Additive Manufacturing with Bamboo
Mechanically Informed Infill Wall Made with Bamboo Dust and Fibers

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Publication date
2024

Document Version
Final published version

Published in
AM PERSPECTIVES

Citation (APA)
Aut, S., Wong, J., & Brancart, S. (2024). Additive Manufacturing with Bamboo: Mechanically Informed Infill Wall Made with Bamboo Dust and Fibers. In P. L. Rosendahl, B. Figueiredo, M. Turrin, U. Knaack, & P. J. S. Cruz (Eds.), *AM PERSPECTIVES: Research in additive manufacturing for architecture and construction* (pp. 149-156). SOAP | Stichting OpenAccess Platforms.

AM Perspectives

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AM Perspectives
Research in additive manufacturing
for architecture and construction

AM Perspectives results from a collaboration between the Landscapes, Heritage and Territory Laboratory, University of Minho (Lab2PT); Architecture, Construction and Technology Hub, University of Minho (ACTech Hub); Institute of Structural Mechanics + Design, TU Darmstadt (ISM+D); the Generative Design Lab, TU Darmstadt (GDL); Faculty of Architecture and the Built Environment, TU Delft; Stichting OpenAccess Platforms (SOAP).

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SOAP – Stichting OpenAccess Platforms, Rotterdam.

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ISBN/EAN 978-90-833861-8-8
e-ISBN 978-989-8963-91-8
DOI 10.47982/a82n7r50

Financial support
AM Perspectives has been made possible by financial support of the Multiannual Funding of the Landscape, Heritage and Territory Laboratory (Lab2PT), Ref. UID/04509/2020, financed by national funds (PIDDAC) through the FCT/MCTES.

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ADDITIVE MANUFACTURING WITH BAMBOO: MECHANICALLY INFORMED INFILL WALL MADE WITH BAMBOO DUST AND FIBERS

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This paper explores the use of bamboo in Additive Manufacturing (AM), specifically towards the development of a building component. The presented study uses bamboo in the form of dust and fibers, which can be sourced from waste streams. This innovative approach not only offers a solution to the challenges of bamboo's anatomy but also has the potential to use bamboo in a more circular way. With this approach, rather than being discarded at the end of its life cycle, bamboo products can be recycled and transformed into valuable powder and fibers, granting them a second life. By leveraging the benefits of additive manufacturing technology, such as reduced material waste and the ability to fabricate complex geometries, the design aimed to create a mechanically informed infill tailored to the loading condition of the building component. After use, the component can be re-introduced into a new mixture to be used in a new AM application, enabling circular use. The project involves a comprehensive workflow, including material research, design development exploration, manufacturing process exploration and prototyping.

INTRODUCTION

The rapid population growth contributes to a considerable increase of the amount of raw materials used and produced worldwide [1]. The aim to create more ecologically friendly and sustainable construction processes has boosted interest in the use of bio-based materials. Timber, for instance, has been a prominent choice, but its availability is constrained as the demand should not exceeds responsible forestry. Bamboo, a non-wood species, holds promise as a potential substitute to wood due to its rapid growth rate. It is a very adaptable plant that can grow well in a variety of climates and elevations, which enables it to contribute to the alleviation of demand for wood as a source of raw materials [2].

This research aims to reimagine the use of bamboo. Often, when bamboo-based products reach the end of their life cycle, they are discarded. To enhance sustainability, we propose a method to recycle the material by reducing it into powder and fibers and creating new products with it. A promising technology that can facilitate the increased utilization of bamboo in this manner is Additive Manufacturing (AM). AM techniques, which have seen significant advancements in the past decades, have also made their way into the building sector, traditionally slower in adopting innovations. These additive manufacturing technologies offer the potential to reduce labor costs, minimize material waste, and enable the fabrication of complex geometries that are challenging to achieve using conventional production methods.

While AM technologies for concrete and steel structures have made significant progress, the research and application of AM with bamboo for architectural purposes still lag.

This research addresses this gap by developing a building component made with bamboo using AM technology. By leveraging the benefits of AM and utilizing bamboo as a renewable and versatile material, this research seeks to promote sustainable practices in the field of architecture.

BAMBOO COMPLEMENTING WOOD

Humanity is facing a serious resource dilemma as a result of global consumption and population growth as well as an addiction to fossil fuels. This has led to a rise in interest in bio-based materials as a means of creating environmentally friendly and construction and manufacturing processes.

Bio-based materials and goods are made from renewable resources, which, in contrast to many mineral and fossil resources, regenerate more quickly than they are used [3]. A replacement of materials manufactured from renewable resources immediately lowers CO2 emissions since most bio-based materials are produced with far less energy than materials like aluminum, steel, and concrete and act as carbon sinks by storing carbon during their growth [3].

Although using bio-based products has many advantages, it also has some limitations. Depletion also results from overexploitation caused by demand that exceeds natural reproduction and responsible harvesting.

According to Ashby, the demand for wood will be impacted by material consumption, which is anticipated to increase over the next 25 years at a 2.8% annual rate [4].

Large-scale reforestation initiatives are required to increase the production capacity of the wood sector in order to support this expansion and the effort to increasingly replace techno-cycle materials. Alternatively, faster-growing plants like bamboo, hemp, flax, seaweed, miscanthus; and cork, as well as various types of algae and fungus like mycelium, may play a significant role in this booming bio-based economy [5].

Bamboo production is seen as a promising climate change mitigation technique due to its quick growth cycle (Fig. 1). Bamboo has highly interesting development characteristics because, in its second and third weeks, it grows quickly longitudinally [6].

The main findings of this project emphasize the potential of bamboo as a sustainable material for construction through AM. A versatile and optimized building material can be created by utilizing bamboo in powdered and fiber form, which can be sourced from waste streams. This waste can include offcuts, trimmings, and bamboo parts that are not suitable for the primary end products or that have reached the end of their life cycle, such as a fractured bamboo pole typically employed in scaffolding.

MECHANICALLY INFORMED INFILL THROUGH ADDITIVE MANUFACTURING

AM presents a distinct advantage in terms of material waste reduction compared to traditional processes like milling. This advantage arises from its capacity to precisely deposit material solely within the object's volume. The resulting form freedom allows to develop shapes that are more efficient in transferring the loads that are imposed on them, thus reducing resource use. This study applies such a mechanically informed workflow on the design of a self-supporting wall element with integrated bench.

This workflow identifies areas where material is necessary and where it is not, all while optimizing the overall structural efficiency and minimizing material consumption.

The initial concept for this research was to demonstrate the potential of the novel material and fabrication technique. Therefore, the design had to be carefully considered to incorporate the capabilities of the selected mixture and AM technology.

The aim is to create a mechanically informed infill that is tailored to the loads on specific parts of the building component. The design process began through a computational model by lofting different sections of a partition wall and benches on both sides (Fig. 2).

The design was heavily influenced by the novelty of the material and the fabrication process, to allow for a more efficient production process, the study focused on a specific section of the overall design (Fig. 3).

AM enables the realization of complex designs, not only in terms of visual aesthetics but also in terms of performance. Through the use of computational design and performance analysis, the material distribution of the component can be optimized within a specified space, considering loads and boundary conditions. This optimization process involves iteratively refining the material distribution.

To optimize the use of material and create a mechanically efficient infill, it is important to consider that the load on the component is not uniformly distributed. Therefore, it is unnecessary to have the same density in the entire geometry. It is a more efficient approach to create an infill that is mechanically informed and tailored to the loads on specific parts of the component.

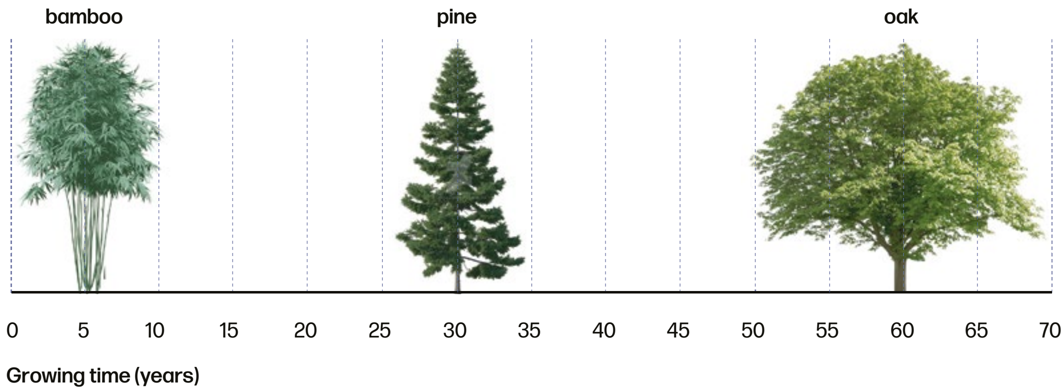

Figure 1: Bamboo, Pine tree and Oak tree growing time [11].

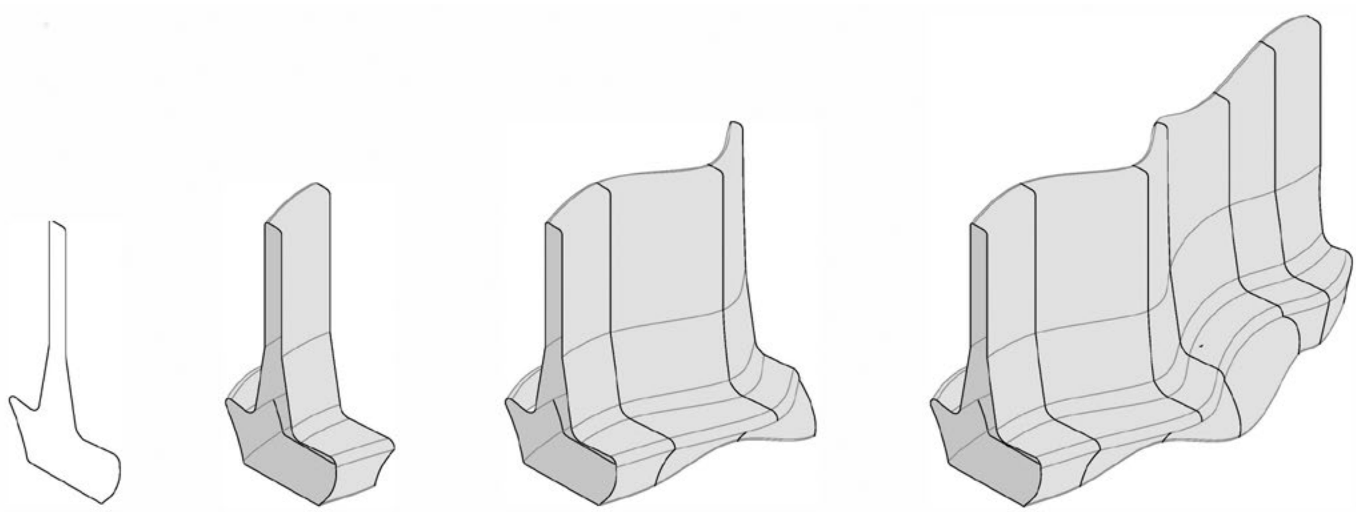

Figure 2: Lofted Design.

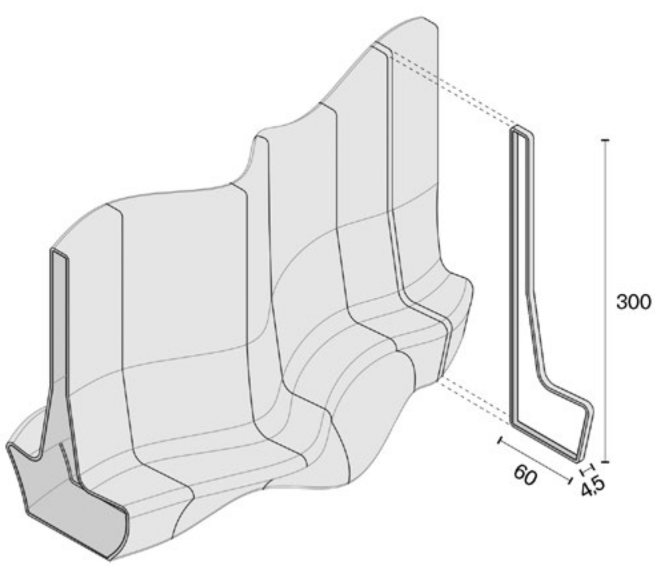

Figure 3: Chosen section.

Figure 4 shows the computational workflow for the mechanically informed infill generation. A structural analysis determines the optimal density distribution within the infill. This analysis involves mapping the density of the infill based on the variable cell size and arrangement. The goal is to identify areas that require higher density to withstand greater loads, as well as regions where lower density can be employed without compromising structural integrity. Once the density mapping is established, the component is designed to generate the toolpath necessary for printing it using a robotic arm.

The workflow begins with generating the mesh geometry of the solid component. After defining the type of support and load conditions a structural analysis generates a color gradient that represents the stress distribution within the component. In this colored mesh, points that are closest to 0% stress are automatically identified as attractor points. The pattern generation is then created, and the center point of each geometry is connected to the closest attractor point. The thickness of the infill is inversely proportional to the distance of the two points, meaning that shorter distances result in thinner thicknesses.

MATERIALS

The raw materials employed in this research were primarily bamboo fibers and dust (Fig. 5).

Bamboo is a viscoelastic and anisotropic material that exhibits differences in physical and mechanical properties along its three orthogonal axes, with variations being more significant along the length of the culm due to the tapered shape and increasing density with height [7].

Bamboo presents impressive versatility, with the potential for nearly 100% material utilization in most cases. Among its various applications, bamboo culms are the most widely used, finding purpose in products ranging from chopsticks to furniture and crafts [7]. In the construction industry, bamboo can serve as a viable replacement for traditional building materials across several components, including trusses, roof structures, walls, flooring, foundations, and scaffolding [8]. Still its adoption in this industry remains limited due to the challenges posed by its hollow tube anatomy and the lack of established building codes for its use. Furthermore, bamboo's physical and mechanical qualities are affected by moisture content, age, and the location on the stem [7].

Waste can be generated from products at the final stage of their life cycle or from leftovers, cuttings, and parts unsuitable for final product assembly.

MATERIAL EXPERIMENTATION

Although AM processes and technologies have recently advanced, there are still urgent research needs to create new sustainable materials [9]. The most popular AM process for bio-based materials are extrusion-based techniques, which are also employed in this research project, more precisely liquid deposition modeling (LDM). Although there are many different kinds of pastes, they may all be thought of as viscous liquids that are created by combining one or more solid elements with a liquid. The primary focus of this study is composite pastes. Binders and fillers are the minimum number of constituent kinds required to create composite paste materials [10].

With the goal of formulating a fully bio-based recipe, a series of experiments was conducted to study the behavior of various bio-based binders, both individually and combined in different ratios.

The material experiments aimed to comprehend the behaviour of bamboo dust and fibers when combined with various binders and solvents, with the objective of creating a stable bio-based composite with optimum viscosity and bonding properties suitable for extrusion via LDM technique. This exploration was carried out in two phases.

In the first phase of the material experiments, the focus was on exploring the binding agents that could be used to develop an extrudable paste. Initially, water was used as a binder to test the extrudability of bamboo dust. Therefore, different bio-based and non-bio-based binders were explored as potential alternatives.

The proportions of the binders were determined through empirical research. The binder was first mixed until it reached a glue-like consistency, and then the bamboo dust was gradually added until it formed a paste. The paste was then introduced into a syringe and pressure was applied to extrude the material. This process was repeated for each binder, with the uniformity of each experiment being assessed before the bamboo dust was added.

Material ratios were calculated throughout the material mixing procedure. Then, in order to compare and evaluate the different recipes, material qualities such as extrudability, bio-based content, shrinkage and strength were examined. The most potential recipes were improved upon and classified for comparison.

After the initial phase of material experimentation, it was determined that a second phase was necessary in order to achieve a more comprehensive evaluation of the mix and to refine key parameters for optimal printability in regard to the AM setup.

During the second phase, each binder was exclusively mixed with bamboo dust, as well as bamboo dust combined with fibers, to facilitate an effective comparison process. The results (Fig. 6) indicate the presence of some specimens that broke or bent during the drying process, categorizing them as faulty.

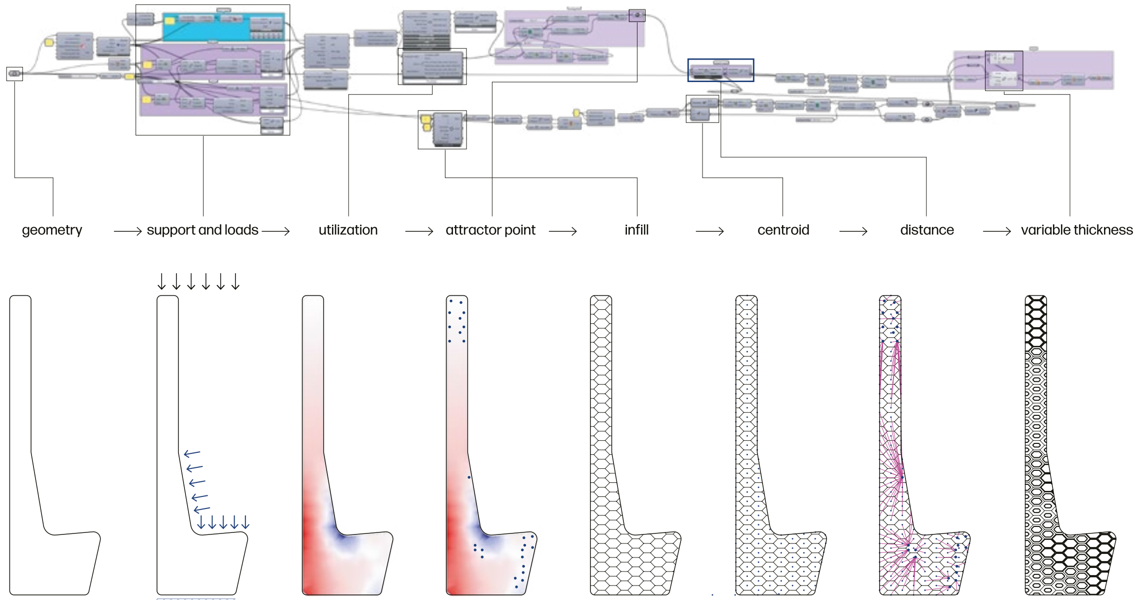

Figure 4: Mechanically Informed Infill Generation.

Figure 5: Bamboo dust (left) and Bamboo fibers (right).

Figure 6: Results of the Second Material Experimentation.

Figure 7: Mixture Procedure.

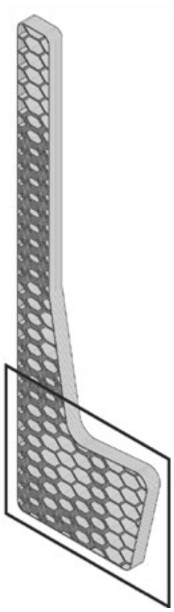

Figure 8: Chosen fragment.

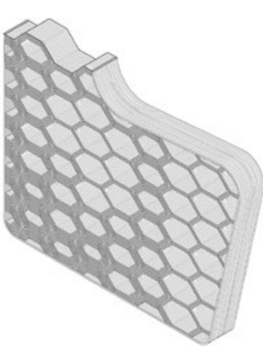

Figure 9: Fragment toolpath.

Figure 10: Printing Process of the Prototype.

The optimal three mixtures, that included the use of potato starch, COLLALL eco-glue and wood glue as binders, were chosen based on a simplified mechanical test and other factors such as printability, cost, and bio-based content. The testing process revealed an interesting correlation between potato starch and eco-glue, as the latter is derived from potato starch. To ensure an effective and efficient testing process, only one binder was chosen for the initial printing test. Consequently, potato starch and eco glue were selected, with potato starch being the more cost-effective option.

The selected mixture is subsequently manufactured in large quantities for the following AM application. This formed the basis for the next phase of the research, which focused on creating an extrudable and printable paste for the AM of a self-supporting wall made from bamboo dust and fibers.

MATERIAL PREPARATION

A large quantity of the selected mixture made with bamboo dust and fibers and potato starch, needed to be produced in order to proceed with the printability test to explore the potential of the selected mixture through AM. After various iterations of different proportions, the optimal consistency was achieved by using specific amounts of each ingredient.

The process of creating the paste involved several steps (Fig. 7), starting with weighing all the necessary ingredients.

The potato starch was then combined with cold water and mixed until fully dissolved. A pan was placed on a heating stove and the mixture was continuously stirred in it until it boiled. After approximately 7 minutes, a thick paste was formed, and the mixture became transparent. The mixture was then cooled in the mixer for a brief period before adding 1/3 of the dust and starting to mix. Another 1/3 of the dust was added, followed by half of the fibers. The remaining fibers were added, followed by the remaining dust. The mixture was mixed thoroughly until it became a thick paste ready for printing.

By following these steps and using the clay mixer, the optimal potato starch mixture was produced and ready for further testing in the printability test.

FABRICATION

The printing process involves two crucial factors that need to be controlled: the amount of extrusion and the movement, which are managed by the extruder and 6- axis robotic arm.

In order to streamline the printing process, we utilized the LDM WASP extruder XL 3.0 for controlling extrusion. It should be noted that the extruder can only be used with the Delta WASP 40100 Clay according to the manufacturer WASP, and thus, a custom wiring arrangement and extruder holder were constructed to enable the prototyping to be conducted using the robotic arm.

The primary objective of this research is to provide proof of concept for printing with bamboo. To achieve this, a 1:1 scale fragment of the design, explained in the Mechanically Informed Infill section, is prototyped. It was not feasible to print the entire prototype due to limitation of the robot work space, available materials, and tools, therefore a fragment of the overall design was prototyped. The selected fragment corresponds to a specific area within the component, which is determined by the reachable working area of the robotic arm (Fig. 8).

The chosen fragment focuses on the bottom part of the component, as it encompasses the three different types of infill designs. This selection allows for a comprehensive representation of the infill variations within the design and demonstrates the capabilities and potential of the proposed approach. In order to achieve successful printing, it is crucial to generate a continuous and uninterrupted toolpath. To address this requirement, a toolpath was meticulously designed and simulated with the robot arm to ensure optimal printing results (Fig. 9).

Consideration was given to the distances between the walls, taking into account the findings from the printability exploration phase. This approach was implemented to prevent any potential issues such as layer overlapping and ensure the integrity and accuracy of the printed prototype.

The prototype was printed on a PVC film-wrapped printing bed to simplify the removal process once it had dried. It should be noted that the consistency of the material mixture varied from one printing session to another, and even throughout the day. As a result, adjustments were made to the pressure and speed of the extruder based on the observed consistency of the material at each instance.

To prevent excessive extrusion of material, particularly when the cartridge is nearly empty and higher pressure is exerted, a precautionary measure was taken. The cartridge was refilled with material after the completion of each layer, ensuring a consistent and controlled extrusion process throughout the printing procedure. This practice helped to maintain the desired quality and integrity of the printed component (Fig. 10).

Once the component is printed, it underwent a natural drying process, with intermittent application of vinegar to prevent the growth of mold. This step is essential for ensuring the stability and durability of the printed prototype.

While the printed fragment represents a smaller portion of the overall design, it serves as tangible proof of concept and provides valuable insights into the feasibility and potential of printing with bamboo.

CONCLUSION

This research project represents an innovative approach in the field of circularity and construction automation within the built environment. By exploring the use of bamboo in AM, it showcases the potential for sustainable material use and advanced fabrication techniques. The ability to re-use the printed component in the mixture enables a continuous printing process, reducing the need for new materials. The design process, informed by structural analysis and tailored infill geometry, showcases the potential of AM to optimize material use and create structurally efficient building components. The project addresses the need for renewable and eco-friendly construction materials, as well as the adoption of AM as a platform for material design. Through this innovative approach, the project contributes to the advancement of sustainable construction practices and highlights the possibilities for utilizing bamboo in the built environment.

Overall, this research project demonstrates the potential of bamboo fibers and dust as a valuable material for architecture through AM. The findings emphasize the benefits of incorporating bamboo into the construction industry, including its rapid growth, renewability, and versatile properties. By promoting the adoption of bamboo and AM techniques, the project contributes to circularity in the built environment and supports the transition towards more sustainable and efficient construction practices.

ACKNOWLEDGEMENTS

We would like to extend our sincere appreciation to Johan Kocks from Bambooder and Alberto Peyron from Made in Bamboo for their generous assistance and provision of the bamboo dust and fibers required for this research. We are also grateful to Paul de Ruiter for his tremendous help in procuring the necessary equipment for 3D printing at LAMA (Laboratory for Additive Manufacturing in Architecture) at TU Delft. His availability and support were instrumental in facilitating the practical aspects of our research.

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