Abstract. The presented paper discusses the combination of cutting edge technology (i.e. 3D-printing) and raw natural grown resources (i.e. bamboo) to develop resource efficient load carrying truss structures in architectural scale. Via visual sensing the individual material properties of various bamboo poles are analyzed and directly used to inform the digital model. Comparing load carrying capacity of the bamboo pole and structural requirements of the design, the poles are placed and the connections designed. Conventional 3D-pinters produce the nodes and connectors and enable to merge natural and “digital” materiality.

Keywords. Visual sensing; digital fabrication; material individuality; 3D-printing; bamboo.
1.2. MATERIAL INDIVIDUAL INFORMATION

The second important recent achievement severing as a foundation for this research is the implementation of “material individual information” in the fabrication process. Sensing devices like cameras, 3D-scanners or even x-ray enable the usage of visual information and its direct integration in the fabrication process. For example, this information is used in industrial application like saw mills, to localize metal scraps enclosed in raw timber logs and protect the cutting tools or to optimize the cutting sequences. While in this example the output still is the standardized production of construction wood according a norm, architects and designers have taken advantage of the accessibility of this information and created sophisticated fabrication cycles to propose up-cycling of discarded and scrap material, feedback based production cycles or to relate the output of a final design to the specific geometry of the raw material input. The proposed formula is relatively simple but effective:

- High congruence of input and output geometry → short fabrication time, low material waste → efficiency in production and material

Individual material properties, usually a handicap in mass fabrication, become an advantage in customization. The project “Bandsawn Bands” for example used a specially shaped timber plank to build a double curved divan (Johns, Foley, 2014) and the research team of the Architectural Association even surveyed a whole forest to identify the best fitting tree forks for the load-carrying arch of their Woodchip Barn (Síbal, Vercruysse, 2017).

1.3. BAMBOO

Bamboo is under continuous investigation as a construction material for its mechanical strength its wide distribution and its renewable property. Among
Vo Trong Nghia Architects, Simon Velez or Shigeru Ban use it multiple and manifold in contemporary architecture, from emergency shelters to big scale domes, from low cost products to exclusive resorts. The versatility of this material is as impressive as its structural behavior. It can be used as a pole, a split, it can be cold or heat bent. The high tensile strength of the fiber even lead to researches using it as concrete reinforcement (Hebel, 2014). Nevertheless the individual properties of each pole are unconsidered. Bundles and redundant structures are designed, the production and here especially the joining methods, is relying on manual labor. Sometimes even called the “Steel of the 21st century” (Niwa, 2016). by its advocates, bamboo still is an “analog” material almost untouched by the digital impact in architecture.

1.4. RESEARCH APPROACH

The presented research combines these two concepts of Additive Manufacturing and Material individual Information, 3d printing and visual sensing to a novel approach: Working with the individual properties of the natural grown material bamboo. While the Additive Manufacturing references have shown the capacity to react to specific conditions, but were used in the combination of highly processed standard materials Material individual Information has demonstrated the possibility to react on the individual material capacity, but still processed the material itself, cutting and milling it into a desired shape. Bamboo is under investigation in architectural context, material research and contemporary architecture, but has been used labor intensively or as a highly processed material, predominantly. The chosen approach of this research aims to use visual sensing to identify the individual strength of raw unprocessed bamboo. 3D-printing technology reacts to the individual geometry and reduces the machining effort of the bamboo poles.

2. Workflow Description

2.1. CONCEPT DESCRIPTION

The defined research approach uses raw bamboo poles as the bars in a node-bar system. Forming hollow straight tubes by its nature, bamboo poles appear to be the ideal base material for trusses and bar-node systems. While the poles serve as the bars, 3D-printed nodes serve as the connectors. Scanning of the bamboo sections informs a Grasshopper(C) Script, which customizes the nodes globally and in detail (Fig. 2).
The production process can be separated into the following steps:

- Generation of the digital model
- Structural analysis of the model
- Bamboo selection regarding the structural analysis
- Cutting to length of the bamboo
- Scanning of the sections
- Implementing of the scanned geometry in the digital model
- “Baking” of the designed node geometry
- 3D-printing of the nodes
- Assembly process of the node-bar system

2.2. DIGITAL WORKFLOW IN DETAIL: FORM MATERIAL ANALYSIS TO ANALYZED MATERIALIZATION

First the desired geometry is designed and transformed into a polyline geometry construable with the designed node-bar system. A self developed Grasshopper(C) script using Karamba(C) analyzes the structure under specific load cases and quantifies the bamboo diameter requested for each bar in the system.
The bamboo poles fitting the specified criteria are selected and cut to length. They are marked with printed stickers on both ends to be identified later in the process. These stickers are aligned via laser level to guarantee the alignment of both scans and that way right orientation of the corresponding nodes, connecting this and other bars in 3D-space. A transportable flatbed scanner allows a 2D-Scan of the sections on both sides. (Note: Focus was set on 2D-Scanning and the corresponding connector type for the realization of the first prototypes, due to handiness of the process. A scanning process using a 3D-scanner attached to an industrial robot was developed and tested as well. This approach enables to gain the 3D-geometry of a bamboo pole close to the node. A dowel system incorporating the analysis and implementation of the bamboo diaphragm and the corresponding dowel is currently under investigation).

Figure 4. 3D and 2D-Scanning of the bamboo geometry.

The image taken by the scanner is uploaded in a script named “bamboleo” (designed and written by Pablo Odorico). This script is use the .jpg of the scans made, identifies the bamboo section as a tube and vectorizes the image and draws the contour curves of the inner and outer edge of the pole. Containing information like section area, inner and outer diameter, the contour curves are saved as .dxf files, processible by the Grasshopper(C) Script. The examples (Fig. 5) show the inner (yellow) and the outer contour curve (purple). Since the bamboo chosen for this example was green on the outside and beige on the inside, the whole section was colored (blue) to highlight the contrast.

Figure 5. Examples of the determined contour curves using the bamboleo script.
In the next step this .dxf is imported into Rhinoceros(C), which generates the equivalent connector geometry (Fig. 6). The outer socket refers to and covers the outer surface, while the information of the inner surface is used to tailor a dowel. Different variations of the dowel design have been tested. The current focus lies on two versions. The dowel system used in the workshop (see chapter 3) works like a wooden plug and uses PU-based glue to be fixed. One other dowel functions as a mechanical connection and works without glue. This enables an easy assembly process and more important reversible disassembly process on site.

Figure 6. Mechanical connector 1 (with integrated dowel) and glued connector 2 (with separated dowel).

In the last step the designed node is “baked” and conventional 3d-printers on PLA base are used to fabricate the nodes and connectors and enable the resource efficient and versatile bar-node production system (Fig. 7).
3. Prototypes

3.1. FIRST PROTOTYPE

The first big scale prototype using this technique was designed in a workshop class held by the authors at Zhejiang University (Fig. 8). The arch presented in this paper consists of 24 nodes and 37 bars and spans 6.87m with a clearance height of 1.85m. Regarding the tight schedule of the class, the node system was split into nodes and connectors. That way the printing of the nodes could be started before the bamboo arrived. The 74 connectors were printed separately and plugged into the nodes. Therefore the connectors were printed with a standard cylinder with a diameter of 30mm on the node side and with a dowel according to the scanned bamboo geometry on the bamboo side. The connections between the connector and the node were fixed using metal bolts, the bamboo poles were glued to the connector using a PU-based glue.
4. Conclusion and ongoing research

4.1. ONGOING RESEARCH

The first prototypes have proven the functionality of the system. The workflow from cutting and scanning of the bamboo poles to the fabrication of the nodes and connectors has been tested successfully and shows high accuracy and reliability. In a next step, the system is going to be tested and presented in a large scale prototype, a temporary pavilion “Sombra Verde” for the Urban Design Festival in Tanjong Pagar, Singapore, March 2018 (Fig 10). In ongoing studies, the different connection types and node geometries will be tested and developed further to enable a bigger variety of node-bar systems, like grid shells or different kinds of spatial truss systems. But to go beyond the scale of the short term usage in temporary structures, it will require more studies on both materials. The degradation of the bamboo under environmental conditions, its effect on the connection, or new 3D-printing materials and technologies, which could enable
new connection details or concepts.

4.2. RESUME

Nevertheless, the information gained via visual sensing shows the capacity to bridge the gap between the former unknown individuality of this construction material and to combine it with the versatile and adaptable fabrication strategy of 3D-printing. The presented application tailors each connector of this bar-node system and provides individual solutions able to react on design intentions, material accessibility or structural performance among other things. The approach presented with this project, integrates individual material information in smart, adaptive and resource efficient digital fabrication processes. That way it opens up new ways of design thinking beyond the project boundaries and sets a general statement to rethink future design and fabrication strategies and enrich them with in-detail analysis of material individuality.

4.3. ACKNOWLEDGMENTS

The script “bamboleo” used to identify the section geometry of the bamboo poles was written by Pablo Odorico. The first prototype “Nautilus” presented in this paper was designed by the students Li Jiaji, Hu Yuxin, Yang Yue, Huang Jiwen, Lan Zhiyu and Huang Jianan, during the workshop class “bamboo in formation” held by the authors. The workshop was held in collaboration with Prof. Jiang Hao, International Design Center, Zhejiang University. The Pavilion “Youzhisan - An urban shelter for Tanjong Pagar” is designed and built by AIRLab
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References