Programmable Bending

grain-informed simulation and design

Shota Tsikoliya¹, Imrich Vasko², Veronika Miškovičová³,
Ivan Olontsev⁴, David Kovařík⁵
¹,²,³,⁴,⁵ Academy of Arts Architecture and Design in Prague
¹ shota.tsikoliya@vsup.cz

The project investigates the potential of programmable bending - a strategy, which informs bending simulations of multilayered veneer elements with the data of its anisotropic grain structure. Project further examines the possibilities of using these irregular material characteristics as a design driver. The project questions the possibility of informing the design with the particular characteristics of the material structure and of creating complex geometries from non-customized or minimally customized mass-produced elements. Project develops a workflow, in which a two-dimensional scan of the material is transformed into a vector field and consequently into a mesh with variable stiffness characteristics. The stiffness of each edge within a mesh was calculated basing on an angle between this edge and the relevant vector within a vector-field. That resulted in realistic simulation, which differentiated bending characteristics along the grain and perpendicular to the grain. Uneven connection of several layers of active-bended veneer allows to accumulate local stresses and pre-program bending characteristics of the structure. As a result active-bended structure forms particular predefined and predesigned shape and possesses locally variable stiffness and flexibility. The project applies this strategy to the design of the pavilion located within the urban context of a public space.

Keywords: programmable bending, grain-informed simulation, veneer, computational design

Introduction

Recent development of computational tools shifted the interest to a new role of materiality and a new role of fabrication processes in the field of architectural design (Menges, Ahlquist, 2011). While initially the new possibilities brought by the information era meant increase and more precise control of the complexity of the built structures, recent research is focused on optimization and re-evaluation of the fabrication techniques and re-approaching of the sustainable pre-industrial materials (Menges, Schwinn, Krieg, 2017, 3). A Programmable Bending project aims at defining a computational approach to the design, fabrication and assembly of complex geome-
tries out of mass fabricated non-customized wooden elements. Project considers anisotropic character of the material and simulates its variable bending characteristic through scanning its grain pattern. The secondary hypothesis of the project is a possibility of using irregular properties of the material as a design driver. Such an approach can result in an architectural structure with predictable free-formed overall geometry and emergent character in the detail level.

**Context**

Contemporary shift from the architecture based purely on notation to the architecture represented by algorithm, which takes into account material characteristics and fabrication processes has been described by Mario Carpo in his works The Alphabet and the Algorithm and Architecture in the Age of Printing as a partial reversal of the opposite process in the Renaissance (Carpo, 2011, 15). Pre-Renaissance and particularly vernacular architecture, for which the indistinguishable processes of design and making are often characteristic, located itself on the verge between the notational and behavioral techniques. It was a common place for the pre-Renaissance master-builders to include the physical interaction with the material to the design process. It is the distinct division of the intellectual and the physical, proposed by Alberti, what pushed the behavioral strategies to the relatively marginal role in architecture (Carpo, 2011, 32).

The introduction of “zero tolerance fabrication” methods, made possible by the rapid development of the fabrication and sensing technology, pursued the aim of reducing material indeterminacy to a marginal level. However the very same technological development brings the possibilities of re-introduction of behavioral-based design and construction processes (Menges, 2015, 30). The introduction of the system of positive and negative feedbacks allows to create a self-regulating flexible process, something that is being thoroughly explored in the multiple fields of industry and has a potential for a revolutionary impact. The technologies of two-dimensional and three-dimensional scanning and, more importantly, of scan processing allow us to apply specific and irregular characteristics of natural materials to be considered within the design. In particular, these possibilities bring new perspectives to the use of anisotropic materials such as wood in architecture.

Being a natural fiber composite, wood has many unmatched qualities as a building material. Its ability to resist forces in tension along fiber direction, which matches that of a steel of the same weight, its wide availability, its sustainability and ease of processing made wood the most popular construction material in pre-industrial era. (Cheret, Seidel, 2013) Wooden constructions were widely used in vernacular architecture as well as in churches, palaces and bridges well into the nineteenth century. The approach of industrialization meant that manual processing techniques were substitute by machine mass production. That led to the increase of use of isotropic materials such as steel and concrete. Wood, being anisotropic material, still was used, however its use became limited. Another consequence of industrialization was a switch of focus to timber, which represents only one third of the available wood. While irregular parts of wood were commonly used in the pre-industrialization era, particularly in shipbuilding, new fabrication methods meant, that regular geometries became preferable (Self, 2017, 129).

With the development of computational tools, a new understanding of material in architecture is beginning to arise (Menges, Ahlquist, 2011). Scanning, scan processing and simulation techniques allow us to take into consideration specific characteristics of the material, while new fabrication tools prove crucial to the reintroduction of traditional craftsmanship into mass production. The potential of this approach lies in particular in the possibility to inform the design process as well as the designed geometry by specific material qualities, thus merging the physical and the digital in one model.
**Methods**

The project questions the possibility of informing the design with the particular characteristics of the material structure and of creating complex geometries from non-customized or minimally customizes mass-produced elements. In order to obtain the information about the material structure, the veneer has been chosen as a main material. Unlike in a case of timber, the inner structure of the veneer is virtually similar to the one on its surface, so the necessary information was collected by two-dimensional scanning of the veneer stripes. A custom-made algorithm has been used to transform the raster image into a vector-field, which took into account a particular grain direction of the material.

The simulation of the material bending characteristics was done in consideration with its inner structure using a spring-based system Kangaroo in a visual scripting platform Grasshopper within a 3d-modelling software Rhinoceros 5.0.

As a part of the research, several approaches of informing the design with the data, obtained from grain scan, have been considered. Milling irregular geometries along the grain direction and connecting them with custom-made 3d-printed joints proved promising in creating visually strong design language yet produced a lot of waste material. As a main fabrication method we chose uneven connection of several layers of active-bended veneer, which allowed to accumulate local stresses and therefore pre-program bending characteristics of the structure. Another method used to produce the design, informed by anisotropic veneer characteristics, involved local grain directions of active bended veneer stripes being represented as virtual three-dimensional force fields, which could be overlaid or mapped on the pre-designed geometry, resulting in optimal organization of the components.

Overall, the project examined a potential of uneven and irregular bending as a design driver - a characteristic most fully defined by the veneer fiber structure.

**Project development and proposal**

Material-informed design has many precedents in pre-digital era. One important example present behavioral construction processes, where each construction step is based on visual, tactile or other material evaluation. The behavioral roots of structural processes can be seen in the non-human built structures, such as wasp hives or ant nests, as well as in the ontogenetic processes of the living nature (Hansell, 2008). This approach has also proved essential to the traditional craftsmanship. When working with wood, craftsman has to consider its structure, its grain pattern and its anisotropic qualities, which he evaluates visually. This approach, optimal in certain areas, has its limits, when implemented in mass production, due to lack of systematic procedure and clear evaluation criteria. Another, entirely different approach is presented by material computation. Known from the work of gothic master-builders, or, more recently, Antonio Gaudi and Frei Otto, material computation searches for the optimal solutions while considering specific material characteristics (Menges, 2015, 30).

Project implements digital parallels to the both approaches and tests their feasibility in architectural design. The behavioral construction of non-human built structures or traditional craftsmanship is substituted by scanning, scan-processing and designing basing on scan data, in other words automating the evaluation-fabrication loop. The material computation is substituted by digital simulation using established methods within existing visual scripting platform.

Advantage of veneer, as scanned material, consists in its two-dimensional character. Unlike timber, which would require complex methods for three-dimensional scanning, such as Computer Tomography, scanning veneer is fast, based on just optical processes, and easily automated. The resulted data are high-resolution black and white raster images, which clearly indicate the grain pattern of the veneer and provide necessary information about its inner structure. Equally important is processing of this information. While the output of the scan is a raster
image, many of the design algorithms, used in the project require a vector-field - a set of vectors with adjusted areas of their effect - in order to operate. A custom-made algorithm divides the image into rectangles three by three or four by four pixels. Within those rectangles, an averages of black pixels position and of white pixels position are located. A vector cross product between a normal to the scanning plane and a vector connecting those averages presents a vector, which would define fiber direction (figure 1). After several iterations of interpolation a realistic vector-field representation of the grain pattern is achieved. The vector-field representation of the grain pattern has been used in order to achieve precise bending simulation of the veneer, which would take into account its specific structure. As the spring-based engine Kangaroo within Grasshopper visual scripting platform efficiently works with mesh geometries, a mesh with variable stiffness characteristics has been used to represent each veneer element (figure 2). The stiffness of each edge within a mesh was calculated basing on an angle between this edge and the relevant vector within a vector-field. That resulted in realistic simulation, which differentiated bending characteristics along the grain and perpendicular to the grain (figure 3).

During initial tests, several approaches have been implemented to affect the design with scanning data. One of this approaches considered transforming through distortion predesigned layouts according to the vector-field grain representation, and milling subsequent layouts in the veneer. Resulting shapes had majority of their borders positioned along the grain direction, which meant more stable surface quality. Additionally, milling speed was optimized basing on the angle between the relevant vector within a vector-field and a milling direction. Joints between veneer elements were generated using particle systems, where particles were affected by the vector-fields of each veneer element. Resulting shape was fluent and continuous connection, fabricated using 3d-printing technology (figure 4). This approach proved to achieve stiff structures with visually strong design language, yet wasteful in its use of material and limited in relation to the mass production and full automation. Additionally, 3d-printing generated joints proved counterproductive, as complex connections are the feature, which requires complex anisotropic inner structure and is widely available in wooden branches (Slater, Ennos, 2015).
A simpler approach included uneven pre-stressing and layering of the several non-customized veneer elements. Uneven connection of several layers of active-bended veneer allows to accumulate local stresses and pre-program bending characteristics of the structure. Anisotropic and irregular character of the veneer meant irregular bending properties. Several iterations of digital and physical simulation allowed to calibrate the digital model and make it precise enough for the design and subsequent fabrication (figure 5). While overall geometry was free-formed basing on several external conditions and limitations, the design was affected and optimized using the knowledge of the specific material properties and its bending behavior. The design procedure went as follows. Initially the target shape was modeled. This target shape was subsequently subdivided into elastically bent elements with variable bending radiiuses. The necessary connection points locations between the layers of the veneer were estimated, in order to achieve such a local stress accumulation for the structure take the required shape through bending. Digital bending simulation tested and if necessary modified the estimated locations according to the irregular grain structure of the veneer. The fabrication process required only the location of connection points in otherwise none-customized elements, therefore being easy to automate. This approach was later developed by creating truly three-dimensional elements by bending the veneer in two directions in order to create u-shaped and 8-shaped loop components. The three-dimensional digital representations of these components were containing the information about their grain pattern and could be overlaid on pre-designed three-dimensional shapes. The curvature of the components was variable and affected by their size and bending characteristics, therefore complex geometries with various curvatures could be designed and fabricated from non-customized elements.
The uneven layering approach was tested on a design and construction of a pavilion in the courtyard of the Bethlehem Chapel in Prague. The pavilion presented a toroidal shape made out of 25 sections, each built from six unevenly connected layers of veneer. The overall shape of the pavilion was designed basing o the environmental and site constraints, pavilion being located in the historic architecture (figure 6). However the resulting geometry was strongly affected by the emergent characteristics of the material, particularly in the scale of the detail (figure 7-9). In another test local grain directions of active bended veneer stripes represented as virtual three-dimensional force fields, were overlaid and mapped on the pre-designed geometry, resulting in optimal organization of the components. The approach was applied to the design and fabrication of a column prototype (figure 10-11).
Figure 8
Grain-specific deformations are particularly influential in the scale of detail.

Figure 9
While overall shape was predesigned, particular curvatures of veneer elements are a result of local equilibrium of the forces.

Figure 10
Column prototype assembly sequence.
Conclusions
As an outlook of the project one can question the significance of the approach in the scale of architectural construction. Unless the process is applicable in those quantities, it will not be relevant for the construction industry. The strategy, examined in the project, can be applied in a bigger scale with a use of both processed and unprocessed wooden elements. Currently the dominant amount of sophisticated wooden structures is being designed and constructed within an industry of glue-laminated timber fabrication, where complex shapes are created through the extensive use of formwork. This approach, while having many advantages, can bring substantial additional costs, especially in the construction industry, where the use of big series of repeatable elements is limited and small series production or customized geometries are prevalent. Absence of a formwork and minimal amount of custom-milled elements being used in order to achieve highly complex geometries seems to be a major advantage of the approaches used in the project.

REFERENCES
Cheret, P, Schwaner, K and Seidel, A 2014, Urbaner Holzbau: Chancen und Potenziale für die Stadt, DOM, Berlin
Hansell, M.H 2008, Animal architecture, Oxford University Press, Oxford
Menges, A and Ahlquist, S (eds) 2011, Computational design thinking, J. Wiley & Sons
Slater, D and Ennos, R 2015, ‘Interlocking wood grain patterns provide improved wood strength properties in forks of hazel (Corylus avellanaL.),’ Arboricultural Journal, 37(1), pp. 21-32