Discrete Shell Structure

Intelligent form-finding and fabrication of mycelium-based composites

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Abstract. This study investigates the integration of mycelium-based composites (MBCs) with computational algorithms to address challenges in sustainable architectural design. While MBCs are valued for their lightweight, biodegradable, and recyclable properties, their application in load-bearing structures is limited by mechanical constraints. By combining material research and computational workflows, this work aims to expand MBCs' potential across diverse architectural scenarios. The material research evaluates the mechanical properties of beechwood particles, straw, and hessian fabric combinations to optimise substrate formulations. Two formulations are identified: BSV, offering lightweight advantages, and BSMLV, exhibiting the highest Young's modulus. These results demonstrate the potential for tailoring MBCs to specific structural requirements. Using form-finding and intelligent classification algorithms, MBC modules with varied mechanical properties were optimally distributed across shell structures, aligning material performance with structural demands. This approach rationalises structural design, reducing reliance on high mechanical performance from MBCs while broadening their application potential. By addressing MBC's traditional limitations, this study provides a framework that integrates material innovation with computational optimisation. Future research will explore additional substrates and environmental factors to further enhance MBC adaptability, advancing its role in sustainable and scalable architectural applications.

Keywords. Shell Structure, Force Diagram, Mycelium-Based Composite (MBC), Reinforcement Learning, Customized modules fabricating

1. Introduction

Mycelium-based composites (MBCs) are sustainable materials that align directly with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13: Climate Action and SDG 12: Responsible Consumption and Production (United Nation, 2023). By utilising agricultural by-products and offering biodegradable, low-energy alternatives, MBCs address the environmental impact of the construction industry through the promotion of carbon reduction and circular resource use. This study leverages the SDG framework to explore methods for improving the mechanical properties of mycelium-based materials, investigating their potential for complex structural applications, and advancing their biodegradability as architectural materials.

Current research on MBCs primarily focuses on mechanical properties and low-stress applications, such as insulation and interior design. However, limited attention had been paid to their potential use in complex architectural structures or their stability in high-stress environments. Lower mechanical performance and inconsistent quality limit MBC adoption in architecture

This study targets to bridge the gap by integrating MBC materials with equilibrium- and fabrication-aware computational design strategies. By using advanced simulation tools, such as Unity3D, and exploring mechanical property optimisation through precise module allocation, this research seeks to address the unique requirements of complex architectural forms. The experimental framework includes the evaluation of substrate formulations using beechwood particles, straw, and hessian fabric, focusing on their compatibility with Ganoderma fungi to enhance material performance. Additionally, the study investigates the interaction between computationally optimized modules and their structural adaptability, promoting MBCs' application in sustainable and scalable design works. This study aims to achieve the following objectives.

- Proposing an innovative computational framework that combines MBC materials with modular optimization strategies to address challenges in non-homogeneous material distribution.
- Demonstrating a low-cost and adaptable cultivation methodology suitable for large-scale production.
- Validating MBCs' structural potential in complex geometries through a comprehensive combination of experimental data and computational analysis.

2. Literature Review

In recent years, research on MBCs has made considerable progress in material formulation, production processes, and application exploration. Holt et al. (2012) studied the impact of fibre substrates on MBC mechanical properties, emphasising their lightweight and biodegradable nature. Appels et al. (2019) validated MBC's environmental benefits, particularly in reducing carbon footprints. Jones et al. (2020) developed modular production methods to enhance homogeneity and scalability. Rigobello et al. (2022) examined the effects of substrates and processing parameters on material strength, providing experimental data for optimisation.

Despite certain advancements, existing research primarily focuses on the mechanical properties of MBCs or their potential for low-stress applications, with limited attention given to optimising structural designs to reduce reliance on MBC mechanical performance in complex geometries or high-stress structures. Given the significantly lower strength of MBCs compared to traditional materials, such as timber, optimising the load-bearing design of individual units within architectural structures is crucial to minimise material weaknesses and enhance overall structural capacity. Achieving this objective requires the adoption of innovative computational methods to overcome the inherent structural limitations of MBCs, thereby facilitating their broader application in the fields of architecture and engineering.

There are numerous computational methods available for creating the topology of a structure. Wang et al. (2019) shows a topological interlocking assembly approach that enables the creation of interlocking topologies with diverse patterns, such as blob, spindle, flower, and so on. Moreover, in the field of 3D-concrete-printed unreinforced masonry arched shell structures, the Striatus bridge (Bhooshan et al., 2022) presents a cutting-edge approach to addressing structural challenges. By employing a compression-optimised global form and masonry block discretisation, this project significantly reduces the reliance on steel reinforcement, mitigating tensile and flexural strength demands. However, the first example overlooks the overall load-bearing capacity of each block, potentially leading to uneven stress distribution within the structure. In contrast, the second approach creates a set of blocks that satisfy the loading limitations of the shell structure. However, considering that MBCs have lower strength compared to traditional materials, our study recognises the need for a more flexible and intelligent module allocation strategy.

This study aims to fill the gaps by employing intelligent geometric structure optimisation and masonry division algorithms to optimise mechanical performance in shell structures. Specifically, the work aims to introduce a novel approach by combining modular distribution and computational strategies to unlock MBCs' architectural potential beyond its mechanical limitations.

3. Methodology

3.1. MYCELIUM-BASED COMPOSITES

This study's framework and parameters follow Adrien Rigobello's methodologies for sample dimensions, drying conditions, and testing protocols (Rigobello et al., 2022; Rigobello & Ayres, 2022). During my master's research, under Adrien's supervision, I independently conducted material preparation, inoculation, cultivation, and testing, with all data derived from direct measurements. Substrate water content ratios were based on Adrien's standards, with slight adjustments to suit this study's objectives, ensuring rigour and reliability.

3.1.1. Material Selection

This study utilises beech wood particles, straw, and hessian fabric for their abundance, environmental benefits, and compatibility with fungi. In China, straw accounts for 30% of global production, with over 50% burned, releasing significant amounts of CO_2 and PM2.5 (Li et al., 2016). Beech wood, a by-product of the timber industry, is often wasted despite its sustainable potential (Cao et al., 2008). Hessian fabric, being low-cost and biodegradable, has a carbon footprint 60% lower than synthetic fibres (Elsacker et al., 2019; Holt et al., 2012). These materials meet the growth requirements of Ganoderma fungi, with beech wood facilitating fungal attachment, straw enhancing colonisation, and hessian fabric reinforcing the composite while reducing cracks (Holt et al., 2012). Together, they demonstrate the potential of biodegradable composites for sustainable architecture and emphasise the importance of circular resource use.

3.1.2. Growth Process

All tools, containers, and workspaces were sterilised, and substrates were autoclaved at 121°C (10–30 minutes depending on substrate volume) and cooled to room temperature to prevent contamination. Beech wood particles were categorised into small (0.5–1 mm), medium (0.75–3 mm), and large (4–12 mm) sizes (Figure 1). Small particles facilitated mycelial growth and bonding, medium particles balanced porosity and strength, and large particles, with lower density and better elastic recovery, were suitable for low-density studies. Water was added at 70% of the dry wood mass (Rigobello et al., 2022) to ensure optimal moisture levels and prevent oversaturation.

Figure 1. Material Preparation

Straw was cut into 3–5 mm segments, with the same water addition ratio of 70%, to maintain controlled moisture levels for stable mycelial colonisation. Hessian fabric was cut to mould dimensions, with a water addition of 10%, and pre-moistened to 10%–20% to enhance adhesion with other substrates. This tailored approach ensured optimal mycelial growth and material performance. The mixing process is illustrated in Figure 2.

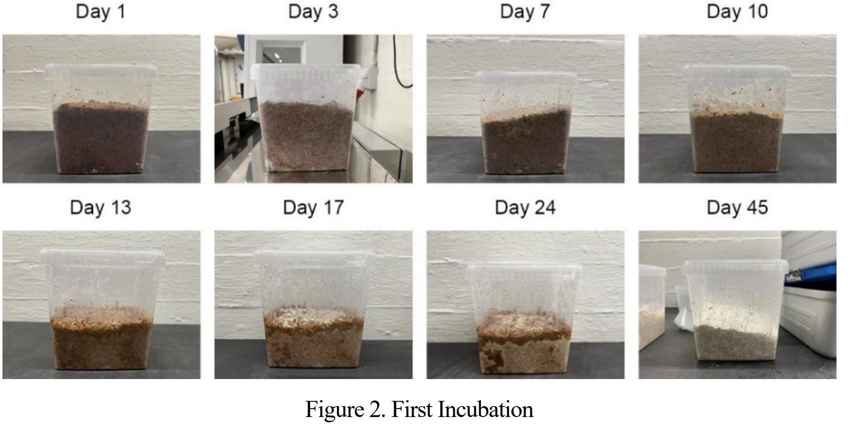

Figure 2. First Incubation

In a sterile environment, the autoclaved substrate, cooled below 30°C, is mixed with Ganoderma fungal spawn at 20% of the wet substrate's mass (Figure 2). The mixture is placed in sterilised ventilated containers, sealed, and incubated in darkness at 20–30°C to promote fungal growth.

The substrate from the first incubation was transferred into standardised ASTM D-1037 moulds (Figure 3) to study the effects of particle size and fibre reinforcement on material performance. Particle sizes were categorised as small (BS, 0.5–1 mm), medium (BM, 0.75–3 mm), large (BL, 4–12 mm), and a 1:1:1 mix of all three (BSML). Reinforcement types included hessian jacketing coaxial with the load (H), unidirectional rattan fibres perpendicular to the load (R), and unidirectional common reed fibres coaxial with the load (V), with isotropic controls set for all particle size categories (Table 1).

This setup produced 16 module configurations, incubated under the same conditions as the first incubation for seven days to further promote mycelial growth and substrate adhesion. By the end of the incubation, mycelial coverage exceeded 95%, resulting in tightly bonded and structurally stable modules.

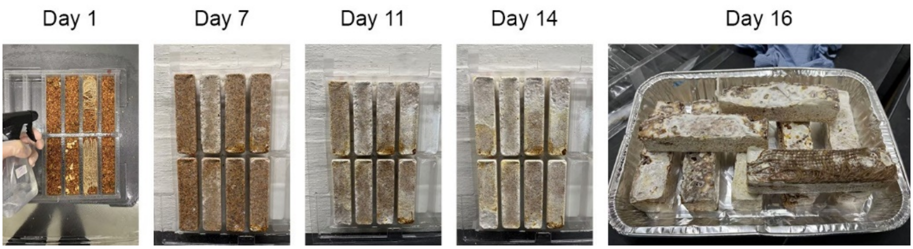

Figure 3. Second Incubation

After the second incubation, the modules were carefully demoulded to preserve their edges and inspected for uniform mycelial growth. They were then dried in a convection oven at 60°C to 80°C for 6 to 48 hours, depending on their size and geometry (Figure 4). This drying process halted mycelial growth and enhanced the material's strength and structural stability.

Figure 4 (left). Drying / (right). Mechanical Performance Test

Table 1. Summary of sample type parameters

Mean Density kg/m3 (s.d.)	BS	BM	BL	BSML
Control	203.72	228.17	212.34	218.73
H	223.65	245.62	270.10	244.33
R	194.41	218.42	248.95	228.90
V	189.10	206.4	206.40	199.76
Mean Young's modulus MPa (s.d.)				
Control	1.72	3.13	2.74	2.45
H	1.50	2.74	3.12	1.95
R	0.45	4.02	2.45	1.54
V	3.45	9.84	8.76	8.02
Mean Ultimate Strength kPa (s.d.)				
Control	178.90	321.33	254.09	252.38
H	168.45	288.78	232.12	192.85
R	76.62	252.12	168.75	156.30
V	166.62	290.31	299.48	348.85

3.1.3. Mechanical Performance Testing

This study strictly adhered to the standard procedures established by Adrien Rigobello to ensure the reliability and reproducibility of mechanical performance testing (Rigobello et al., 2022; Rigobello & Ayres, 2022). Test specimens were prepared using ASTM D-1037-compliant moulds (Figure 4) and stored at 23°C and 50% relative humidity for at least 24 hours after demoulding to achieve moisture equilibrium. Testing followed ASTM D-1037 standards, with a high-precision compression machine recording stress and strain data under controlled conditions of 23°C and 50% relative humidity. Pressure was applied along the longitudinal axis of each specimen at a loading rate of 2 mm/min to avoid deviations caused by dynamic impacts. Key metrics included density, mean Young's modulus, and ultimate compressive strength (all with standard deviations), with at least five specimens tested per configuration to ensure statistical reliability and scientific validity.

3.2. FORM-FINDING AND OPTIMIZATION

Following the collection of mechanical data for MBCs, defining a reasonable geometry has become the main goal of this phase. This involves designing subdivided modules in a way that ensures the forces within each module remain within the acceptable tolerance range. Based on the Thrust Network Analysis (TNA) algorithm, this research establishes a parametric design process in Rhinoceros and Grasshopper environments. Based on the COMPAS framework (Iannuzzo et al., 2021), the process begins with a mesh surface as the basis for morphological generation. The design is iteratively refined through a serial optimisation process to calculate the optimal arched structure under compression and deadweight only. This funicular structure can rely entirely on the compressive resistance of masonry materials without any external reinforcement measures, which benefit the MBCs.

As shown in Figure 5, the overall shape design of the shell starts with a user-specified 2D graphic representing the shell spine (Figure 5a). By default, the endpoints of the graphic are assumed to represent the footings of the shell. Subsequently, the user designs the vertex positions of the mesh surface and retains all topological information (Figure 5c), which can be used for subsequent modifications.

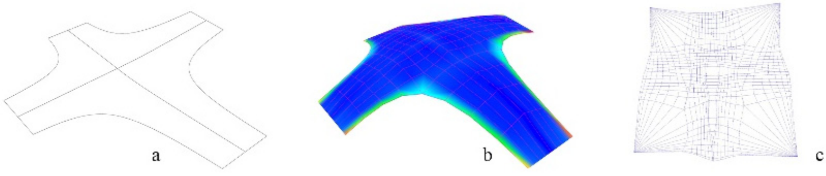

Figure 5. Shell design and fit simulation

3.3. DISTRIBUTION OF MBC APPLICATION VALIDATION

In building structures, the force characteristics of components vary depending on their location and load conditions. To ensure the stability and efficiency of the shell, it is essential to allocate modules with different mechanical properties based on functional requirements. From the 16 materials obtained in Section 2.1, two types of modules were selected: high-strength modules (BSMLV) and low-density modules (BSV). BSMLV are used in load-bearing areas of the shell, such as the foundation and boundaries, to withstand concentrated loads and vertical pressure, reduce deformation or failure risks, and maintain structural stability. BSV are placed in non-load-bearing areas of the shell to reduce the overall weight and foundation pressure, optimising material utilisation and improving construction efficiency.

An evaluation method for assessing the dynamic stability of an arch structure was developed to achieve an optimised distribution of modular components. This method serves as the reward mechanism in a reinforcement learning framework implemented using Unity3D and ML-Agent. Specifically, the stability of the structure is assessed by monitoring the motion state of each individual module within the structure. Each module (block) is equipped with physical components, including a Rigidbody and a Fixed Joint, which record its velocity and the forces it experiences.

In preliminary tests, the Rigidbody mass volume is set to 1. For BSMLVs, the joint force was configured to 1186.9 while the torque was set to 1396. BSVs were assigned a force of 599.43 and a torque of 750. As the characteristics illustrated in table 1, using BSV modules exclusively resulted in structural collapse suggested on the left of Figure 6, whereas utilising BSMLV around the footings enabled stability, showing on the right of Figure 6.

Following this preparation, the ML-Agents toolkit was utilized to optimize modular distributions. The reward mechanism, as shown in Figure 7, is designed to observe the positions and rotations of all blocks. At each timestep, the average velocity of all modules was calculated to represent the overall movement intensity of the structure,

$$\text{stabilityScore} = 1 - \left(\frac{\text{averageVelocity}}{\text{maxPossibleVelocity}}\right)$$

serving as a metric of instability. To convert instability into a measure of stability, a simple formula was applied:

Lower movement velocities correspond to higher stability scores. This score is employed as the reward function in the reinforcement learning algorithm which enables the iteratively optimize of the distribution for BSMLV and BSV.

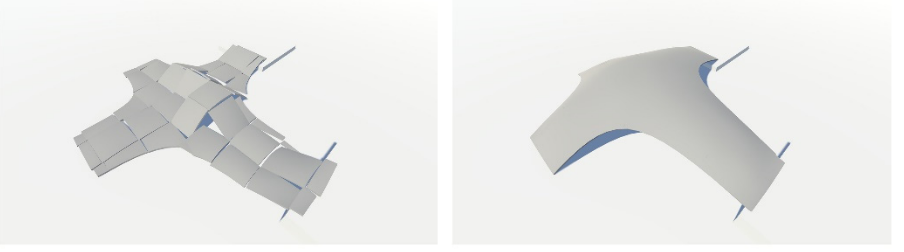

Figure 6. Force simulation of shell structure with one and two sets of MBCs

```
Initialize totalForce = 0
Initialize blockRigidbodies = list of all blocks' rigidbodies

Function EvaluateStructureStability():
    totalForce = 0
    For each rigidbody in blockRigidbodies:
        totalForce += rigidbody.velocity.magnitude
    stabilityScore = 1 - (totalForce / Length(blockRigidbodies))

    Return Max(0, stabilityScore)

Function Reward():
    stability = EvaluateStructureStability()
    If stability is high:
        Give positive reward to agent
    Else:
        Give negative reward to agent
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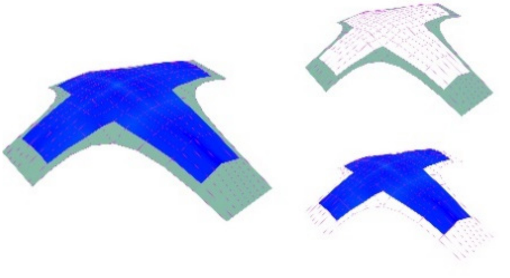

Figure 7. Reward Functions for training process

Figure 8. Distribution of modules

4. Results and Discussion

Based on material experiments and algorithm optimisation, this study constructed a 1:10 scaled prototype shell structure (Figure 9) to evaluate the applicability of MBC modules in complex geometrical designs. The production and assembly of the prototype further validated the feasibility of algorithmic simulation results and demonstrated the material's performance in real-world conditions.

The prototype construction began with the preliminary cultivation of substrates. Ganoderma fungal spawn was thoroughly mixed with the substrates (including the BSV and BSMLV formulations) and placed in isolated bags for a two-week cultivation period. During this time, the substrates and fungal spawn combined evenly, maintaining optimal humidity and growth conditions. Subsequently, shell modules are designed and 3d printed. After the initial cultivation, the two prepared substrate formulations were filled into the respective moulds, sealed with cling film, and equipped with ventilation holes at the top. The substrates continued to cultivate within the moulds for another two weeks, during which the mycelium further permeated and developed preliminary strength.

Upon completing the cultivation, the substrates were carefully demoulded and placed in a convection oven for drying at 60–80°C for 24 hours, with the temperature dynamically adjusted based on substrate conditions. This drying pro-cess terminated mycelial growth and enhanced the material's strength. The final shell modules met the shape and strength requirements for subsequent assembly.

As shown in Figure 8, assembly testing revealed that BSMLV were distributed along the base and edges, to provide stable support, while BSV were placed in the middle and upper sections to reduce overall weight. The results indicated that the stability of the shell structure closely aligned with the computational simulation outcomes, validating the effectiveness of the integrated form-finding and intelligent classification algorithms.

Moreover, our study shows that not only the Young's modulus, but also the shear resistance of the module is also worth considering. This is also an important factor in whether the modules can be built with large spans, which provides a direction for our subsequent research. The influence of diverse topological graphics on the stability of the shell structure (Wang et al., 2019) will be studied, and the potential for adding more environmental variables (such as block size and random force) to improve the generalization ability of the model will be discussed.

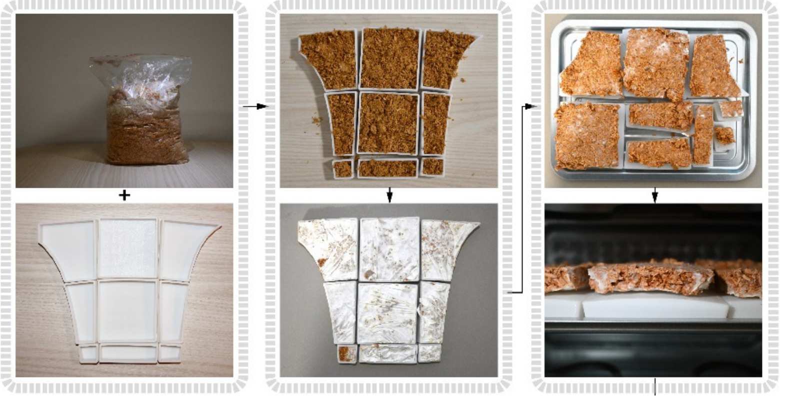

Figure 9. Modules fabrication

5. Conclusion

This study establishes an innovative methodology combining MBCs with computational design to address challenges in sustainable architectural design. By optimising formulations of beechwood particles, straw, and hessian fabric, the research explores the potential enhancements in MBC mechanical performance. The developed computational framework, integrating form-finding and intelligent classification algorithms, enables the rational distribution of MBC modules within shell structures, thereby reducing reliance on high mechanical performance and expanding their application potential.

The goal is to develop fully biodegradable construction materials from recyclable agricultural waste, thereby contributing to environmental impact reduction and promoting circular resource utilization in architecture. Moreover, the proposed methods significantly enhance the adaptability of MBCs, demonstrating the material's great potential to meet complex structural demands. This research envisions broader adoption of MBCs in diverse architectural contexts, driving progress in sustainable, scalable, and environmentally responsible design.

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