around 40 ± 3% RH (relative humidity) and to close at around 80 ± 3% RH, a common humidity range for Central European climate (see Fig. 13).

2.4. Simulation methods

Real-time simulation of the curling motion greatly supports the design process by allowing pre-visualization of morphological changes at various stages and the troubleshooting of problematic stages that may cause interlocking between elements. Additionally, a secondary collision detection indication routine has been implemented to visualize, identify and resolve the intersections of pieces in complex multi-component assemblies. The digital curling simulation has been addressed using two different approaches: (a) a linear geometric representation model (GRM) and (b) a non-linear simulation model using a non-linear spring-based method (SSM).

(a) *Geometric representation model*—The geometric representation model (GRM) approximates the curling motion by simplifying the curvature to specific curling behaviour using digital geometry representation. (Fig. 7(a)). The approximated model is based on optical measurements of physical, empirical tests and can cover the entire range of motion (Fig. 14) while allowing for a seamlessly integration of the varying states into an associative geometry model. Empirical tests indicate that most triangular specimens show more travel than those that are rectangular. It is speculated that this phenomenon is related to a decreased bending resistance towards the tip of the element. The GRM's simplicity and correlated low computational complexity enable complex assemblies with numerous individual pieces to be digitally deformed and analyzed at various stages. Since the actuation is not simulated but approximated geometrically, various stages of deformation can be easily drafted at any given point providing fast and reliable feedback to the designer.

(b) *Spring-based simulation model*—The non-linear spring-based simulation model (SSM) simulates the expansion of the material by using a spring-based method (Fig. 14). Through a three-dimensional topology of elongating springs, the three expansion coefficients (radial, tangential and longitudinal) of wood can be directly inserted into the model; in this way, the behaviour of geometries with various shapes, thicknesses and complex fibre directions can be simulated. Accuracy of

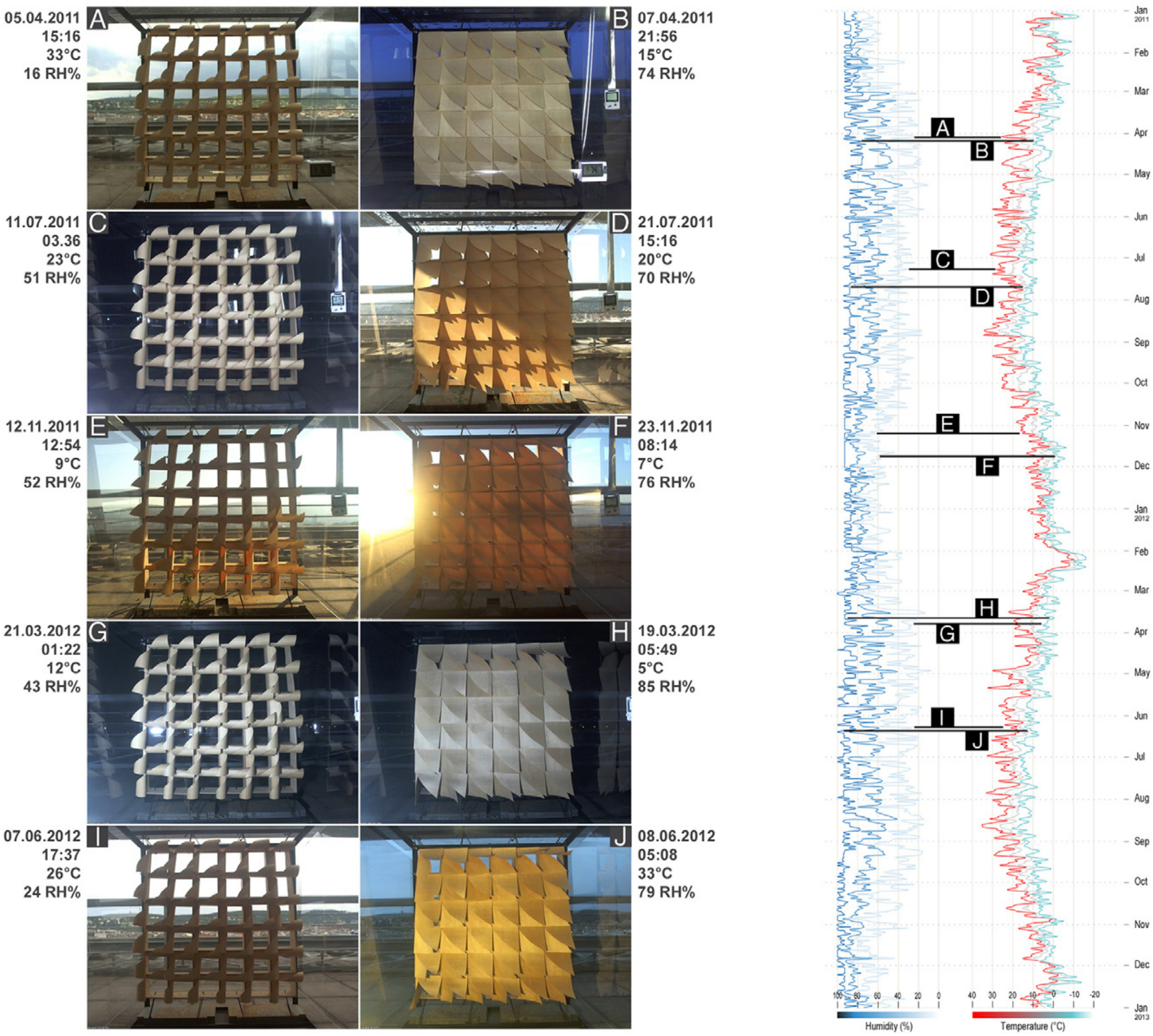

Fig. 12. Long term performance test, over a two year period, a 6×6 reactive specimen was exposed to Central European atmospheric conditions (Stuttgart). While protected from direct precipitation, the specimens maintained a consistent range of responsive motion and actuation over thousands of cycles.

the simulation can be adjusted by the resolution of the topology. Although this method can provide more extensive information on the system's behaviour, its integration into a design model requires increased computational resources. Additionally, depending on the computational platform used, this method can present difficulties in providing accurate geometries at intermediate simulation stages (not fully curled).

3. Results

3.1. Architectural prototypes

The two physical prototypes discussed in this paper present an autonomous responsive architectural system that has been achieved through a biomimetic rather than an electromechanical paradigm. The projects build upon the previous research on material embedded programming with passive, autonomous hygroscopic actuation, while suggesting an architectural approach based on inherent material behavioural capacities that can respond to exterior climate changes.

The following prototypes demonstrate the range of performance capacities enabled by the previously developed responsive system. While the "HygroScope" prototype is configured to open as relative humidity levels increase, the "HygroSkin" prototype follows the converse response, closing under high relative humidity levels. Both demonstrators offer a tangible direction towards an integrative design process where design thinking involves the development of responsive and systems (Fig. 15).

3.2. Meteorosensitive morphology: HygroScope installation, Centre Pompidou Paris

The installation '*Hygroscope—Meteorosensitive Morphology*' was designed and realized for the permanent collection of the Centre Pompidou in Paris and was first shown in the context of the special exhibition "Multiversité créatives" (2012) (Fig. 16).

The project, being exhibited in the interior space of the museum, has to operate in one of the most stable climate zones in the world—the highly controlled indoor climate of the Pompidou that would not trigger any responsiveness. Therefore, the meteorosensitive morphology has been suspended in a fully transparent glass case with a custom, programmable climate-controlled system; the

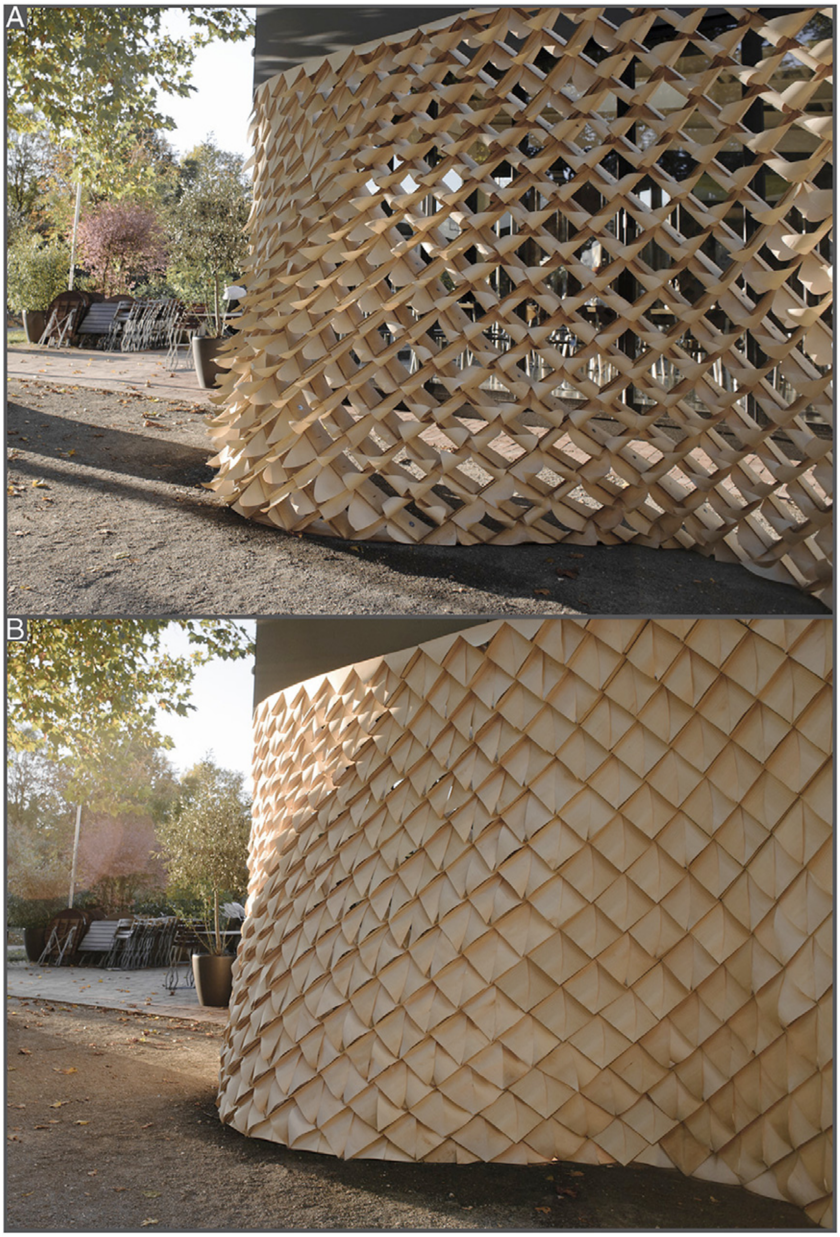

Fig. 13. Architectural building skin: A greater functional prototype constructed to explore the functional possibilities of the presented material system.

case serves as a container for the climatic patterns based on local Parisian weather data within the stable conditions of the museum. The sculpture's material assembly is programmed to acutely respond to changes in the environment's relative humidity and allows one to visually experience the otherwise invisible humidity changes of Paris. When moisture levels rise, the system changes its surface porosity to breathe and ventilate the moisture-saturated air. The climatic changes within the case directly influence the system's behaviour; therefore, the micro-climate inside the case is based on Parisian atmospheric patterns. This is achieved through the use of custom humidity control mechanisms enclosed within the case's base.

For the implementation of this project, the development of the computational construct and its generative algorithmic capacities were as important as the material system research itself. An algorithmically generated, hierarchical associative model served as visual representation to explore and evaluate aesthetics, constructive complexity and economical parameters as well as the generation basis for digital fabrication information such as milling tool paths. Robotic fabrication parameters and constraints – maximum and minimum milling angles, for example – were integrated as design boundaries within the computational construct, providing real-time fabrication feedback into the design development. Furthermore, simulated climate data (Fig. 17) was used to generate differentiated climatic zones within the system. Mimicking the dynamics of ontogenetic development, the generative algorithm derives the system through striated linear growth patterns cumulating in cellular arrangements in climatically unstable regions. The GRM (see Section 2.4) was integrated into the generative digital process to visually represent the opening and closing process of the responsive elements and to detect, verify and eliminate malfunctioning situations.

With the use of computational design and its custom generative digital model, the design of the prototype object was approached as a system with reciprocal connected parameters and allowed the designers to navigate through the design morphospace [38] of acceptable possibilities while concurrently managing the constructive complexity. The articulation of environmental parameters during the fabrication process corresponds to the parameter

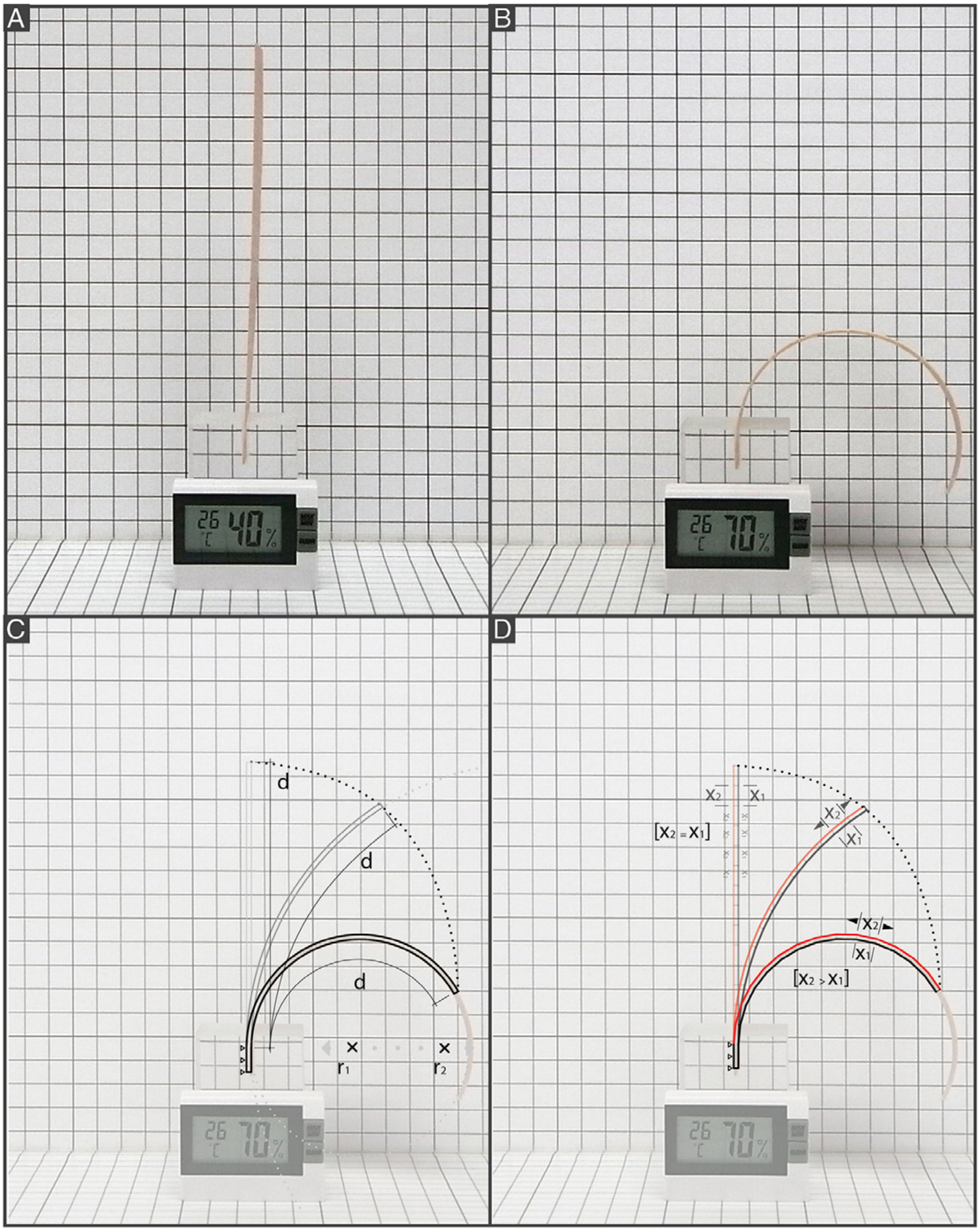

Fig. 14. Reactive veneer–composite specimen at (A) 40 RH% and (B) 70 RH%. The specimen shows circular curling behaviour that can be described using a (C) geometric representation model (GRM) or (D) a spring simulation method (SSM).

dependencies in the digital code that articulate the system's morphology.

The overall assembly of the demonstrator consists of more than 4000 singular and geometrically unique composite elements digitally fabricated from a combination of quarter cut maple veneer and synthetic composites.

The reactive component arrangement is organized in a differentiated manner performing as a physical self-constraining mechanism (Figs. 9(k), 15(a)). This arrangement allows for controlled overlapping, in sequential order, among the veneer elements while improving the ability of the members to seal the apertures or openings. The overlap can also mechanically aid and constrain the motion of the arrangement. For example, in the case where humidity levels would exceed the targeted humidity range, the geometric layout in combination with its carefully designed overlap self-interlocks into a fully constrained closed component. From that point, the motion of the cell is terminated and invagination is avoided.

The installation began operating in 2012 and it is fully calibrated to operate autonomously through its integrated computer controlled climate system (Fig. 18(c)). The custom-built climate system incorporates two separate mechanisms to release moisture; an ultrasonic humidifier generates a gradual and homogeneous climate change while a steam-based humidifier allows for very fast, localized change in relative humidity. The installation itself also functions as a long term testing experiment providing valuable performance data on the material systems and the climatic control mechanisms.

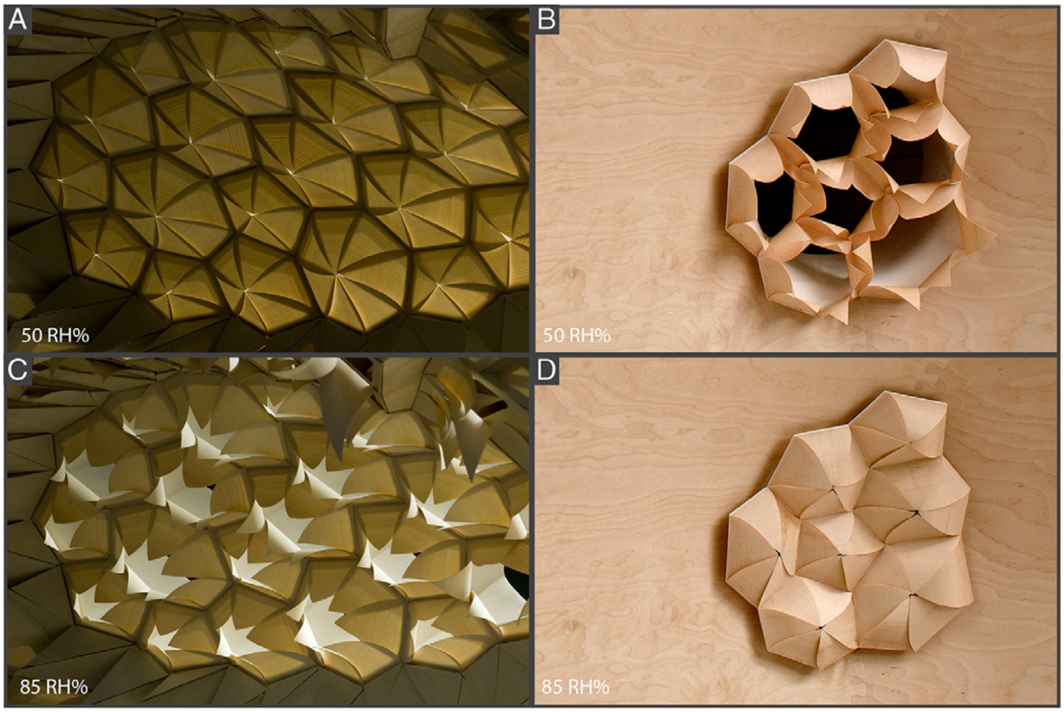

Fig. 15. HygroScope installation calibrated to (A) 50 RH% (closed) and (B) 85 RH% (open). Exterior HygroSkin installation designed to perform inverted behaviour: (A) 50 RH% to (open) and (B) 85 RH% (closed).

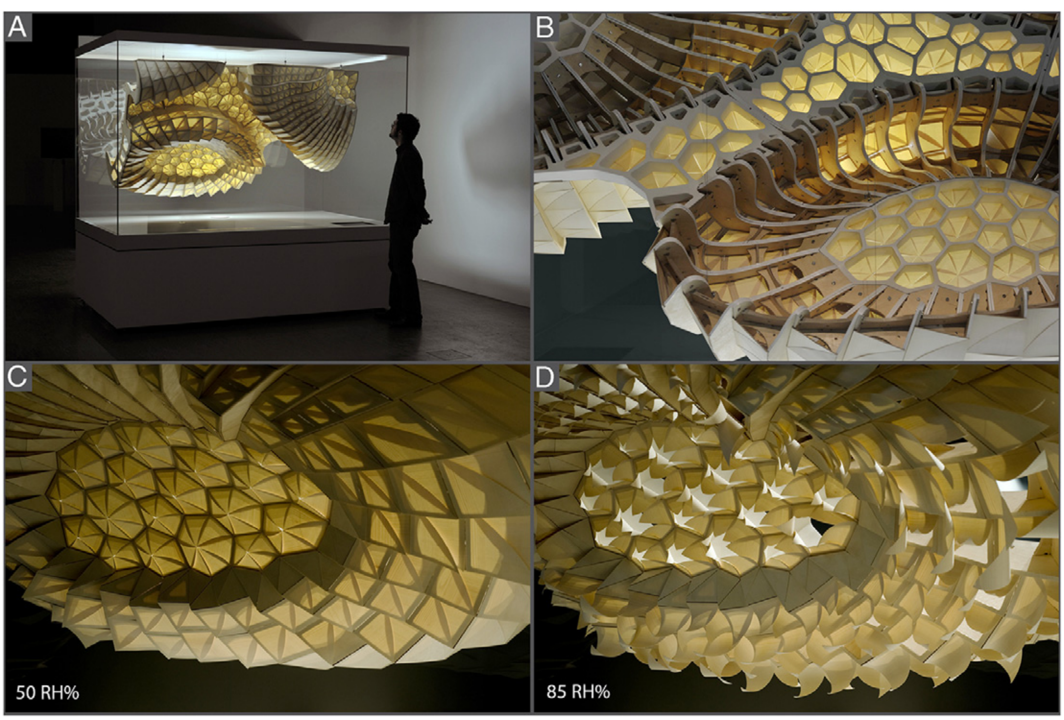

Fig. 16. HygroScope installation at the Centre Pompidou, Paris.

3.3. Meteorosensitive Pavilion: HygroSkin Pavilion, FRAC Centre Orleans

The Architectural prototype "*HygroSkin—Meteorosensitive Pavilion*" was designed and developed for the 2013 ArchiLab exhibition at the FRAC (Fonds Regional d'Art Contemporain) centre in Orléans (France). The project demonstrates the integration of a responsive material system into a functional, modular and highly adaptable system in architectural dimension (Fig. 19).

The modular assembly is composed of conical panels produced through the elastic bending of planar sheets of plywood. The 4 mm plywood sheets produce self-forming conical shapes by interlocking CNC milled puzzle type joints along their edges. Each panel becomes a "sandwich" component by enclosing a layer of foam in

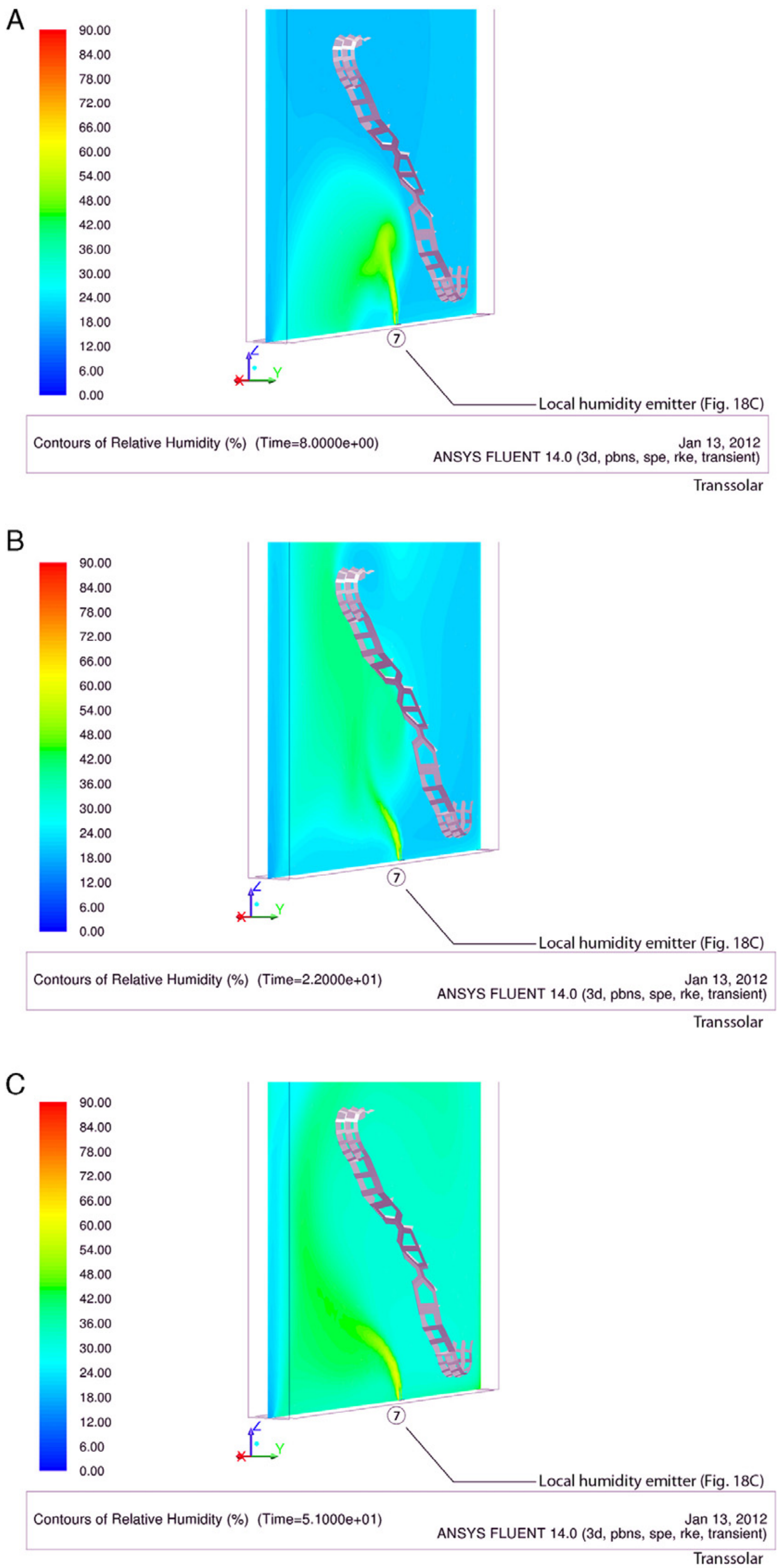

Fig. 17. CFD simulation of heterogeneous distribution of relative humidity levels within the glass case based on local humidity emitter.

between two plywood layers. This configuration ensures structural rigidity while minimizing weight. Subsequently, a lightweight vacuum moulding process normalizes any irregularities in the foam while a robotic cutting and milling process ensure dimensional accuracy. The system is not only highly adaptable but also structurally stable and lightweight. In this assembly the hygroscopically responsive elements are supported by a polyurethane lattice that geometrically mediates the linear actuation of the responsive elements in their polygonal arrangement with the conical geometry of the panels.

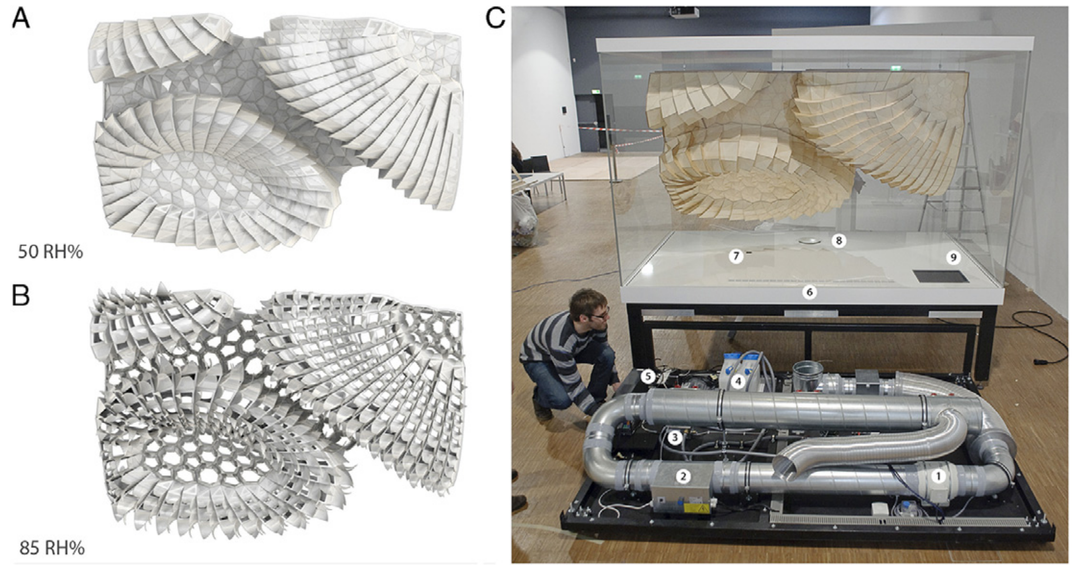

Fig. 18. (A), (B) Computational design model. (C) (1) variable displacement fan, (2) air heating coil unit, (3) ultrasonic humidifier, (4) steam-based humidifier, (5) controller unit, (6) diffuser outlet for global humidity conditioning, (7) local humidity emitter, (8) return-air intake, (9) LCD display.

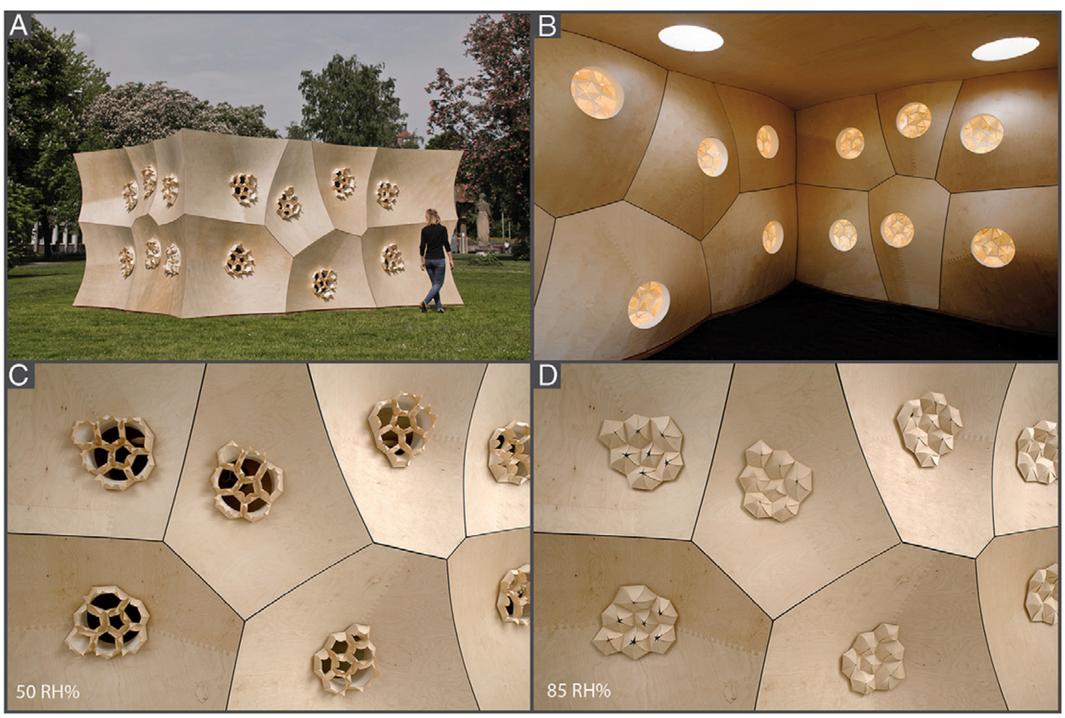

Fig. 19. HydroSkin Pavilion: (A) Temporary outdoor exhibit at Stadtgarten, Stuttgart, (B) environmental mediation of interior space through responsive apertures, (C) open and (D) close condition through calibration to local atmospheric range.

The responsive system functions as an active mediator between the indoor and the outdoor environments of the panellised enclosure. The components are calibrated to operate within the local range of atmospheric conditions (relative humidity and temperature) but the responsive behaviour is also locally affected by other internal and external conditions (occupation, radiation obstructions, etc.) (Fig. 20). To achieve this, the hygroscopically actuated veneer has been arranged into clusters of apertures that are positioned at the oculus of each conical panel (geometrically similar to '*Hygroscope*'). This configuration architecturally enhances the aesthetic role of the responsive system but it also has a functional interdependent relation; the conical shape of the panel provides protection to the responsive veneer from precipitation and focuses the exchange of flows (air, heat, moisture, light, etc.) into a discrete area. Reciprocally, the oculus-responsive assembly fits the formal space in the curvature of the panel (dictated by the radius of the oculus) beyond the elastic range of the plywood sheets, which form the exterior surfaces of the panels; thus, forming a highly performative and materially informed architectural assembly. Due to the material performance characteristics presented earlier (see Sections 2.1(a), 2.3(a)), the decentralized adaptiveness of the system enables a dynamic range of concerted responses, encompassing global changes from larger cyclical occurrences in atmospheric conditions (RH and temperature, seasonal or daily) with localized micro-climatic conditions due to solar radiation or occupancy. Within a single daily cycle, the *HygroSkin Pavilion*

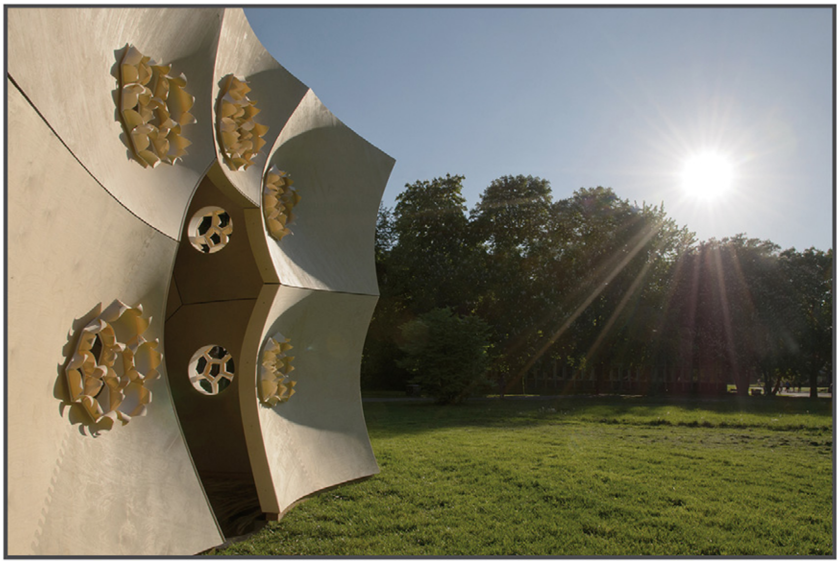

Fig. 20. HydroSkin Pavilion. Decentralized response of elements due to localized changes (solar radiation). Elements not yet exposed (top and bottom right) still partially closed before global RH drops or a localized change takes place due to exposure to the morning sun.

choreographs a seamless, autonomous and multi-dimensional experience; over 24 h, changes in solar angles, air temperature and use enable a singular responsive performance.

4. Discussion

4.1. System design methodology

Sensory technology gathers, storages and catalogues a multitude of information about users, environments and processes at a global scale. This information not only presents the multitude and variation inherent within a complex system but it also forms the basis for gaining further understanding into the reciprocal relationship that exists between parameters, constraints, input and output influences. This understanding renders imperative the development of architecture as a system rather than as an isolated object or space.

The presented research demonstrates two main innovative shifts in paradigms for design. The first examines sensing, actuation, control and power as design functions outside of an electromechanical paradigm. Through the instrumentalisation of the intrinsic hygroscopic properties of wood in combination with its custom computational and fabrication tools, structures can be designed and fabricated that show energy efficient, highly complex decentralized behaviour without the use of electronic equipment—leading to a different perception for design solutions. The second innovative paradigm considers computational design tools as enablers for a reciprocal engagement with the multi-dimensional design morphospace. While this capacity serves the basis for managing a higher degree of constructive complexity it simultaneously facilitates the potential for higher efficiency and reduced material usage.

4.2. Material limitations

The development of the material system presents some technical challenges that need to be considered and further expanded on through future research. One such aspect involves the dimensional limits and homogeneity between samples; Maple veneer usually offers very linear grain but all samples still require fairly rigorous quality control to ensure consistent grain curvature. However, given the organic and extensive parameters of wood as a vascular tissue, the length of the reactive elements is limited by the commonly available veneer sizes. The length of the veneer piece is generally perpendicular to the grain and therefore limited to the average tree width. Common stock material is available in quarter cut veneer ranging from 120 to 200 mm in width, limiting the maximum workable width to about 180 mm. Additionally, current designs rely on a homogeneous, linear grain pattern for all the elements. This fibre topology allows curling in a constant cylindrical manner.

Wood that is kept constantly dry does not decay and wood that is kept constantly submerged does not decay significantly regardless of the wood species [34,35]. However, great variations in temperature and humidity render the material more susceptible to fungi, particularly in high humidity and high temperature areas. Direct exposure to moisture on the responsive veneer by "wetting" through either water spray or precipitation triggers an accelerated moisture intake by the system but it also requires a longer time to lose, by diffusion, the additional unbound water. As presented earlier, dimensional changes in the material beyond the saturation point are considerable [31] but any additional moisture beyond fibre saturation point – as unbound water – reduces the response time of the system while increasing the susceptibility of the system to fungi. Moreover, the uneven distribution of moisture across the grain – from water droplets – correlates with an uneven distribution of strain in the system, which may consequently result in microstructural damage and an overall reduction in responsiveness over time [39].

Material decay in the composite reactive elements due to exposure to atmospheric elements and UV radiation over extended periods of time can be mitigated but not completely eliminated. Sheltering from direct precipitation or radiation exposure combined with appropriate material selection can substantially extend the operational life of the system.

4.3. Outlook

Programming formal responses through mechanisms that react and respond to environmental conditions make use of the inherent computational capacity of an organic system. The material is itself a machine using limited information processing mechanisms and a physical instrumentality to process both information and energy. The presented research not only opens the window into the practical implementation of such methodologies, but it also provides the blueprint for further research that may extract some of the physical constructs that enable this computation in biological organisms and transfer it into synthetic ones.

Although it may be difficult to develop a synthetic system that encompasses the biological and structural complexity of wood, some singular aspects may be abstracted. For instance, through the use of hydrogels [40], which swell with an increase in absorbed moisture content, in combination with less responsive polymers in a bilayer configuration, it may be possible to perform similar curling deformations [19,41]. Although research into these polymers has, thus far, indicated clear strength limitations when compared to wood, it is possible to speculate that through industrial production mechanisms it may be possible to incorporate additional performance properties and to overcome wood size limitations. Increasing the size of the responsive elements can suit other architectural scales (for instance, large roofs, or at a smaller scale, valves). Calibration rates can also be further fine-tuned to respond within narrower climatic ranges while complex fibre orientation may allow for complex motions. Multilayer composites with complex fibre directions calibrated at different ranges may easily present opportunities for enclosure in much more complex systems. This subsequent incorporation of embedded technology may encompass a wider range of technical applications outside of architecture. However, long-term resistance, and polymer complexity may also increase the carbon footprint of the material while increasing the lifecycle implications of its production.

5. Conclusions

Complex electromechanical mechanisms require high maintenance and constant oversight, while their computational capacity can easily extend beyond the required task—a great asset in many applications. However, extended use in simple applications where instructions and signals follow predictable cycles may be best addressed by reverting to systems where embedded instructions and controls can be implemented. Not only are complex systems more prone to failure over an extended period of time—due to more points of failure in controllers, connections, energy supply, etc.—but they also tend to be more unreliable when performing repetitive tasks. In contrast, material systems based on biomimetic principles distribute the embedded knowledge at a molecular level; this framework reduces the number of failure points and allows the system to operate even when substantial sections of the system fail. The presented work illustrates how this interdependence between the system and its environment can be best harnessed when it serves an analogue's purpose, as is the case with the relation of wood and atmospheric conditions. Here, the material system has been instrumentalized to compute morphological operations in response to the environment, which conversely actively affects such environment.

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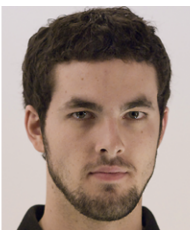

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