Mycelion: A wood-mycelium composite-based, experimental pavilion with multiple growth phases

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Abstract. In a search for more sustainable materials, fungi have proven increasingly effective as a new building material. Mycelium composites are part of this discussion and experimentation. This research discusses the construction of a pavilion in a shell shape made of wooden construction elements filled with mycelium-hemp substrate. This paper explores how the fungus can work in symbiosis with other biomaterials, observing its behavior in two growth phases. The first growth phase took place in a temperature and humidity-controlled lab environment. The second phase was about testing the further growth behavior in an outdoor environment with a relatively wide range of temperature and humidity conditions.

Keywords: Digital fabrication, Mycelium-based construction, Growing phases, Computational design, Bioconstruction.

1 Introduction

Advancements in technology, biology, and digital computation, along with the pressing need for eco-friendly manufacturing methods, are driving the development of new materials and production techniques through collaborative interdisciplinary efforts. The consequence of a world marked by several decades of irresponsible mass production with a high environmental impact resulted in the accumulation of waste, earth and river pollution, and depletion of natural resources. To address these challenges, researchers from different fields exchange knowledge to achieve alternatives for the future of manufacturing (Womer et al., 2023). A wide field of research on developing nature-based materials and alternatives derived from renewable resources is being studied intensively.

Mycelium has gained attention for its potential as a sustainable and biodegradable material very much in packaging but also design and construction. It provides a great alternative material in construction and especially has much potential with its integration in generative, digital fabrication processes. Herby is now becoming a large area of research among architects and computational designers (Kontovourkis et al., 2020).

The present research investigates how mycelium can be used as a construction material and how different growth procedures can be applied in the production phase. In the development of an experimental study in a 1:1 pavilion, it has been observed how the mycelium interacts with a wood shell structure under specific conditions in the different growth phases. The outcome derives from various experiments and large-scale construction prototyping with mycelium, having a double-layer wood cassette as the main structure where the mycelium grows inside. With these various prototypes in a specific range of scales, different mycelium batches, compositions, and drying processes were tested and evaluated.

1.1 State of the art of mycelium as a construction material

In the past decades, mycelium has transitioned from being primarily used as a biodegradable material in packaging to gaining attention as a potential construction material due to its exceptional thermal performance (Xing et al., 2017). Notably, the "Hy-Fi" pavilion, constructed on MoMA's PS1 in 2014 by the architectural firm The Living, marked a significant moment in adopting mycelium-composite as a building material (Dessi-Olive, 2022). Subsequent projects, such as "The Circular Garden" by CRA - Carlo Ratti *Associati* in 2019 and "The Growing Pavilion" for the Dutch Design Week in the same year (Sydor et al., 2022), further explored the structural properties and circularity of mycelium-based construction materials.

A relevant precedent to the research presented in this article is the "Shell Mycelium Pavilion," created by BEETLES 3.3 and Yassin Areddia Designs in 2016 for the Kochi Muziris Biennale in India. This pavilion featured a shell structure constructed with triangular wood elements facing the interior layer of the shell and an exterior layer composed of mycelium composite reinforced with coconut fiber, with a focus on observing mycelium growth and degradation under natural weather conditions (Bitting et al., 2022).

However, there remains a significant knowledge gap concerning the preservation of mycelium composite in different growth phases and environments and its potential symbiosis with other biomaterials, which constitutes the primary focus of the current research.

2 Methodology

In 2020, an initial pavilion proposal for the *Landesgartenschau* in Höxter was developed in an internal architectural design and landscape design competition in partnership between Landscape Architecture students and students of the Master of Integrated Design from the Detmold School of Architecture and Interior Architecture (TH OWL). The initial first prize-winning group consisted of 4 students from the two mentioned disciplines, who developed a proposal of mycelium structure. The related project study program module has been initiated and led by Prof. Hans-Peter Rohler (Landscape Architecture) and Prof. Hans Sachs (CAAD, Architecture), who developed the first proposal. As part of the first prize, the team received funding to realize the pavilion in spring 2023 at the *Landesgartenschau* in Höxter, Germany. The final pavilion construction experienced significant changes from the initial proposal due to uncertainty in the development process and a lack of experience dealing with such material within the team.

In the development phase of the first 1:1 prototypes, realized by the MID student Ardalan Mirhadinejadfard, significant changes have been made compared to the initial proposal for the design competition in 2020. The proposal needed to be modified and especially modularized to set a stronger focus on the material and its application in such a construction.

The driving force of the research was to investigate the use of mycelium in combination with wood and to observe the symbiosis of two biomaterials with different properties: While the wood performs the larger structural part at first, the mycelium creates a complex living material infill. (Vanden Elsacker, 2021).

In this chapter, all the prototyping and the final development phase will be discussed, presented, and described.

Figure 1. Construction prototype development. Combination of modular elements as a variable vault structure. Author: Ardalan Mirhadinejadfard, 2022**.**

2.1 Prototype 1

Since the competition in 2020, several design studies and prototypes have been made. Initially, the first prototype consisted of a vault composed of identical modular elements with a wooden frame filled with mycelium reinforced by sawdust substrate (Figure 1). Prototype 1 tested the feasibility of a single module and consisted of CNC-milled OSB assembled in a waffle-like structure. A thin perforated textile in the inner part of the modules was applied to keep the mycelium in place while growing. The asepsis is crucial while handling fungus-based material, so the room where the mycelium was kept for one week was meticulously cleaned, such as the entire modular structure already assembled.

To grow properly, the mycelium composite requires a climate-controlled environment. Therefore, the room where the growing phase happened had the heaters set to temperatures from 23 to 25 degrees Celsius, promoting intense fungus growth for one week.

With the room ready, water, flour, and mycelium were placed in an industrial mixer to prepare the composite. Once mixed, it was ready to be cast in the wood frame inside the structure slots. Once every void was filled, a thin plastic foil covered the composite to keep the moisture that helped the humid conditions for the fungus to grow. After one and a half weeks of growing, it was time to remove the plastic foil and let the mycelium dry outside the controlled temperature room.

After drying, the prototype was exposed for a few weeks to observe how the mycelium would react to external weather conditions. The OSB wood, unsuitable for this condition, softened, and the mycelium darkened but was still attached to the structure.

Figure 2. Prototype 1. From left to right, from top to bottom: OSB wood structure; Perforated textile that kept the mycelium in place; Mycelium mixing; Casted mycelium with a thin plastic foil; Results after one week; Cracks observed in some areas after drying; Testing the reaction to the weather conditions after one month. Author: Ardalan Mirhadinejadfard, 2022**.**

The problems observed at this point were that each module had very large dimensions, which made the OSB wood structure unstable because the wood plates were sensitive to rainwater. The mycelium batch used during the first prototyping needed water in the mixture, damaging the OSB structure even more. Even though each module's structure was segmented to give more stability, there was not enough surface area where the mixture could attach to the wood. The overload weight damaged the structure, leading to cracks and shrinkage after drying the mycelium, which became unstable.

As a conclusion of the first prototyping, it was observed that the pavilion needed (1) a new design proposal with smaller parts capable of protecting the mycelium from weather conditions, (2) a water-resistant wood, and (3) a mycelium substrate that does not need additional water on the mixture.

2.2 Prototype 2

In November 2022, the same mycelium substrate used in prototype 1 was tested on smaller scales. For this new prototyping phase, which focused on form, size, and material, various tests were held in different kinds of compartments, shapes, and foils, and some of them were baked in the oven to be dried, as recommended by the manufacturer of the substrate. The preparation steps were done precisely in the same way as with prototype 1. However, some smaller test samples were baked in a conventional oven, while others had grown for one more week and just dried at room temperature and moderate humidity.

Figure 3. Prototype 2. From left to right, from top to bottom: Mycelium substrate; Styrofoam cast; Wood and plastic cast; Growing phase controlling the temperature and air humidity; Bucket casts without baking in the oven; Grown test baked in the oven. Source: Authors, 2022**.**

The results of Prototype 2 partly presented a better outcome due to a more sophisticated casting process with more compact molds with larger and smoother surface areas made of polycarbonate plastic sheets and foils. The best results from the experiments were those baked in an oven above 80 degrees Celsius for at least one hour. However, baking large-scale building components was unrealistic because of the lack of access to an industrial oven and the fact that it would consume a lot of energy. Therefore, this research focused on applying the composite wood-fungi material while not killing the mycelium entirely in baking, which would typically happen if baked at high temperatures. This process allows and requires the study of mycelium's behavior in other growth phases.

2.3 Final Assembly

Considering the observations made on the previous prototypes, the final design for the pavilion proposes a compression-only shell structure developed by the first-semester Computational Design students from the MID program in November 2022. Using a different substrate based on hemp fiber and mycelium does not require additional water and has a much higher structural performance than the sawdust-based substrate, especially in tension, so the cured material is more stable in its shape. The pavilion construction consists of a triangular-structured vault to reduce and evenly distribute forces in the structure (Figure 4). The 82 triangular elements with edge lengths from around 0.8 to 1.7 meters were generated based on a self-developed Grasshopper algorithm and, to a large part manufactured with a 5-axis CNC machine. The triangular extrusion bodies of Douglas fir 3-layer core board have one open side facing the internal space of the pavilion and one closed face on the outside to protect the mycelium from rainwater and moisture (Figure 5). This design allows the mycelium and the water-resistant wood to be individual composite building elements that would grow together on-site to form a single, continuous shell structure. The shape of the parts evolves from the construction algorithm to adjust their shape individually, responding to a structurally optimized vault structure and specifically generated connections based on Douglas fir wood connectors (cross-spacers) and stainless-steel cable ties (metal straps).

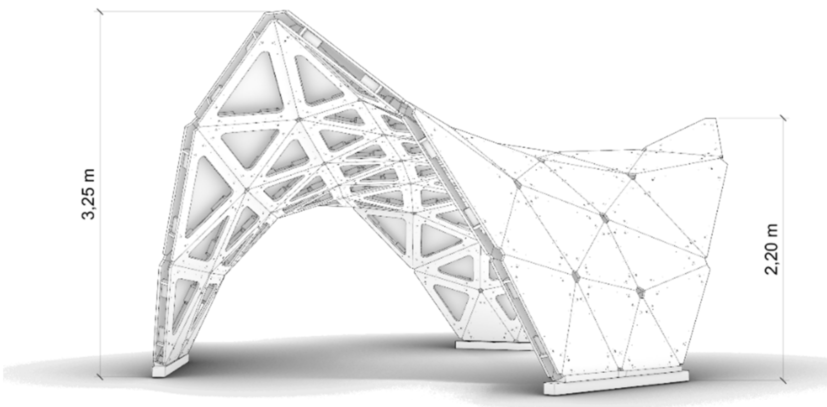

Figure 4. Perspective view of the final pavilion design. Source: Author, 2023.

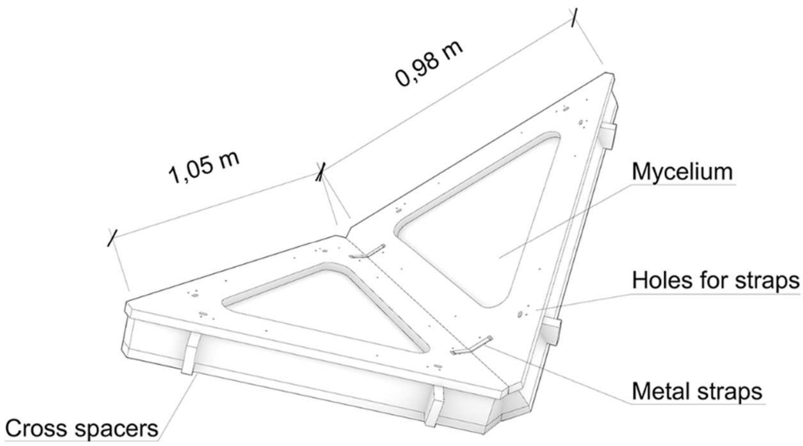

Figure 5. Drawing of two triangular elements. Source: Author, 2023.

The final assembly consisted of three key phases:

1. The mycelium has been filled in the triangular wood cassettes, and the initial growth started in a climate-controlled lab environment.
2. The cassettes have been assembled on-site after one and a half weeks of growth and pre-drying process.
3. The second mycelium growth phase took place on-site, where the mycelium in the wooden cassettes was supposed to connect to the neighboring composite elements by letting the mycelium in the open-sided boxes grow together in natural weather conditions.

2.3.1 Assembly Phase 1: Pre-fabrication in Lab

The triangular wood cassettes were assembled in 2 weeks and followed by the asepsis process before starting the mycelium mixing. The preparation of the mycelium hemp composite required an addition of 30g of flour to each 1kg of mycelium. After mixing the composite material, the casting occurred by filling every triangular element with the mixture and covering every surface with plastic foil with needle-sized holes every 5 centimeters. The filling process of all 82 elements took five days for a team of 5 students. The room was adjusted to a 22 to 24 degrees Celsius temperature with at least 60% air humidity. The already filled triangular elements were stacked with 2,5 cm wood spacers between them and a black plastic sheet on top of them to protect them from sunlight and keep the moisture inside. They stayed in the room for one and a half weeks to grow.

Figure 6. Phase 01 - From left to right: Materials used during the filling process; Triangular element filled with the mycelium composite; and triangular elements filled and stacked before growing. Source: Author, 2023**.**

2.3.2 Assembly Phase 2: On-site installation

The plastic foil was removed after one week of growing in a climate-controlled environment lab to start a slow drying process. The cross-spacers were added to the sides of the triangular elements. Some triangular parts filled with pre-cured mycelium substrate have been pre-assembled in the lab to facilitate transportation to and reduce work effort on site. After facing difficulties with tolerances in the assembly of the first parts, the construction strategy needed to be changed at various times. The initial assembly plan was not applicable due to the weight of the parts and resulting tolerances in the connections. Finally, two arches were initially erected, and missing parts were added step-by-step towards the opposing third arch. After assembling every triangular element, stainless steel straps were mounted between each pair of triangular parts. The overall construction has been done within eight days.

Figure 7. Phase 02 - From left to right: Two triangular elements already joined with the cross spacers and stainless-steel strap; Construction of the pavilion; and Final assembly of the pavilion. Source: Author, 2023**.**

2.3.3 Assembly Phase 3: Self-assembly "growing together"

The pavilion was on site and exhibited at the *Landesgartenschau* in *Höxter*, Germany, from April to mid-October 2023, experiencing alternating weather conditions. The goal was to observe if the mycelium keeps growing, how it reacts with the wood and the environmental conditions.

Figure 8. Assembly Phase 3: Self-assembly "growing together" One week after the construction – inner view of the pavilion. Source: Author, 2023**.**

Figure 9. Phase 3: Two months after the construction – inner view of the pavilion.
Source: Author, 2023

3 Results

In the final assembly at the beginning of phase 2, when the plastic foil was removed from the triangular elements, it was noticed that around 1/10 of the parts were too wet, with mold and water accumulation on the mycelium substrate's surface. A hypothesis is that the stacking of the triangular elements stopped the air circulation between some of the parts critically. The detrimental mold was removed from the critical parts, and a new mycelium mixture was added, but as the parts were infected by the mold, they could not effectively be reconditioned. It has also been observed that the mycelium in the elements with mold stopped growing. The mold severely affected the fiber structure of the fungus, resulting in the outfall of some of the substrate from the triangular wooden cassettes. However, the elements that did not have visible mold seemed to grow successfully in the first growing phase. One of the biggest challenges faced by the team was the assembly phase of the pavilion on site. The parts became extremely heavy to be carried and placed in a vault-like structure. However, after several trials and errors, the student team created a solution of first building two arches by pulling the parts together with tension belts and vertical columns. After building the first two arches, the pavilion became more stable, and missing parts could be integrated more easily and more accurately.

Twenty-two weeks later, the pavilion suffered exposition to extreme weather conditions, from heavy rains to intense sun from the Spring to the beginning of Autumn. Few changes have been observed since its construction. The structure of the fungi proved to be highly resistant to weathering and gravity, as the wooden cassettes are open on the underside. The wood color changed due to its exposure to the weather, but the mycelium properties were preserved from the initial construction. The only parts that fell off were the ones that had mold initially from the growing phase 1. No thermal comfort aspects could be mentioned since the pavilion consists of an open shell in a park. Regarding the final assembly phase, it was not possible to determine the state of the mycelium connection between the triangular elements and themselves.

4 Discussion

Overall, this research's most significant achievement was observing how the mycelium composite behaved in external weather conditions, experiencing rain, low temperatures (-4 to 34 degrees Celsius), sun, wind, and gravity action. It has been proven to preserve its fiber structural integrity, creating an optimal relationship with the wood.

Nevertheless, on the other hand, we note that some choices could have been different. The wooden cassettes took a long time to assemble. The weight of the pieces was underestimated regarding handling the parts in the on-site assembly process.

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