Performative Wood: Integral Computational Design for Timber Constructions

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Figure 1 Detail of lintel and sill system

ABSTRACT
Wood differs from most building materials in that it is a naturally grown biological tissue. Thus wood displays significant differentiation in its material makeup and structure as compared to most industrially produced, isotropic materials. Upon closer examination wood can be described as an anisotropic natural fiber system with different material characteristics and related behavior in different directions relative to the main grain orientation. Because of its differentiated internal capillary structure wood is also hygroscopic. It absorbs and releases moisture in exchange with the environment and these fluctuations cause differential dimensional changes. In architectural history the inherent heterogeneity of wood and the related more complex material characteristics have been mainly understood as a major deficiency by the related crafts, timber industry, engineers and architects alike. This paper will present an alternative design approach and associated computational design tools that aim at understanding wood's differentiated material make up as its major capacity rather than a deficiency. Along two design experiments the related research on an integral computational design approach towards unfolding wood's intrinsic material characteristics and performative capacity will be discussed. The first experiment explores the anisotropic characteristics of wood by exploiting the differential bending behavior in relation to the local induction of forces through which a specific overall morphology can be achieved. The second experiment focuses on the hygroscopic property of wood as the base for developing a surface structure that responds to changes in relative humidity with no need for any additional electronic or mechanical control.

1 INTRODUCTION: THE COMPLEX STRUCTURE AND CHARACTERISTICS OF WOOD
Wood differs significantly from most other building materials in that it is naturally grown. The resulting differentiated material makeup of wood accounts for most of its properties and characteristics (Barnett and Jeronimidis 2003). As the computational design approach presented in this paper aims at exploring ways of capturing and capitalizing on the specific material characteristics of wood, first its heterogeneous structure needs to be understood in greater detail.

Therefore the following paragraphs will serve as a short introduction to the material makeup and anatomical features of wood that are of particular relevance to the research and related design experiments presented in this paper.

Contrary to building materials specifically designed and produced to satisfy the needs of architects and engineers, wood evolved as a functional tissue of trees. All trees, despite their wide diversity, share certain characteristics. They are all vascular, perennial plants capable of secondary thickening, or in other words, of adding yearly growth to previously grown wood. Growth mainly happens in the cambium, a microscopically thin layer of living cells between the bark and the inner stem structure of sapwood and heartwood. Cambial cells have very thin primary walls and divide lengthwise during the growing season. Following the cell division, one of the two newly formed cells enlarges to become yet another cambial mother cell while the other matures either into a bark cell or, if formed toward the inside of the cambium, a new wood cell. Once these cells have developed to their ultimate shape and size, on the inner surface of the fragile primary cell wall, a secondary wall is built from cellulose consisting of long-chain polymers. The long-chain cellulose molecules are mainly oriented in the direction of the long axis of the cells, which accounts for many of the basic properties of wood. The resulting cellulosic structure is subsequently reinforced by lignin, the material that characterizes woody plants (Hoadley 2000).

In order to understand the following research on integral computational design for timber constructions it is critical to recognize the heterogeneous makeup and anisotropic characteristics of wood resulting from the arrangements of growth layers in the tree, as well as the horizontal or vertical orientation of the individual cells (Dinwoodie 2000). The cell structures of softwoods differ considerably from those of hardwoods, which are believed to have evolved much later than the softwoods. In the relatively simple structure of softwoods more than 90% of the wood volume comprises of tracheids, the remainder being mostly ray tissues consisting either of ray tracheids or ray parenchyma cells (fig. 1a). The tracheids are fiberlike cells arranged parallel to the stem axis in radial/tangential layers and have an approximate length/diameter ratio of 100/1, in which the length can vary from 2 to 6 millimeters in different species. The tracheid morphology largely determines the structural characteristics of the respective wood.

A much greater diversity of cell types and more variation in their arrangements are present in hardwoods (fig. 1b) than in softwood. The function of support and conduction is accomplished by the evolution of a range of specialized cells. For example vessel elements, which have a very large diameter, and thin side walls but no end walls, are arranged end-to-end parallel to the stem axis to form continuous channels for sap conduction. When cut transversely, the exposed open ends of the large conduit-like vessels are called pores. As all hardwoods contain vessel elements they are also referred to as porous woods. In contrast to tracheids and particularly vessels, fiber cells are much smaller in diameter and posses closed ends and thick walls, and mainly contribute to the strength of the wood. Critical for the appearance and, more importantly, uniformity of hardness in the transverse or radial plane of a hardwood are the size, number and distribution of vessels and fibers. For both softwood and hardwood the structure, distribution and orientation of cells are the determining factors for the anisotropic, structural, and hygroscopic characteristics of wood (Wagenführ 1999).

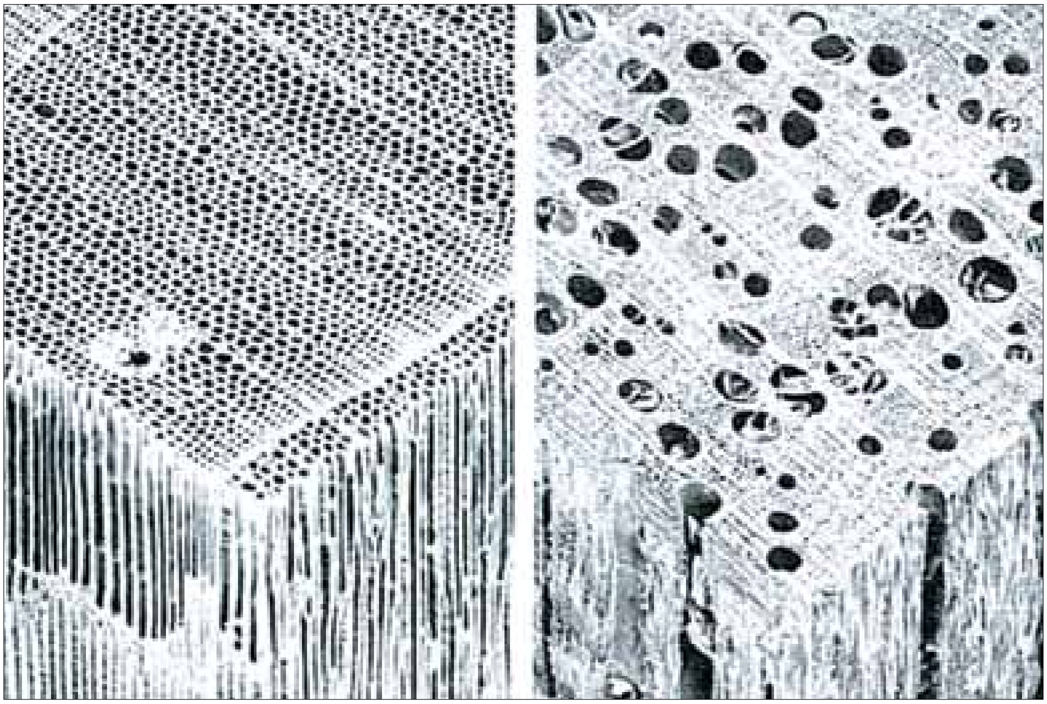

Figure 1a/b Microscopic Photograph of White Pine (left) and Black Walnut (right) (Hoadley 2000)

2 INTEGRAL COMPUTATIONAL DESIGN

In architecture and structural engineering, the anisotropic and hygroscopic characteristics of wood resulting from its internal cellular structure are traditionally seen as problematic and disadvantageous compared to more homogeneous, impervious and stable, industrially produced materials. While it is commonly understood that any genuine design approach for timber constructions requires knowledge of its internal cellular structure, the awareness of its material makeup has been mostly employed to counterbalance its complex material behavior by the related crafts, timber industry, engineers, and architects alike (Herzog 2003). The more recent history of timber construction is littered with attempts of compensating for the supposed deficiency of wood, ranging from special construction techniques to the development of industrial wood products that seek to homogenize the material.

This paper will present an alternative design approach that aims at understanding wood's complex material makeup and behavior as major advantages rather than deficiencies. Computational design lends itself to such an approach as it enables employing complex behavior rather than just modeling a particular shape or form. The transition from currently predominant modes of Computer Aided Design (CAD) to Computational Design allows for a significant change of employing the computer's capacity to instrumentalize wood's complex behavior in the design process. CAD is very much based on computerized processes of drawing and modeling, stemming from established representational techniques in architectural design (Terzidis 2006). In this regard, one of the key differences lies in the fact that CAD internalizes the coexistence of form and information, whereas Computational Design externalizes this relation and thus enables the conceptualization of material behavior and related formative processes (Hensel and Menges 2006). In Computational Design, form is not defined through a sequence of drawing or modeling procedures but generated through parametric, rule-based processes. The ensuing externalization of the interrelation between algorithmic processing of information and resultant form generation permits the systematic distinction between process, information and form. Hence, any specific shape can be understood as resulting from the interaction of system-intrinsic information and external influences within a morphogenetic process (Menges 2008).

Conceiving of computational design processes as morphogenetic enables the systematic integration of material characteristics and constraints. Therefore, the complex behavior of wood resulting from its differentiated material makeup and structure can constitute an integral aspect of the genotypic datasets from which a specific, phenotypic shape is derived. Obviously this requires both in-depth empirical studies of the microstructure and resultant behavior of the wood to be used, as well as the development of appropriate computational design techniques. The two research projects explained in the following paragraphs present different takes on developing such computational design techniques and related timber constructions, each with a special focus on wood-specific characteristics.

3 PERFORMATIVE WOOD: TWO RESEARCH PROJECTS

The following two projects form part of the author's larger research project investigating the possible integration of computational form generation and materialization. They were chosen as they present two different facets of the development of an alternative, performance oriented approach to the design of timber constructions that unfolds from the inherent characteristics of wood.

3.1 DIFFERENTIAL ACTUATION OF UNIFORM TIMBER ELEMENTS

The first research project was developed in the context of the GPA Studio (Michael Hensel, Prof. Achim Menges) by David Newton and Joe Kellner at Rice University's School of Architecture. It explores the possibility of utilizing the anisotropy of timber to construct a material system consisting of uniform elements that can be employed to achieve variable yet stable structural configurations with complex curvature through a vast array of local actuations.

As a result of its fibrousness, wood displays anisotropic properties. While anisotropy is most often understood as a problematic characteristic of wood, this project explores ways of strategically exploiting it as a significant material capacity (Wagenführ 2008). The considerable difference in modulus of elasticity in relation to fiber direction is of particular interest, with the modulus of elasticity parallel to the main fiber direction (between 9000 to 16000 N/mm² for different kinds of wood) generally being approximately fifteen times higher than perpendicular to the fibers (between 600 to 1000 N/mm²). In other words, wood has the interesting characteristic of variable stiffness in relation to grain orientation.

This project explores the possibility of utilizing the differential elastic deformation of wood under the influence of an external force to form a material system with enhanced structural capacity. The basic system constituent for achieving this is incredibly simple: an element consisting of two thin, rectangular timber patches, which are fastened to one another in two opposite corners, while the two other corners are equipped with a basic actuator element, in this case simple bolts that act as adjustable spacers. Once these bolts are "actuated," that is tightened to induce a bending force to the lower patch, the element starts to bend along its longitudinal axis, as the main fiber direction of both patches is initially parallel to the longer rectangle edge. If the main fiber direction is changed in one or both patches in relation to the longitudinal axis, changes in bending behavior and resultant element geometry can be observed. In general, the bending behavior is dependent on a number of parameters such as patch size, length to width to thickness ratio, actuation force (measured as the torque setting of the bolt), the aforementioned main fiber direction and related modulus of elasticity, as well as the general material properties of the chosen type of wood.

The same parameters are critical if a larger panel is covered with arrays of these small patches. For such an assembly of multiple elements mounted to one panel, the incremental actuation and consequential bending of each individual element leads to a cumulative induction of curvature in the panel (fig. 2).

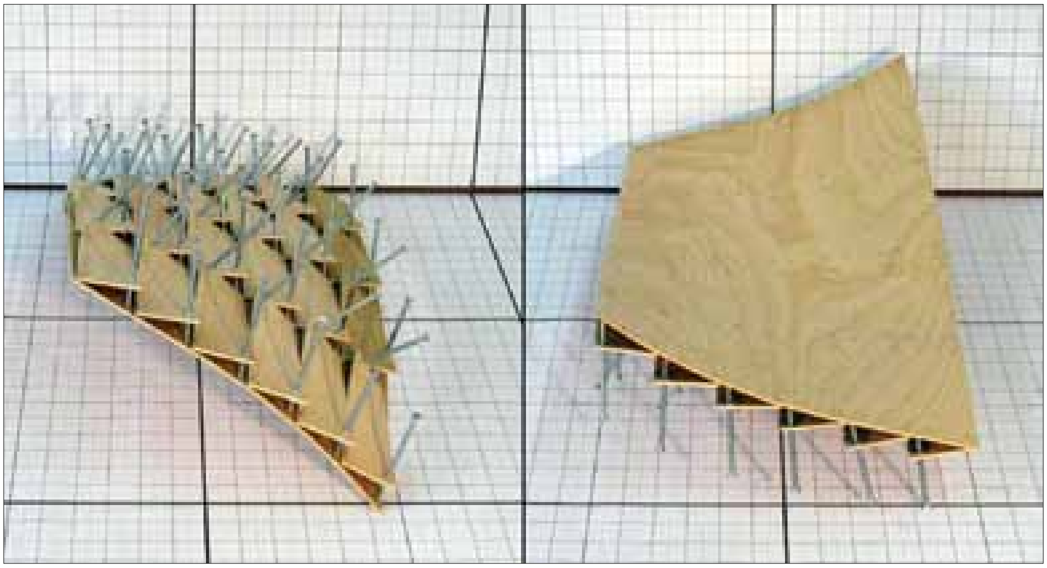

Figure 2 Top (left) and Bottom Side (Right) of Initial Test Model

Elaborate empirical tests and comparative analysis established the relation between different variable settings for the aforementioned parameters and the resultant shape changes of the panel assembly. For these particular experiments, and all subsequent tests, birch was chosen due to its remarkable properties of being relatively elastic while having high bending strength at the same time.

Based on the findings of the first tests, the number of variable parameters was limited to [i] the main orientation of elements on either side of the panel, [ii] the actuation setting for each bolt (specified through the torque setting) and [iii] the changes of main fiber direction (defined as the deviation angle from the longitudinal axis). In subsequent empirical test series, the specific behavior of the panel's shape change resulting from changes to these parameters' variables was investigated and encoded step by step in a parametric computational model. Based on the empirically established database, which remains open and extendable in case more information becomes available in the future, a number of interrelated recursive procedures derive the parameter settings, and the related actuation protocol required for the construction of any specified system geometry within the limits of the material capacity.

The computational set-up was further refined by additional tests exploring the changes in behavior of larger assemblies, consisting of arrangements with multiple horizontal and vertical rows of panels (fig. 3). The investigation of the non-linear increase in gravitational impact, especially in areas of system overhang, as well as the increase in stiffness at overlapping panel joints, further informed the developed computational process for modelling the required construction data for larger material systems.

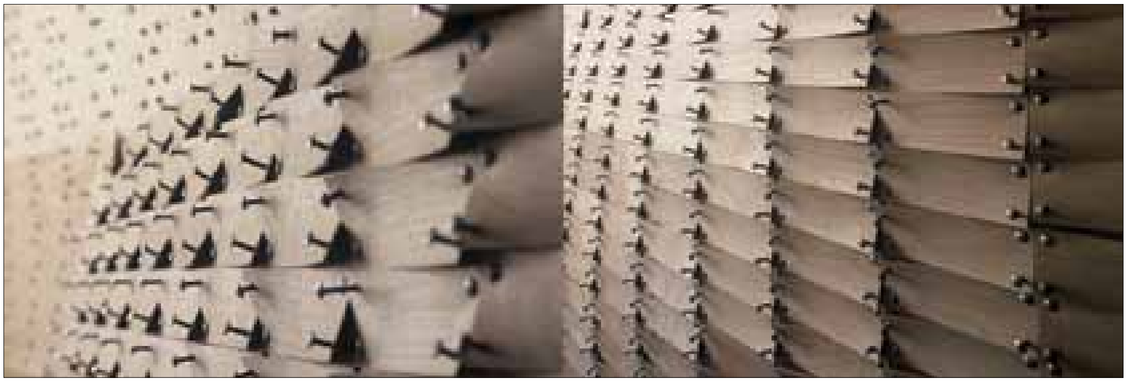

Figure 3 Actuators on Larger Surface Assemblies

As a final corroboration of the developed integral computational design process and related material system, a large scale prototype was constructed based on the information obtained by the computationally derived assembly and actuation protocols (fig. 4). Consisting of 48 identical panels, 1920 equal patches, and 7680 bolts, the structure initially remains to be entirely planar and flexible. Only through the subsequent tightening of each actuator bolt,

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guided by the computationally derived data, does the structure incrementally assume curvature and rise into a stable, self-supporting state.

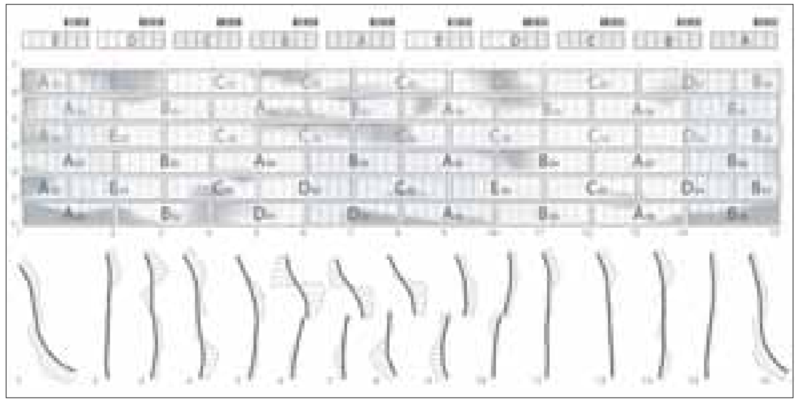

Figure 4 Graphic of Computationally Derived Assembly and Actuation Protocol

Due to the significant convex and concave curvature assumed in the ultimate state of actuation, the system gains considerable load-bearing capacity (fig. 5). The ten-meter-long but just four-millimetres-thick structure becomes astonishingly stiff and displays a remarkable level of structural performance, especially when compared to the extremely flexible state after primary assembly. In addition, if need be, the shape of the system can be changed at any time by changing the actuator setting based on an updated actuation protocol. This demonstrates how an integral computational design process based on the capacity inherent to the anisotropic nature of wood can derive a reconfigurable, performative material system made up of amazingly simple, uniform timber elements.

3.2 RESPONSIVE VENEER SURFACE STRUCTURE

The second research project was developed in the Department for Form Generation and Materialisation (Prof. Achim Menges) by Steffen Reichert at HFG Offenbach. It investigates the hygroscopic characteristics of wood and aims at employing the related dimensional changes of wood resulting from changes in relative humidity to construct a climate-responsive surface structure.

Figure 5 Large Scale Prototype

The fiber saturation point describes the state in which the cell walls of timber are fully saturated with bound water, whereas the cell cavities are emptied of free water. How much of the bound water evaporates and therefore how much shrinkage will occur mainly depends on the relative humidity level of the atmosphere; for example at 100% relative humidity, no bound water is lost while all bound water would be removed at zero relative humidity. As explained in the introduction, the long axis of the cells is more or less parallel to the orientation of the long-chain cellulosic structure in the cell walls. Consequently, as water molecules leave and enter the cell walls due to changes in relative humidity, the resulting shrinkage or swelling is mainly perpendicular to the cell walls and does almost not influence their length. Thus the main effect of changing bound water content in wood occurs in tangential shrinkage and swelling and the correlated dimensional changes. The anatomical structure of wood causes the main difference between tangential and radial shrinkage and swelling, the later having generally a considerably lower value due to the restraining effect of wood rays, whose long axes are radially oriented (Skaar 1988).

The main focus of this project is utilizing the hygroscopic characteristics of wood in the development of a surface structure capable of adapting its porosity to changing humidity levels. Rather than employing complicated electro-mechanical control devices, the project aims at employing the shape change of simple veneer elements triggered by changing bound-water content. The gaps opening up between the deformed veneer elements and the substructure locally regulate the structure's degree of porosity. At any stage in the design process, the complex reciprocal modulation of environmental conditions triggering changes in thermodynamic behavior and at the same time affecting the material response to changes in relative humidity needs to be considered.

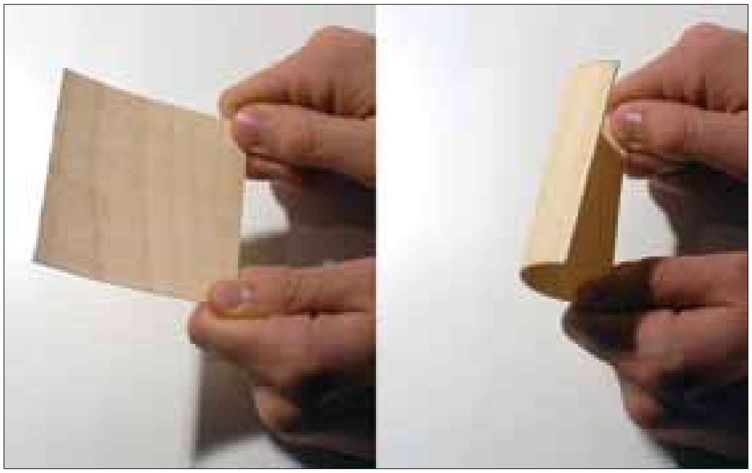

Figure 6 Composite Veneer Plate Responding to Changes in Relative Humidity

The development process commenced with a series of physical experiments investigating a simple composite veneer element (fig. 6). Critical variables of the key element's parameters, as for example the length-width-thickness ratio in relation to main fiber directionality, were tested for their influence on the element's shape change and response time in changing humidity conditions. Initially, rotary cut beech veneer was selected on the base of its high-swelling and shrinkage value in the tangential plane. However, a number of comparative empirical tests proved that sycamore maple veneer was more suitable due to its considerably lower elastic modulus.

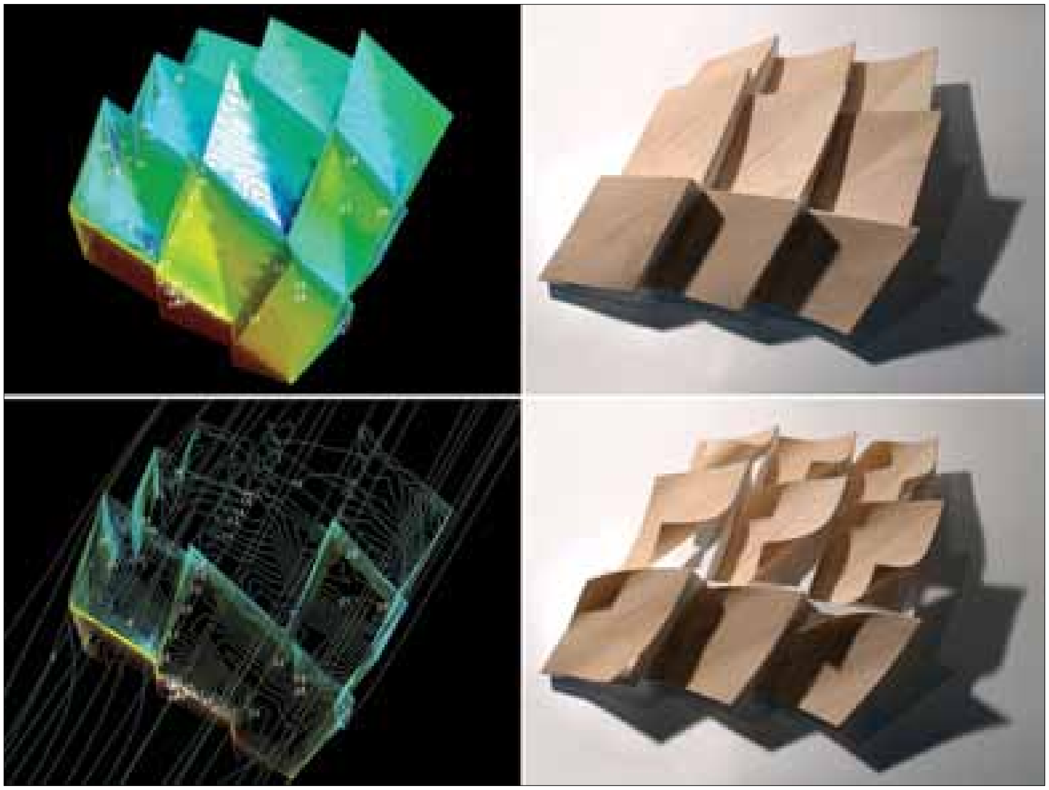

Figure 7a/b CFD Analysis (left) / Components in Closed and Opened State (right)

Following the first series of empirical tests, the development of a surface element as the basic constituent of the system commenced. Through iterative computational and physical test models, the element is derived as an associative geometric component based on the manufacturing and assembly logics of a larger, multi-component system, as well as investigations of the thermodynamic behavior of the element's open and closed state (fig. 7a). The resulting surface component consists of a load-bearing substructure on which two triangular veneer elements are mounted along their long edge. The substructure to which the moisture-sensitive elements are attached is developed as a parametrically defined folded structure with planar component-to-component attachment faces. The cut pattern of each component to be constructed from sheet material is automatically generated through the parametric computational model. Similarly, the associative model defines the main fiber direction of the element as being parallel to the fixed edge, which is also reflected in the automatically derived cut pattern of each element. The veneer element's shape change perpendicular to the main fiber direction caused by changes in relative humidity results in local surface openings (fig. 7b).

An increase of moisture content triggered by a rising level of relative humidity causes the swelling of the veneer elements. Due to the fibrous restrictions of wood anatomy explained above, the elements expand primarily in the tangential plane orthogonal to the grain. This dimensional change causes a shape change and the veneer elements curl up, creating an opening for ventilation. A large number of test cycles verified that the movement induced by moisture absorption is fully reversible. Furthermore, the response time is surprisingly short. The shift from a closed to a fully open state takes less than 20 seconds given a substantial increase in relative humidity.

Instrumentalizing the material's hygroscopic behavior, the simple veneer elements are in one sensor, actuator and porosity control element. The developed component enables the construction of a locally controlled, humidity-responsive surface structure, in which each sub-location independently senses changes of local humidity concentrations and reacts by changing the local level of system porosity. The emergent thermodynamic modulation along and across the surface is directly influenced by both the local component geometry as well as the overall system morphology (fig. 8).

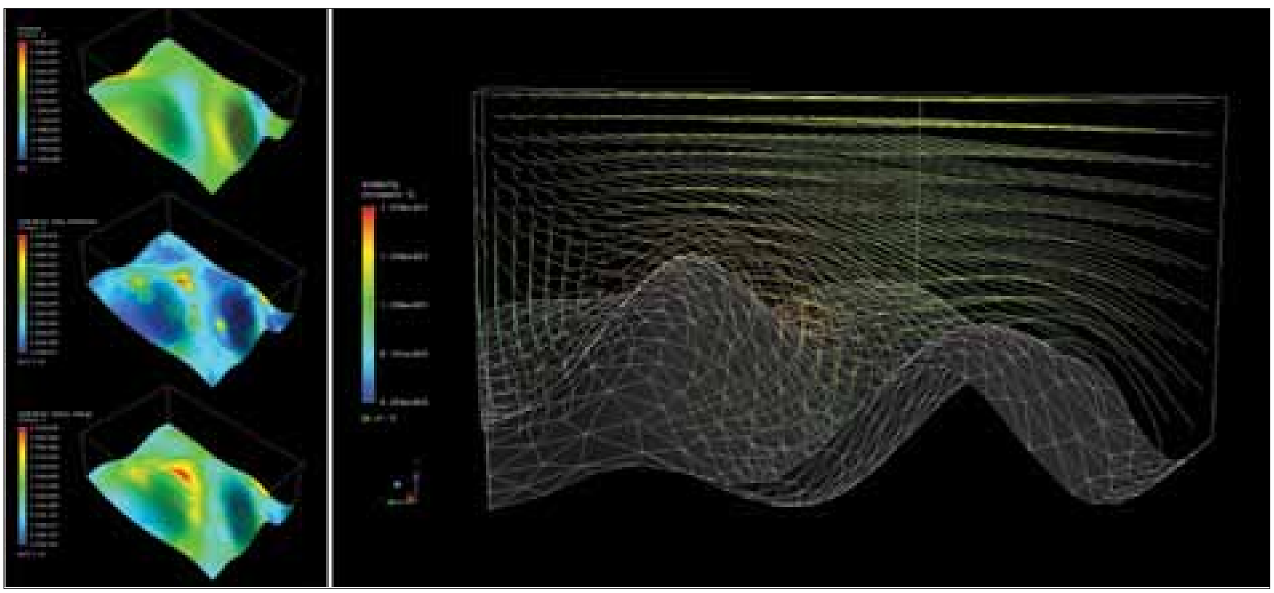

Figure 8 Iterative CFD Analysis During The Global Surface Evolution

In order to account for the complex reciprocity of individual component and overall system behavior and related macro- and micro-thermodynamic modulations, a feedback-based evolutionary computational process is used to prototypically develop a global surface articulation. For this process, the surface geometry is mathematically controlled through an equation with a number of variables. Iterative changes to these variables provide a robust yet simple base for the hygromorphic evolution of the surface geometry. This process is driven by the stochastic alteration of the mathematical surface, the subsequent associative component generation, and the related Computer Fluid Dynamics analysis of each system instance's behavior. The relevant data is continuously fed back and informs the next system generation. The evolving load-bearing structure's overall curvature orients the responsive veneer elements either towards or away from local airstreams and humidity concentrations. The resultant calibration of overall curvature and local component morphology in different opening states enables a highly specific modulation of airflow and related humidity levels across and along the system.

Figure 9a/b Functional Prototype (left) with Responsive Veneer Skin (right)

Figure 10 Functional Full-Scale Prototype (left) / Close-Up View (Right)

In order to verify and further inform the developed integral design approach, a full-scale, functional surface prototype was built from 600 geometrically different components (fig. 9a). Subsequent test cycles confirmed the performative capacity of the responsive surface structure (fig. 9b). Once exposed to changes in relative humidity, the veneer composite elements respond by opening or closing components, resulting in different degrees of porosity over time and across the surface. Thus the resultant material system is directly responsive to environmental influences with no need for any additional electronic or mechanical control. This demonstrates the high level of integration of form, structure, and material capacity enabled by the computational design process (fig. 10).

CONCLUSION

The research presented in this paper demonstrates both the potentiality inherent to an integral design approach utilizing the particular material characteristics of wood and the capacity of computational design tools to facilitate such an approach. The innovation in design methodology presented through the two research projects is based on an in-depth investigation of the material anatomy and resultant characteristics from which performative material systems are developed through custom-scripted computational design tools.

Nevertheless, what has been presented here needs to be understood as the first development stages of basic research requiring further elaboration. One obvious goal may be the more comprehensive integration of material simulation procedures as developed for timber engineering applications in order to achieve more precise feedback in the design oriented tools. However, this only becomes productive and coherent with the overarching argument presented here, if the variability inherent to timber anatomy can be more directly embedded as well. For example, one of the obvious shortcomings of both research projects presented above is the way they generalize material make-up and, in particular, fiber direction. While the integration of wood properties approximated more as orthotropic rather than truly anisotropic characteristics is already a step forward, the full recognition and integration of individual fiber direction in more adaptive computational design processes may yield further potential. For this purpose, high-speed pre-scanning of the individual anatomy of each timber element to be used may be necessary. As such, processes are already in use in the timber industry, as for example, for the recognition and removal of knotholes in high-quality timber panels. This seems to be a realistic goal rather than a mere vision.

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