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Robotic wickering: Fiber-mycelium hybrid modular system

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ABSTRACT: The pressing environmental challenges place significant constraints on resources, triggering the search for efficiency and performance characteristics in sustainable solutions. Mycelium-based composites (MBC) as biodegradable products and their diverse applications have the potential to replace conventional materials. Despite MBCs advantages, they remain not fully exploited in the construction sector due to their limited structural capabilities. This research focuses on improving the structural performance of MBC by integrating Mycelium and Natural Fiber-Reinforced Polymer (NFRP) as a material-efficient hybrid system. For reinforcement, a 2D wicker-lattice system is designed through custom robotic additive manufacturing processes guiding mycelium's growth, improving its mechanical behavior, and eliminating the need for special formwork. A computationally optimized workflow is used to inform material distribution, achieving efficient geometrical and structural performance. A slab panel is realized, showcasing the potential of this hybrid building system and expanding the use of bio-based composite materials in modular architecture applications.

1 INTRODUCTION

1.1 *Mycelium in Architecture*

The construction industry is under significant pressure to fight climate change, driven by the need to use fewer resources and reduce greenhouse gas (GHG) emissions. To address these challenges, it is essential to enhance the efficiency and performance of material resources through computational design and robotic fabrication processes (Dambrosio et al., 2021). Diversifying material sources, adopting circular design, and promoting sustainable use are also necessary to maximize material service life, and minimize waste (Dahy, 2019). Bio-based materials can be a potential solution (Hebel & Heisel, 2017). Particularly, mycelium has gained attention for its possible applications in construction. These materials use natural biological processes and low-energy fabrication methods to produce biodegradable, regenerative, cost-effective composites, promoting waste reduction and material reuse (Maraveas, 2020). Mycelium-based composites (MBC) are recognized for their renewable and low-carbon emissions, as well as their lightweight nature and distinctive mechanical properties under impact loads relative to their weight (Jones et al., 2017; Attias et al., 2020; Akan et al., 2018). Despite these advantages, MBCs have not been widely adopted in the construction sector due to their limited capacity to endure strong longitudinal stresses such as compression, tension, and bending (Heisel et al., 2017). However, the customizable nature of these composites allows for tailored applications (Madurwar et al., 2013) and presents significant potential for various sustainable construction applications.

In recent years, numerous applications of mycelium-based composites in architecture have emerged. A prevalent strategy involves manufacturing smaller components that are subsequently combined to achieve larger designs (Kırdök et al., 2022). While this approach is common and effective, there is growing interest in producing larger elements as single units for architectural applications

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(Attias et al., 2021), which requires substantial production facilities, extended cultivation and growth times, and increased fabrication costs due to the need for large molds. Moreover, these systems often necessitate extensive scaffolding and reinforcement structures that assume the structural role of mycelium, thereby limiting its application primarily to surface finishes (Dessi-Olive, 2019). Selected reviewed projects have therefore focused on integrating reinforcement strategies, such as natural and wood fibers, similar to how steel reinforcement enhances concrete's strength to enhance the structural capabilities of mycelium-based materials (Özdemir et al., 2022; Göbert et al., 2022).

In a furniture-scale application, Mycomerge stool demonstrates the load-bearing capabilities of mycelium reinforced with a natural rattan framework through an innovative design approach to guide the growth of mycelium. This integration enhances mycelium's effectiveness in load-bearing applications, enabling it to support weights exceeding 20 times its mass. At the University of Kassel, a large-scale 3D-printed wood veneer lattice (HOME) was developed as a reinforcement system and lost mold for mycelium growth in interior applications. A robotic process was engineered to efficiently fabricate these 3D lattice structures using a 6-axis industrial robot arm and a custom end-effector. This system enabled extrusion, cutting, and binding of the lattice to pre-positioned strips. Tests showed significant enhancements in elastic modulus and strength of mycelium-based composites (MBC), demonstrating their suitability for large-scale architectural applications.

1.2 *Natural Fiber in Architecture*

In recent years, Fiber Reinforced Polymers (FRPs) such as carbon or glass have been integrated into high performance in automotive, aerospace, and naval industries due to their strength and lightweight (Truong, 2020; Rajak et al., 2019). However, their use in construction is less common due to cost. Natural fiber-reinforced polymers (NFRPs) utilize plant-based fibers such as flax, hemp, and jute and require low-cost production methods to produce composites, offering more sustainable alternatives and readily available in Europe (Saslawsky et al., 2024). Recent research has shown that NFRPs can show comparable mechanical properties for composite materials (Safi, 2020) and enhance structural design and material efficiency, expanding their potential applications in the architectural context (Humphreys, 2003). LivMatS pavilion from ICD Stuttgart showcases the potential of using natural fiber composites in architecture applications the first full-scale application of load-bearing, coreless wound natural flax fiber parts. Fifteen components were robotically produced using flax fibers, where fibers have varied densities and are placed according to various load distributions to achieve structural integrity (Pérez et al., 2022). A varying opacity of fibers was used, to achieve visual connections with the surrounding.

1.3 *Scope*

For this paper, the focus is primarily on developing reinforcement strategies for MBCs, to enhance the structural performance for large-scale applications while simplifying the complexity of the fabrication process and required molds and formwork. The goal is to develop material-efficient hybrid components that leverage mycelium's compression properties and natural fibers' capabilities in tension and bending within the composite system. A 2D wicker-lattice frame from natural fibers was designed using custom robotic additive manufacturing processes tailored for specific load cases to guide mycelium growth. This frame serves as a lost mold and reinforcement system within the MBC matrix, aiming to increase structural capacity. The system can be modularly fabricated from a single mold type, reducing fabrication complexity. The computational workflow utilized seeks to expand the application of bio-based composite materials in architectural practices.

2 ROBOTICS WICKERING

2.1 *Wickering Pattern*

Different strategies for robotic path planning were developed to accommodate varying levels of complexity while maintaining the simplicity of the process. In this process, a UR10 e 6-axis robotic arm is used, controlled, and programmed using the Robots plugin within the Rhino/Grasshopper visual programming interface, which enables the creation and simulation of robot programs. The initial wicker pattern served as the guiding principle for developing a tailored frame and can be broken down into the following tasks. A grid is defined with horizontal and vertical segments. First, a node is created at the first anchor in the first row. Second, a zigzag pattern is used to transition vertically to the last anchor in the same row by alternating movements around each anchor. At the last anchor, another node is created but in the opposite direction then return to the first anchor and repeat the process. After completing one group of segments, automatically transition to the other group of segments. Following these tasks can achieve a frame or lattice-like structure. By adjusting the distance between grid segments, the density of the wicker frame changes accordingly, contributing to different visual and mechanical properties. For different applications, a collection of wicker syntax strategies (Figure 1) is developed, tailored to the geometric system and achieving various functionalities while maintaining the simplicity of the frames.

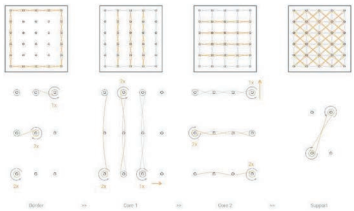

Figure 1. Wickering winding syntax catalog. Authors, 2024.

2.2 *Fabrication Workflow*

To generate a fabricable wickering pattern that can be directly translated into robotic tasks, custom Grasshopper components were developed. By setting basic inputs, such as application type (e.g., slab or wall), anchor point distances, initial curves, and degree of curvature, the components produce an immediate output of wickering and anchor TCP planes, along with fabrication-ready information. A comprehensive description of these components lies beyond the scope of this paper. The robotic fabrication process was tested using a specifically developed end effector by extruding continuous jute fiber filaments impregnated with adhesive producing two wicker frames: 32 x 24 cm and 18 x 12 cm.

The robotic winding path program was prepared, end effector was assembled and connected using a tool connection (Figure 2), and the adhesive was loaded into the container. The overall process took five minutes with pauses to refill the adhesive container, and the frames were left to dry for two hours. The speed of the process is essential due to the adhesive's setting time (open time), ensuring a properly dried layer forms before pressing for maximum strength capacity. The frame can be removed as a single element allowing fabrication boards to be reused for additional

Figure 2. (Left to right) The wickering end-effector tool consists of several parts that can be assembled to perform as a single component for winding, tension control, and precise navigation along specified paths; Fabrication setup and workflow for the robotic winding process; prototype (18 x 12 cm). Authors, 2024.

elements, eliminating the need for new board production. This approach promotes system reuse, sustainability, and resource efficiency, in contrast to other projects. Initial physical testing further revealed an observation that the module with less adhesive (19 x 14 cm) exhibited greater stiffness in both tension and compression, whereas the module with excessive adhesive (32 x 27 cm) deformed more due to its retained flexibility. This initial observation indicates that controlling adhesive application not only affects drying time but could also significantly influence the mechanical properties of the final structure. These findings need to be verified through a series of tests, comparing specimens with and without adhesive, to validate the results.

3 MYCELIUM AND FIBER COMPATIBILITY

To investigate the compatibility of developing a hybrid material, the wicker frames were prepared to investigate the interaction of mycelium with adhesive and fiber (Figure 3). Due to the constraints of maintaining a sterile environment and the long growth period required, a commercially sourced pre-grown substrate (mycelium with hemp) from Grown.bio (Heerewaarden, The Netherlands) was used. First, a water-based polyvinyl acetate (PVAc) adhesive with low volatile organic compounds (VOCs) was chosen as a sustainable alternative to petroleum-based adhesives, contributing to the system's biodegradability. It also acted as an intermediate layer, protecting the fiber from mycelial degradation. Second, the pre-grown mycelium substrate was mixed with psyllium husk to create a clay-like consistency, improving both bonding strength and growth. After growing the samples for five days in a controlled environment (23 °C, 80 % humidity) in a dark environment, the samples were fully incubated. Subsequently, the samples were air-dried for two days and then oven-dried at 100 °C for 1 hour to complete the drying process. All samples showed successful integration as proof of developing a hybrid material. The smaller sample with controlled adhesive displayed more stiffness. However, this needs validation through mechanical testing.

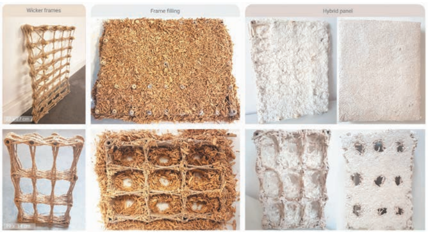

Figure 3. Mycelium – wicker frame compatibility test. Authors, 2024.

4 SYSTEM EXPLORATIONS

4.1 *Wickers as Slabs*

Computational methods were employed, translating this wickering pattern into architectural applications, that consider structural analysis and optimization methodologies to inform material articulation. Within the Grasshopper environment, Finite Element Analysis (FEA) plugin Karamba3D (Duque Estrada et al., 2021) was used to design and analyze a shell element of a slab with dimensions of 3 x 3 m square geometry with four anchor supports (Figure 4). A gravity load case of 3 kN was applied and a cross-section of 10 cm was also defined. The displacement values were measured at 3 mm, which was within the acceptable limits for this application. The shell element incorporated material-specific properties for mycelium, utilizing state-of-the-art values to define fundamental parameters such as Young's modulus, shear forces, and maximum allowable tensile and compressive strengths. This enabled a more accurate representation of the composite's response to structural forces.

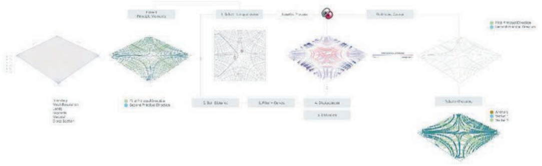

Figure 4. Computational workflow: (left to right) Karamba3D digital model of the slab; structural analysis extracting principle moments; optimization process based on threshold distance using Galapagos; selected curves are analyzed as beam elements in Karamba3D; extracting wicker syntax for the robotic fabrication process. Authors, 2024.

The utilization analysis displayed areas of tension and compression concentration, providing insights into the global structural behavior and informing the optimal placement of material relative to stress distribution. The first and second principal moment curves were extracted, serving as input to generate tailored robotic wickering lines. In the next step, an optimization process aimed at minimizing their number in relation to structural behavior and displacement constraints by using Galapagos evolutionary solver. In this process, the longest curve is first selected, a distance threshold is defined, and iteratively curves are excluded that have a distance below a defined distance while storing those that meet or exceed it. Second, selected curves are defined as beam elements and evaluated to ensure they fall within an acceptable displacement range. Curves that meet these criteria are stored, while those that do not are iteratively replaced with alternative curves until the structural requirements are satisfied. As a result of this process, the fiber frames have a tailored geometry that considers the slab's force flow. The main components of the slab are a fiber wicker frame integrated with mycelium, and top and bottom wooden plates serve as covers resulting in a sandwich construction.

4.2 *Prototyping*

A segmenting strategy was used to segment the floor slab system into modular components for ease of fabrication, transport, and assembly (Figure 5). Flexible segmentation strategies were experimented (Orozco et al., 2024), and can be easily adapted to irregular boundaries, producing fewer cut-outs. The prototypical building was designed to be on a footprint of 18 m², with dimensions of 6 x 3 m and a height of 3 m. However, due to fabrication limitations and time constraints, one panel was selected in dimensions of 1.4 x 1.269 x 0.08 m to validate the system.

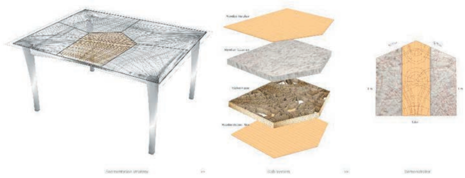

Figure 5. Segmentation strategies for architectural application; Demonstrator panel with exposed fiber-mycelium wicker frame (1.4 x 1.269 x 0.08 m). Authors, 2024.

4.3 *Assembly*

The model is prepared into 2D drawings suitable for fabrication. Wooden construction begins by preparing top and bottom plates, and anchors, with dimensions and locations determined directly from the wickering component. For the top and bottom plates, birch plywood multiplex wood 10 mm boards were selected for their compatibility with mycelium growth and its inherent strength, while also serving two main functions: enabling a sandwich panel configuration for load-bearing tests and providing a rigid covering essential for the three-point bending test, To securely position the plates within the wicker frame, perpendicular webs were constructed, with wooden dowels connection for easy alignment and assembly process. Subsequently, one improvement in the fabrication process involves using wood anchors that can be inoculated with mycelium, potentially speeding up the fabrication process. To showcase the internal structure, only half of the wooden construction was completed, leaving the fiber-mycelium wicker frame exposed for examination. A total length of 800 m of Jute fiber 2 mm was used to wound around the anchors and follow the wickering paths (Figure 6). The robotic winding logic was initially planned to start with horizontal curves before moving to vertical ones to overlap and enhance structural strength. However, it became noticeable during the first test that the overlap of anchors between horizontal and vertical lines posed a significant problem, complicating the path flow. Therefore, adjustments were made to ensure the winding curves aligned properly with adjacent anchors.

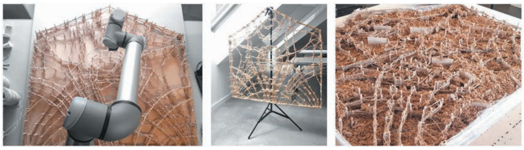

Figure 6. (Left to right) Overview of robotic wickering process fabricating demonstrator slab panel; final wicker frame; filling process of wicker frame with mycelium-substrate for the growing process. Authors, 2024.

The second challenge encountered was the short open time of the adhesive, requiring a faster and continuous application of adhesive during the entire process to achieve a cohesive, connected frame. The frame was constructed in a total of four hours and left to dry for a day before disassembly of the whole structure. The wicker frame was easily disassembled from the wooden board, enabling the board's reuse for constructing other frames or panel elements achieving the primary goal. Afterward, the frame was sterilized before the filling process began. In total, two bags of 27 L of pre-grown substrate (mycelium with hemp) were used in an incremental filling process to ensure even distribution for mycelium growth and expansion. The wicker frame is then left to grow in a dark environment in a temperature between 22 to 26 °C and humidity around 80% for nine days to allow for optimal growth. Due to the panel size, the frame was dried outdoors for four days with an average temperature of 26 °C, fluctuating between a high of 35 °C and a low of 17 °C, and humidity between 80-100%, resulting in the finished product.

5 RESULTS

The weight of the demonstrator was initially heavy due to the large volume of pre-grown substrate contained with water. After growth and drying process, the panel's weight was significantly reduced, demonstrating complete integration of the mycelium with the wicker frame and interaction with the top and bottom wooden plates (Figure 7). The sandwich panel is solid, stiff, and exhibited slight curvature stemming from the type of additive used. The load-bearing behavior of the demonstrator was tested in a non-destructive walking test, where users could walk on the wooden plates supported at both ends supporting a user weight of 85 kg, with deflection ranging

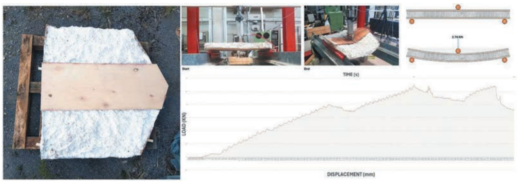

Figure 7. Final prototype: fiber-mycelium- hybrid modular system; three-point bending test, demonstrating flexibility. Authors, 2024.

from 4 to 7 mm. Three-point bending test was conducted on the final prototype, which demonstrated a load-bearing capacity of 2.7649 kN, and displacement of 79.61 mm at failure, indicating significant flexibility. While the material's performance is promising in the context of sustainable construction, its performance is lower than that of conventional materials, such as concrete or engineered timber. Further reinforcement and material optimization are necessary for it to compete with conventional building materials in more demanding structural contexts.

6 DISCUSSION AND CONCLUSIONS

The three-point bending test showed that failure primarily occurred at the top and bottom of wooden plates, while the overall structure displayed significant bending flexibility, without immediate structural failure, achieving a bending radius of 3.11 m. This behavior contrasts with what would be expected from mycelium alone, with limited capacity to endure strong longitudinal forces, typically breaks under bending, and lacks elasticity. Although a control test on unreinforced mycelium was not conducted in this study, existing literature suggests that mycelium alone would demonstrate significantly lower bending resistance (Heisel et al. 2017). Integrating a wicker frame with mycelium allowed both materials to work together, becoming mutually supportive and essential in maintaining the structure's integrity. This system achieves the main goal of developing a hybrid system that leverages mycelium's compressive qualities and the tensile strength of natural fibers to achieve higher structural performance, thereby extending mycelium's functionality beyond its traditional role. Future work will integrate material-specific properties into the structural simulation, transforming it into a digital twin of the physical prototype, to gain insights into material behavior and performance within the composite, relying on the mechanical testing data sets. Most of the longitudinal deflection observed can be attributed to the type of additives used in the composite material, which significantly influences the elastic deformation behavior of the frame. Although this degree of flexibility is less desirable for load-bearing slab elements, it demonstrates the potential to improve mycelium's structural capabilities. Flexibility could be advantageous in non-structural architectural contexts, such as adaptive façades, and partition walls. For load-bearing applications, further research into stronger surface covering for the sandwich panel, such as flax or hemp compressed boards and a stiffer adhesive is required to reduce flexibility and enhance the system's load-bearing capacity, which needs to be verified through a series of specimens and tests. Various other prototypes to develop a 3D spatial wickering reinforcement composition are currently under study by the authors for connecting the top and the bottom plates as a truss system integrating structural criteria achieving greater stiffness and stability of the system using varied anchor heights. Exploring gradients within the wickering pattern is also being investigated, as it could potentially enhance the mechanical properties of mycelium. The robotic wickering process developed has the potential for further investigation into a more rapid, multi-fiber winding technique and tool (Figure 8).

In conclusion, this paper presents an innovative approach to enhancing the structural performance of MBC by integrating Mycelium and Natural Fiber-Reinforced Polymer (NFRP) into an efficient hybrid system. Through robotic fabrication and computational optimization, a 2D wicker-lattice system was designed and integrated to enhance composite structural properties. The initial prototype demonstrated promising results as a hybrid system and extended the mycelium's functionality structurally beyond its traditional role. Further experiments showed the demonstrator's capacity to support weights with minimal deflection and display significant flexibility, without immediate structural failure showcasing both materials working together and being mutually

Figure 8. Concept for architectural proposal "prototypical building. Authors, 2024.

supportive. Further research is required to improve reinforcement strategies, surface covering, and a stiffer adhesive to extend the composite's applications to larger-scale, load-bearing scenarios, supporting the adoption of bio-based materials in architecture.

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