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Material Information:
Integrating Material Characteristics and Behavior
in Computational Design for Performative Wood Construction

:abstract

Architecture as a material practice is still predominantly based on design approaches that are characterized by a hierarchical relationship that prioritizes the generation of geometric information for the description of architectural systems and elements over material specific information. Thus, in the early design stage, the material's innate characteristics and inherent capacities remain largely unconsidered. This is particularly evident in the way wood constructions are designed today. In comparison to most construction materials that are industrially produced and thus relatively homogeneous and isotropic, wood is profoundly different in that it is a naturally grown biological tissue with a highly differentiated material makeup
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This paper will present research investigating how the transition from currently predominant modes of representational Computer Aided Design to algorithmic Computational Design allows for a significant change in employing wood's complex anisotropic behaviour, resulting from its differentiated anatomical structure. In computational design, the relation between procedural formation, driving information, and ensuing form, enables the systematic integration of material information. This materially informed computational design processes will be explained through two research projects and the resultant prototype structures. The first project shows how an information feedback between material properties, system behaviour, the generative computational process, and robotic manufacturing allows for unfolding material-specific gestalt and tapping into the performative potential of wood. The second project focuses on embedding the unique material information and anatomical features of individual wooden elements in a continuous scanning, computational design and digital fabrication process, and thus introduces novel ways of integrating the biological variability and natural irregularities of wood in architectural design.
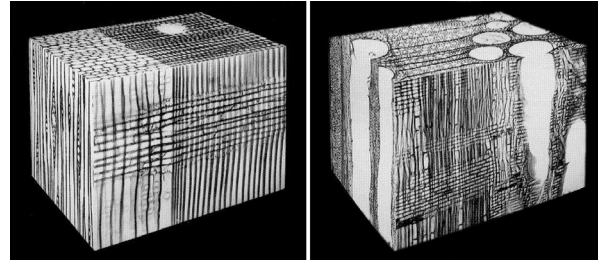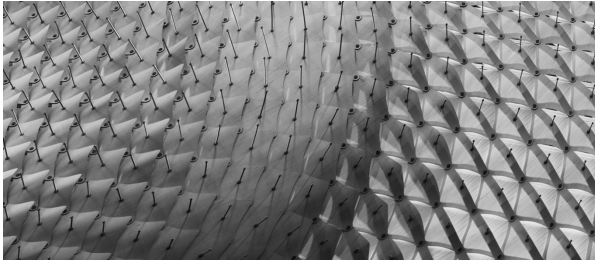
Figure 1a/1b. Softwood / Hardwood anatomy (Dinwoodie 2000).

1 Material Information: Anatomy and Behavior of Wood

Most construction materials used today are industrially produced and feature a standardized and relatively homogenous material structure. Wood is profoundly different from such materials in that it is a biological tissue. On the one hand, this means that wood has some increasingly important advantages over most industrially produced materials: it is a naturally grown, renewable, fully recyclable, and an extremely energy efficient building material. For example, wood needs 50 times less energy than steel to ensure a given stiffness in a structure as whole *(Gordon 2003)*. On the other hand, the fact that wood develops as a functional tissue of a tree results in a heterogeneous and highly differentiated material make up. During the growth process, cells in the cambium, which is a thin layer of living cells located between the inner stem structure and the bark, divide lengthwise and form two new cells: one new cambial cell and either one new bark or wood cell. Once the primary cell wall of a wood cell has matured to its ultimate size, an additional secondary cell wall is constructed from cellulose, with the long chain cellulose molecules being mainly oriented parallel to the cell's long axis, and subsequently reinforced by lignin. The material structure of the cell walls together with the cells' distribution and orientation determines most of the resulting properties and characteristics of wood *(Wagenführ 1999)*.

The anatomy of hardwoods (Figure 1a) and softwoods (Figure 1b) differ considerably in regards to their cellular structures. Nine tenth of the volume of softwood consists of one cell type only: tracheids. These are fiber like cells approximately one hundred times longer than wide, which are assembled in radial layers parallel to the stem axis. By comparison, hardwood evolved a greater

variety of cell arrangements and more specialized cell types. In addition to tracheids, this also includes vessels, rays, and fiber cells. For both softwood and hardwood, the specific structure, distribution, and orientation of cells accounts for the particular characteristics and behavior of the material *(Dinwoodie 2000)*.

As a consequence, and in contrast to most industrially produced, isotropic materials such as steel and glass, wood is anisotropic, which means its properties and behavior vary significantly in relation to the fiber direction. For example, anyone working with wood or veneer has probably experienced the considerable difference in stiffness depending on the grain direction. The modulus of elasticity parallel to the main fiber direction (between 9000 to 16000 N/mm² for different kinds of wood) is approximately fifteen times higher than perpendicular to the fibers (between 600 to 1000 N/mm²). Similarly, the compressive strength of wood differs significantly depending on grain direction (Fiber stress at proportional limit is between 25 to 45 N/mm² parallel and 3 to 12 N/mm² perpendicular to the grain), as do most other mechanical and material properties *(Hoadley 2000)*.

More often than not, these anisotropic properties and heterogeneous make up of wood have been conceived as problematic by architects, engineers, and woodworkers alike. In addition, the natural irregularities and biological variability have been difficult to reconcile with the increasing standardization of building materials and elements as necessitated by the industrialization of the building sector in the 20th century. Thus the development of most engineered wood products, such as for example plywood or cross-laminated-timber elements, has been seeking more homogenous and isotropic material characteristics *(Herzog 2003)*.

2 Material Integration: Informed Computational Design Processes

The anisotropic properties, heterogeneous material make-up, and related differentiated behavior of wood pose a considerable challenge for established design processes based on representational models and drawings. The predominant, contemporary Computer-Aided Design tools, with their inherent focus on geometric information, are not capable of integrating the critical material information. Hence, in order to utilize the aforementioned, significant ecological advantages of wood and to understand its anisotropy as beneficial (Wagenführ 2008) rather than problematic for the development of performative wood constructions, materially informed digital design processes are required. This paper presents research that investigates how a shift from representational Computer-Aided Design applications to algorithmic Computational Design processes offers the possibility to inform the design process with material characteristics and behavior *(Menges 2008).*

Current CAD applications are conceptually directly related to analogue design techniques based on descriptive drawings and representational models (Terzidis 2006). The related primacy of geometric information, which comprises both the notation during the design processes and the basic instruction for the translation from drawing to building, inevitably results in a hierarchical relation between the definition of form and its subsequent materialization. The research presented in this paper aims for an alternative approach to design: here, the computational generation of form is directly driven and informed by physical behavior and material characteristics (Hensel and Menges 2006). In Computational Design, form is not defined through direct drawing or modeling procedures, but derived through rule-based, algorithmic processes. Thus, contrary to the congruence of form and information innate to representational Computer-Aided Design, Computational Design externalizes the relation between the process of formation, the driving information, and the resulting form. The conceptual reciprocity between the algorithmic processing of information and the generation of form enables the architect to inform the design process with material properties and physical behavior from the very start of the design process. It is important to note, however, that there is a crucial difference between established processes of material simulation and this design-oriented research: while material simulations require all variables of the system
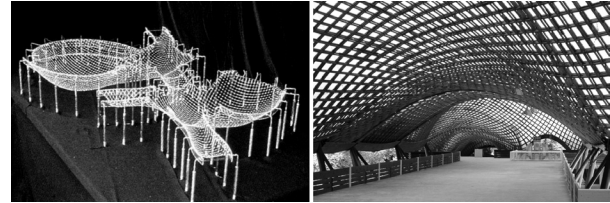

Figure 2a/2b. Multihalle form-finding model
(Burkhardt 1978) / Lattice shell.

to be defined at the onset, the computational approach developed in this research enables the exploration of the design space established by the characteristics, constraints and behavior of material systems, which leads to results that are not a priori fully determined.

3 Performative Wood: Two research projects

In order to explain the development of computational design processes that are directly informed by material characteristics and physical behavior, two projects will be introduced that are part of the author's related larger research on material specific, integral computational design. The first project was chosen as an example for how an information feedback between material properties, system behavior, the generative computational process, and robotic manufacturing allows for unfolding material-specific gestalt and tapping into the performative potential of wood. The second project focuses on embedding the unique material information and anatomical features of individual wooden elements in a continuous computational scanning, design and fabrication process, and thus introduces novel ways of integrating the biological variability and natural irregularities of wood in architecture. Both projects were developed in the context of the author's visiting professorship at the Harvard Graduate School of Design.

1.1 Research Project 1: Wooden lattice structure with robotically fabricated laths of non-uniform cross section and stressed actuator skin

Wooden lattice shells are structures initially constructed as a planar lattice of timber laths bolted together at uniform spacing in two directions, which is subsequently either hoisted or lowered at strategic local points to form a double curved, form-active surface structure. Still one of the most advanced examples of wooden lattice shells is the Multihalle in Mannheim by Frei Otto, Carlfried Mutschler, and Ove Arup & Partners completed in 1975 (Burkhardt 1978). Considering the bending characteristics of the wooden laths, the geometry of the

Mannheim grid shell was form-found through physical suspended net models as a shell with no bending moments resulting from self weight (Figure 2a).

The critical difference to most lattice structures digitally designed today is that the specific shapes of the aforementioned gridshells were not geometrically defined by the architect and subsequently rationalized for construction, but rather form-found, based on material behavior and structural characteristics *(Hensel and Menges 2009)*. As a consequence, these grid shells are extremely material efficient structures when compared to some of today's lattice structures. For example the recently completed wooden roof structure of the Centre Pompidou in Metz by Shigeru Ban, Jean de Gastines, and Ove Arup & Partners, which is often referred to as a state-of-art, digitally designed wood construction, requires six layers of gluelam beams with a cross section of 140 x 440 mm to achieve a 50 m clear span. An additional 50 percent of material was required and milled off during the fabrication process in order to achieve the desired shape. In contrast to this, the double layered grid of the Multihalle Mannheim spans up to 60 meters consisting of members that just measure 50 x 50 mmillimeters, in cross section (Figure 2b).

Until today, the geometry of lattice shells derived through form-finding processes has been based on the bending behavior of wooden elements with a uniform cross section. The first research objective of this project developed by Jian Huang and Minwhan Park *(Performative Wood Studio, Achim Menges, Harvard GSD, 2009)* was to extend the range of possible lattice geometries based on the bending behavior of wooden elements with varying cross-sectional dimensions along their length. Thus, a robotic water jet cutting technique (Figure 3a) was developed that gradually reduced the cross section of such elements without damage to the perimeter fibres, reducing the risk of splitting during the subsequent bending process. Through the related fabrication variables, each wooden element's stiffness can now be adjusted by locally reducing its structural depth. This differentiation of the cross section allowed building up an entire catalogue of possible bending behavior of the lattice elements (Figure 3b), which was computationally established based on a large number of physical tests. This information was embedded in computational design tool for form-finding the lattice shape (Figure 3c) in relation to the differential bending behavior of its members, which also provides the fabrication data for constructing the initially planar grid (Figure 3d).
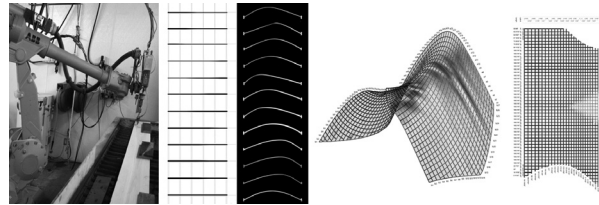

Figure 3a/3b/3c/3d. Robotic lath fabrication / catalogue of laths' bending behavior / Computational form finding of lattice geometry / Flat lattice fabrication data.
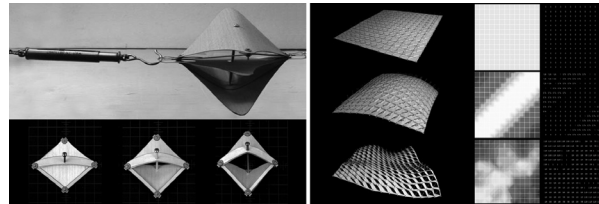

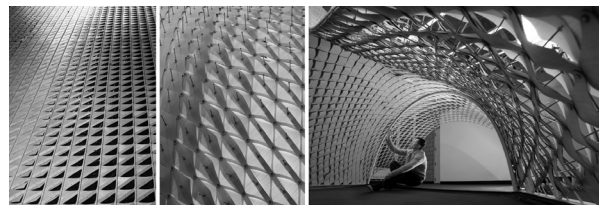Figure 4a/4b. Skin actuator elements / Computationally derived skin actuation data.

Figure 5a/5b/5c. Flat lattice / Actuator skin / Double curved wooden lattice.

The second research objective of this project was developing an alternative way of erecting such a flat lattice without the need for additional scaffolding or hoists. A stressed wooden skin was developed, which gradually forces the lattice into its structurally stable, double curved state by the local actuation of each skin element. A local actuator element was developed consisting of two skin panels with additional diagonal members and a variable spacer bolt that can adjust the diagonal distance of each respective grid field (Figure 4a). Based on detailed studies of the achievable actuation force and related element variables such as size, thickness and fibre orientation, actuator locations and required torque, a computational tool for deriving the related actuation protocol was developed and tested in a full scale prototype (Figure 4b).

For the prototype construction, the robotically fabricated members with varying cross-section, together with the laser cut skin elements, are assembled as flat lattice (Figure 5a). But once the actuators are adjusted according to the digitally derived protocol, the lattice

raises into its computationally defined, structurally stable, double curved form. Integrating the critical material characteristics and behavior of wood in the computational design process for both the local stressed skin actuators and the non-uniform bending behavior of elements with locally reduced stiffness allows for a more specific articulation of the lattice geometry. In the resulting structure, the differentiated transparency and articulation of the skin (Figure 5b) registers the embedded forces, which maintain equilibrium in the very thin, non-uniformly bent lattice (Figure 5c).

4 Research Project 2: Compressive veneer surface system with computationally defined earlywood cutouts

Whereas the first example project focused on developing a computational design process based on information feedback between wood's material properties, elastic behavior, and its manipulation through computer-aided manufacturing processes on the macroscopic level, the next project explored ways of integrating the microscopic irregularities of wood in a computational design process. In this way, the project opens up novel ways of responding to the biological variability of wood and utilizing the anatomical uniqueness of any wooden element in the design process.

The following research project developed by Jose Ahedo *(Performative Wood Studio, Achim Menges, Harvard GSD, 2009)* aimed at developing a computational design process based on a continuous information flow from scanning the individual anatomical features of each wood piece to the eventual digital fabrication. The project consists of connected vertical veneer strips that are assembled as an undulated wall element (Figure 6a). The main fiber direction of the quarter sawn pine veneer is oriented parallel to the long axis of the vertical strips. As a consequence, the significantly lower stiffness, perpendicular to the grain, allows the forming of a horizontal curvature in each strip. This local curvature together with the larger undulation of the larger system contributes to the significant compressive strength of this extremely thin walled construction. The structural behavior and internal forces were analyzed using a special finite element analysis application for anisotropic materials (Figure 6b). The following development phase was based on the hypothesis that the majority of the

material's compressive strength can be contributed to the thick and dense latewood cells. Thus, proportionally to the internal force intensity, parts of earlywood cells can be removed without having a major effect on the overall structural capacity.

Latewood features a much denser cell arrangement with considerably thicker cell walls as compared to the relatively fast growing early wood (Figure 7a). The visible grain of wood, in this case the aforementioned quarter sawn pine veneer (Figure 7b), results from this anatomical difference between latewood and earlywood cells. Hence an optical scanning process was developed on which the following fully integrated computational design and fabrication process is based.

First, a Finite Element Analysis of the overall system is conducted and the strain and stress intensity is mapped on a dense registration mesh. At the same time, the elements from which the overall system will be assembled are computationally defined and referenced to the actual veneer elements intended for construction. Once each veneer element has received an ID tag that identifies its location in the final assembly, the pieces are scanned on a purpose-built optical scanner (Figure 8a). Based on pre-calibrated threshold parameters, an algorithmic procedure converts the high resolution pixel data into vector information that separates the earlywood form the latewood regions (Figure 8b). In a subsequent step, the computational process correlates this data with the registration mesh of the structural analysis (Figure 8c) and derives a specific cutting pattern for each sublocation, whereby the stress intensity defines the cut-outs' size and density (Figure 8d). In a last step, the resultant cutting patterns are formatted for immediate use with a precision laser cutter (Figure 8e), which can then be employed to remove and directly recycle the dispensable early wood. In this way, digital fabrication responds directly to the unique anatomy of each wood piece.

The entire information flow and algorithmic processing is fully automated and operates with a high degree of precision. First tests have indicated that the remarkable patterns of removed and directly recycled cutouts (Figure 9) significantly reduce the material's mass but only have a marginal effect on the load bearing capacity. More importantly, it begins to show how digital fabrication can now be conceived of as fully embedded in an information feedback from material scan to computational design, analysis and manufacturing. This is of particular interest if one considers the

following: Today, log scanning technology is already in place in advanced sawmills. X-ray tomography is used to produce information about the shape of the log, its grain structure and anatomical features. This data algorithmically determines the most profitable breakdown pattern of the log and executes that pattern by controlling the head saw and carriage of the log. Currently the technology is primarily employed to identify what lumber manufacturers often refer to as "defects", such as for example knots. But the byproduct of this process is a comprehensive dataset including information on the log's individual internal material makeup and related properties. Until today, this information is of no further use once the log has been broken down and thus is usually lost once the timber leaves the sawmill. The increasing availability of such advanced scanning technologies in sawmills shows that the design integration of wood's specific anatomical information is becoming a realistic proposition rather than an idealized goal.

5 Conclusion

The presented research indicates how the development of computational design processes integrating material information opens up novel design opportunities based on material specific characteristics and behavior. Based on such an approach, the research projects show how wood, one of the oldest construction materials, can now be conceived of as a natural, high performance composite material that is, compared to any synthetic composite or industrially produced material, extremely energy efficient, fully recyclable and naturally renewable. However, in most cases the properties of wood are still generalized in standardized species-specific information sets, which generalize the anisotropic characteristics in orthotropic categories differentiating only between parallelism and perpendicularity in relation to the main fiber direction. Thus the second research project outlines one particular relevant area of feature research: the integration of the specific, individual anatomical information of wood in the design process. This will enable utilizing the biological variability and natural irregularities of wood in a truly material-based architecture.
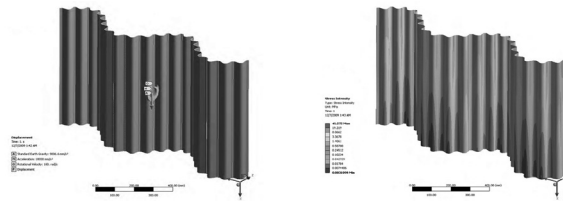

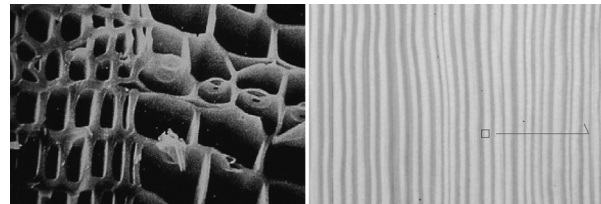Figure 6a/6b. Compressive veneer surface element / Structural FEA analysis

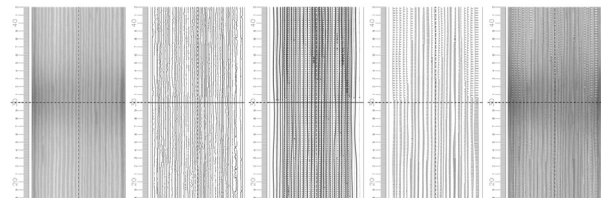Figure 7a/7b. Latewood/earlywood cells (www.engr.wisc.edu) / Grain of pine veneer.

Figure 8a/8b/8c/8d/8e. Scanned veneer / Earlywood/latewood separation / Structural data correlation / Cutting pattern derivation / Digital fabrication.
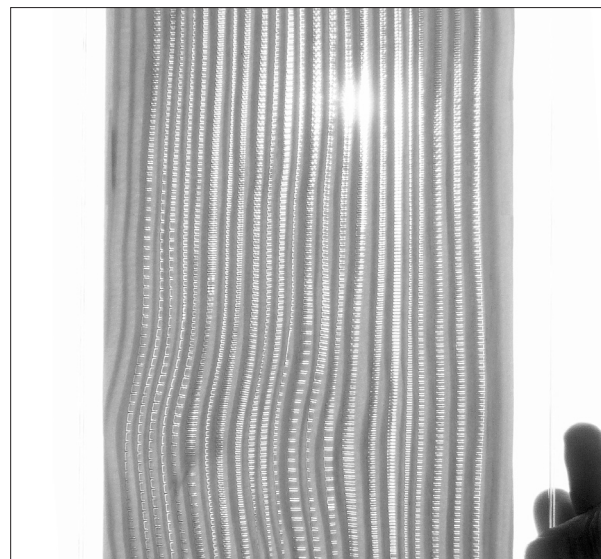

Figure 9. Veneer element with anatomy-specific earlywood cutouts.

Acknowledgement

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