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Investigating A Design and Construction Approach for Fungal Architectures

Phil Ayres[1], Adrien Rigobello[1], Ji You-Wen[1], Claudia Colmo[1], Jack Young[1] and Karl-Johan Sørensen[1]

[1] Centre for Information Technology and Architecture (CITA), Royal Danish Academy, Copenhagen, Denmark
phil.ayres@kglakademi.dk
home page: https://kglakademi.dk/cita

Abstract. The design research presented in this paper grounds itself in a tradition of seeking new architectural form from the affordances and proclivities of new materials. We report on the developmental stages of a construction concept that involves the growing of mycelium-based composites within stay-in-place scaffolds produced using Kagome weaving techniques. We demonstrate how speculative design is used to generate hypotheses - testable design statements - for directing empirical investigation, and how results drive the progression of the design inquiry and its associated digital design tools. Our core contribution is to expose new design pathways that operate reciprocally between material, tectonic and spatial exploration. We argue that such reciprocity is a prerequisite for supporting the invention of new architectural forms, vocabularies and systems.

Keywords: biohybrid architecture, mycelium composites, kagome weaving, biofabrication, living architecture, living materials.

1 Introduction

Mycelium-based composites (MBC) are a relatively new class of biodegradable materials generally derived from the fungal colonisation of lignocellulosic substrates. Such substrates can be readily found as agricultural and land-management waste streams, making MBC an exemplary embodiment of circular economy principles [1]. They also exhibit many properties suited for application within building construction [2]. This makes them an attractive and necessary target for research, with disruptive potential against the backdrop of challenges facing the construction industry, particularly in relation to resource scarcity for the production of conventional materials.

Much of the research in this rapidly expanding arena is motivated by the worthy ambition of substantiating mycelium composites as viable replacements for materials with less positive environmental credentials due to, for example, reliance on non-renewable resources and/or having high embodied energy. Within an industry context, the aim of the replacement paradigm is to support incorporation into existing construction systems and practices. However, it can be argued that operating within a paradigm of 'replacement' risks constraint within an established repertoire of expectations and design thinking. It also risks missing other interesting properties exhibited by these materials - especially in their living state - such as regeneration, adaptation, decision making, reproduction and resource balancing.

The research reported on in this paper, grounds itself in a tradition of seeking new architectural form from the affordances and proclivities of new materials. We develop a construction concept that involves the growing of mycelium based composites within stay-in-place scaffolds produced using Kagome weaving techniques. The research operates across various scales of thinking and engagement, constructing bilateral relations of influence between material composition, architectural tectonics and spatial configuration. We demonstrate how speculative design generates hypotheses - testable design statements - for directing empirical investigation, and how results not only refine the design inquiry, but become instrumentalised within digital design tools. This reciprocal and iterative approach creates a rich design space for architectural investigation leading to novel outcomes and producing research results within material, tectonic and spatial spheres of design activity.

2 State of the Art

The most common approach to MBC product production is through moulding and assembly as discrete units [3, 4]. In general, once colonisation has reached satisfactory levels, units are denatured by heat-treatment thereby preserving functional properties. As an alternative, the denaturing process can be avoided, leaving units hydrated and biologically active so that the parts can fuse once assembled - assuming cultivation conditions are kept favourable [5]. Particularly within the architectural research community, the scope of production approaches has been enriched in recent years, to include monolithic production [6], 3d printing [7, 8] and hybrid production techniques involving fusing of discrete blocks and shaping of the living composite into geometric design targets using robotic wire-cutting [9]. In Figure 1 we present an overview matrix of projects within this field, as represented in the literature. In the research reported here, we develop architectural proposition that combines monolithic and unit based approaches, with extensions to the state-of-the-art in terms of a combined stay-in-place mould and reinforcement strategy for monolithic production. Standard protocols are followed for discrete unit production.

Prior to engagement with production methods, MBC material-level specification must be determined. This opens a vast and under-explored MBC design space between parameters of substrate composition and the wealth of widely distributed saprotrophic (dead wood decomposing) fungi that can be used for binding. Substrate structure can take the form of wood shavings, dusts, straws, shives, husks and even include proportions of non-organic constituents - all of which have been investigated in the literature and demonstrated to impact functional properties. Desired properties can therefore be targeted by curating aggregates for their geometry, size, nature and

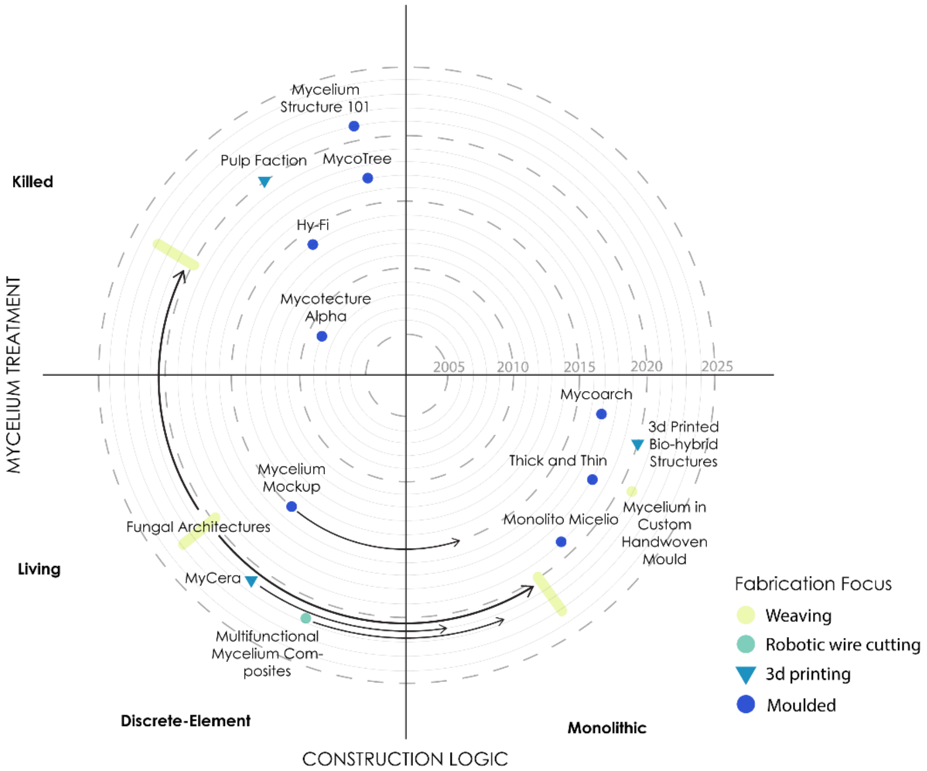

Fig. 1. A mapping of the state-of-the-art in architecturally focused projects employing MBC, reported in the literature.

distribution. As an extension of this mode of aggregate curation, in which the aggregate is generally homogeneous, we have previously demonstrated that the introduction of structuring natural fibres and organic textiles - that is, designing and curating a heterogeneous aggregate structure with bias towards orientated fibres - can have significant effect on compressive and flexural mechanical behaviour [10, 11]. A further dimension of MBC property tuning is by supplementing the chemical profile of the substrate to modify the mycelium expression [12].

The research described in this paper offers new ways of engaging with this material aspect of the state-of-the-art by seeking ways of instrumentalising material-level MBC specification as an integrated part of the architectural design workflow, thereby contributing to broader efforts at enhancing design engagement across scales [13].

3 Methods

The overarching aim of investigating how novel materials can inform the synthesis of new architectural form, and vice versa, necessitates a plurality of research approaches and methods that oscillate between the foundational, use-inspired and applied [14].

As such, we employ speculative design proposition as a method of hypothesis building by identifying specific testable statements/conditions from the design proposition. We then develop experimental setups for investigation and integrate results into subsequent iterations of design proposition. This can occur at the scale of material design through to full architectural proposition. Here, we report upon the use of this iterative research approach to investigate the development of a construction method that seeks to combine MBC with triaxial Kagome weaves. This novel combination is motivated by the fact that MBC production is generally predicated on the use of moulds to constrain the growth phase to a desired shape, and that Kagome weaves can approximate any shape describable by a manifold mesh whilst being producible with straight strips of material. Therefore, we hypothesise that the weave can act as a combined stay-in-place mould, reinforcement and nutritional supplement.

With regard to the Kagome weave, we have previously demonstrated the digital instrumentalisation of topological principles underlying Kagome patterns and their relation to the generation of local surface curvature [15, 16]. We extend this work with the development of a digital design workflow allowing the design and investigation of topologically principled weave patterns for arbitrary manifold geometries.

The base geometry is randomly generated to create many regions of stiffening double curvature. A secondary weave is introduced that acts as the MBC stay-in-place mould, reinforcement and supplement. This weave adopts a similar but higher resolution geometry and intersects the primary weave (Fig.2). The difference between these two weaves creates a rich a varied set of conditions interior and exterior conditions, clearly exhibited in the scaffold prototype shown in Figure.3. Within the digital design space, both geometries can be locally adapted in response to simulation feedback of the parameters under investigation until objectives are satisfied.

We present, compare and evaluate design iterations to demonstrate the process of design development through methods of hypothesis generating using speculative design, and targeted inquiries through empirical experimentation and physical prototyping.

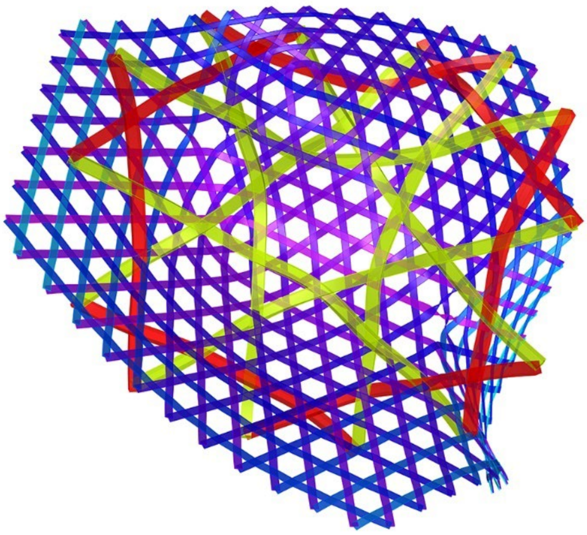

Fig. 2. Digital model of a weave fragment combining a structural Kagome grid-shell layer and a higher density Kagome layer to receive mycelium composite.

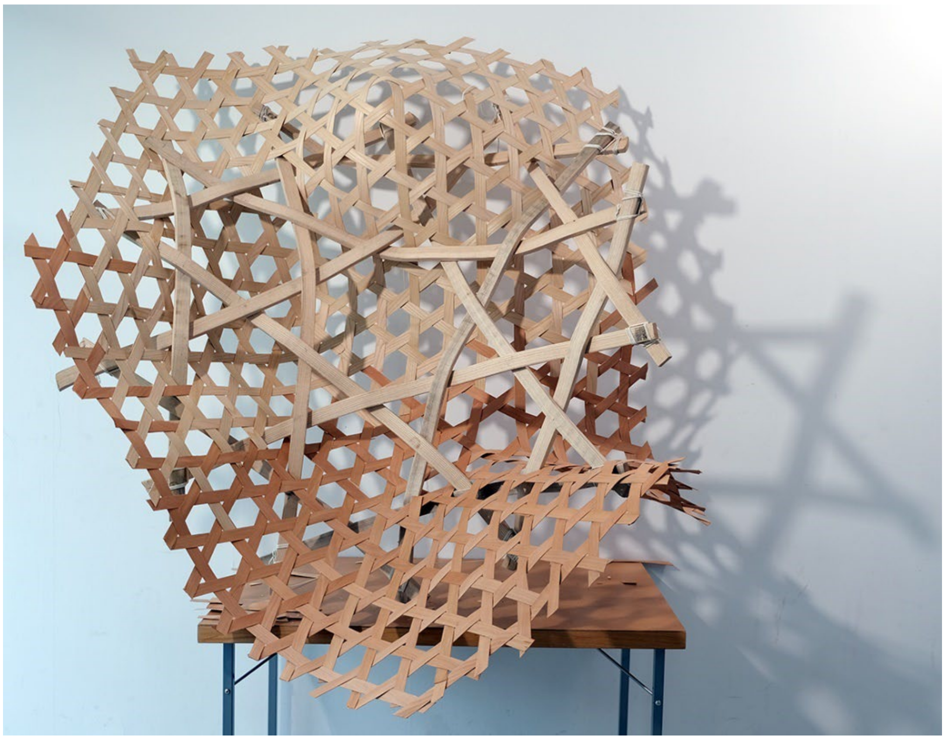

Fig. 3. Physical scaffold prototype of the digital model shown in Fig.2

4 Case studies and results

4.1 MBC composition studies

Based on a material engineering review of the enzymatic activity of ligninolytic fungi [12], we have identified three principal material design strategies for MBC systems: *densification* (by dense packing, cold or hot-pressing), *composition* (by introducing structuring elements, or modifying particles and/or fibre properties), and *supplementation* (targeting mycelium properties based on chemical tuning of the substrate). Of these three strategies, we have conducted an experimental series targeting composition, which remains the least investigated strategy in the MBC literature. Drawing upon insights from the field of synthetic composite design, in which fibre composition is a primary design vector for functional property tuning, we have reported on a substrate composition approach of orientated fibres in combination with different particle sizes and geometries for the bulk MBC volume.

Fig. 4. Compression series. (left) bulk volume substrate particle sizes. (right) four post-compression samples illustrating different mechanical properties resulting from different structuring approaches.

We have demonstrated the significance of introducing structuring fibres using approaches such as jacketing with hessian and reinforcement with reed or rattan fibres for both compressive and flexural behaviour (Fig.4). With an optimal substrate bulk material particle size of 0.75 – 3.0 mm, the introduction of common reed fibres coaxial to the load axis resulted in a 2.77-fold increase of the compressive modulus [10]. The flexural modulus of a longitudinally rattan-reinforced group of specimens was of 1.34 GPa for a density of 249.48 kg/m3 (control: 192.71 MPa, 232.24 kg/m3) [11]. It is anticipated that these preliminary results can be improved upon with hybrid material design strategies, for example, composition in combination with supplementation.

In an on-ongoing experimental series we are determining the effect of substrate composition on thermal performance. Three series of MBC panels representing different substrate densities and particle geometries are being evaluated according to ISO-9869 [17]. Early results indicate that the medium density substrate is the best performing. Thermal conductivity values, derived from the U-value experimental results, are in the range 0.0352 − 0.0516W/mK, which approaches the thermal conductivity of standard commercial mineral wool products (≈ 0.035W/mK). The experimental plan, protocols of preparation and production, results and evaluation will be the subject of a forthcoming paper.

The results of these investigations into the functional properties of MBC should be understood as validating courses of action for tuning performance, rather than results indicating optimal performance - that is to say, they can likely be improved upon but are satisfactory for sanctioning a period of informed design speculation through which we can cycle back into MBC material design with more refined performance demands.

4.2 Steps towards weave and MBC integration

Early probing experiments sought to establish plausibility for the construction concept of utilising Kagome weaves as a stay-in-place mould, reinforcement and feed-stock supplementation. A Y-branch component with branches ≈ 65mm diameter and comprising a rattan weave with a series of valence 7 singularities to achieve the morphology, was successfully cultivated. Here, our measures of success include consistency of fungal growth, incorporation of the Kagome scaffold by the mycelium and minimisation of contamination. The visual record provides evidence that these criteria were met (Fig.5(left)).

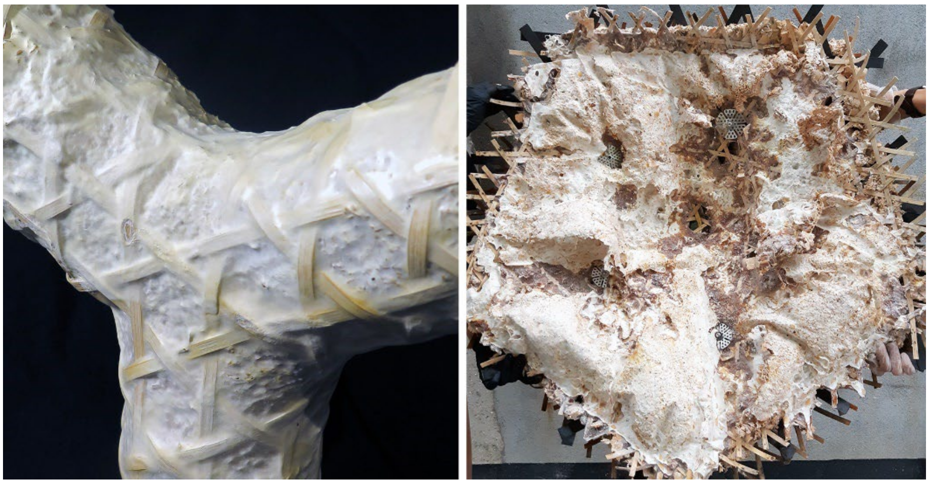

Fig. 5. Preliminary prototypes of Kagome weave and MBC integration. (left) A Y-branch component with good integration of the rattan weave within the mycelium skin. (right) A synclastic fragment of an enclosure surface composed as a sandwich of weaves - rattan on external faces and a structural carbon-fibre weave, internally bound. The MBC in this case is much less conforming, but spatially suggestive.

Building off this result, a subsequent probing experiment tackled a larger scale (≈ 1m diameter) assembly for a notional enclosure condition. This presented new functional demands and design challenges. For example, the self-weight of the MBC would be greater and new loading cases had to be considered. Where rattan weaving material had been sufficient for the Y-branch component, at this scale it would not provide adequate support. To resolve this, the design concept was modified to include a stiffening carbon fibre (CF) weave. This was developed as a sandwich construction with the CF weave enclosed in MBC and rattan weaves on external faces to contain it. Two prototypes were fabricated exhibiting synclastic and anticlastic curvature respectively. The results demonstrated the challenges of scaling up with poor consistency of colonisation and significant degrees of contamination. However, the lack on conformity, exhibited through both pocketing and excessive material build-up, suggested creative spatial and tectonic opportunities that could be investigated further (Fig.5(right)).

Articulating these newly found qualities commenced with an initial design hypothesis of two weaves interfering to create a heterogeneous set of spatial conditions whereby regions of the primary weave can be expressed internally, externally or contained. An arbitrary perlin-noise surface was generated to act as the target geometry of the primary structural weave. A secondary 'enclosure' weave geometry was generated with a higher frequency value. To achieve a level of geometric coherence between the weaves, a wave summation principle was employed to bring the secondary weave into alignment with the structural weave.

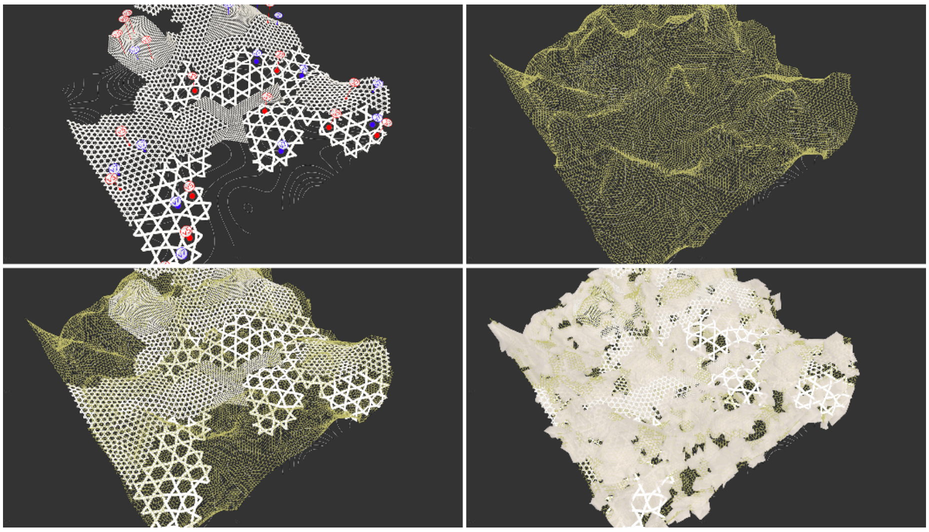

Fig. 6. The buildup of primary and secondary weaves, articulating the spatial qualities of the prototype shown in Fig.5(right). The frame, bottom-right, shows a 'maturing' stage design hypothesis with MBC colonising the weaves.

Fig. 7. The (left) A valence 5 (note the pentagon, lower center) beech weave using timber members of 40 x 20mm cross-section. (right) Detail of the interlacing density achieved with 60 x 30mm solid beech members. Note the plastic deformation of the members, achievable whilst they have a high moisture content.

Furthermore, using the loop subdivision methods on the mesh faces of the weave representation, we hypothesised that discrete changes in weave density for the structural weave could be achieved, embedding the possibility of altering weave density towards functional objectives in later design iterations (Fig.6). From this design hypothesis, an experimental plan was devised to empirically determine weave parameters (most importantly, minimum reciprocal triangle size) given solid beech and ash weavers of compressed timber with cross-section 40 x 20mm and 60 x 30mm respectively. The timber was provided in maximum lengths of 3m due to processing limits. The timber was firstly heat-steamed and then compressed, rendering the material significantly more pliable whilst it retains a high moisture content.

Two weaves were produced using the 40 x 20mm timber - a valence 5 (yielding a snyclastic surface, see Fig.7(left)) and a valence 7 (yielding an anti-clastic surface). A single valence 5 weave was produced using the 60 x 30mm timber (see detail, Fig.7(right)). All weaves were assembled without the use of, or subsequent need, for mechanical or chemical fixings. This exploits the inherent jamming properties of the reciprocal triangles in the Kagome pattern, and the plastic deformation of the timber into sinusodial geometry to realise material interlacing. An impromptu load-test was conducted without boundary restraints on the valence 5 weave composed of 60 x 30mm weavers. A load of ≈ 250kg was applied around the weave's singularity and comfortably accommodated.

It was found that the relationship between material cross-sectional dimension and reciprocal triangle dimension would not allow discrete changes in weave density - disproving our hypothesis. However, it was found that a continuous change of weave density could be supported. Based on measurements of the minimum achievable reciprocal triangle dimension across the material cross-sections utilised, equation (1) was determined from the geometric relations presented in Figure.8 and incorporated into the design workflow to refine our weave design approach. The minimum edge length of the reciprocal triangle for a given material cross-section is determined by:

$$\sqrt{2r^2 - (2r - T)^2} + \left(\tan A * \frac{w1}{2} + \frac{w2}{2\sin A}\right) + \left(\tan B * \frac{w1}{2} + \frac{w3}{2\sin B}\right) \tag{1}$$

This equation is incorporated into the digital tools to support the modelling of continuous changes in weaver density which can be associated to different model features and design objectives; two cases are shown with density changes driven either through distance to an attractor point (Fig.9, left), or mean curvature analysis (Fig.9, right).

With these refinements instrumentalised, a new design hypothesis was developed (Fig.10). In this case, a context was chosen to force the consideration of spatial conditions relative to context. Entrances, extended thresholds, internal courtyards, ground sculpting and spatial organisation were now explicitly considered. In addition, the parallel material understanding developed for MBC functional performance tuning, permits geometric conditions to be assessed and specified according to intended performance requirements as suggested in Figure.11.

Further iterations of MBC design in conjunction with spatial design developments will focus on additional refinements informed through specific structural, spatial, environmental and functional objectives.

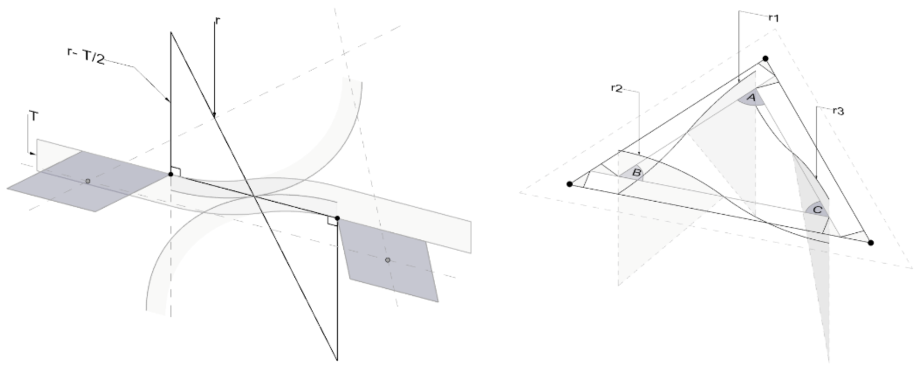

Fig. 8. Description of geometric relationships employed to construct an equation relating material cross-section dimensions to the minimum dimensions of a woven reciprocal triangle.

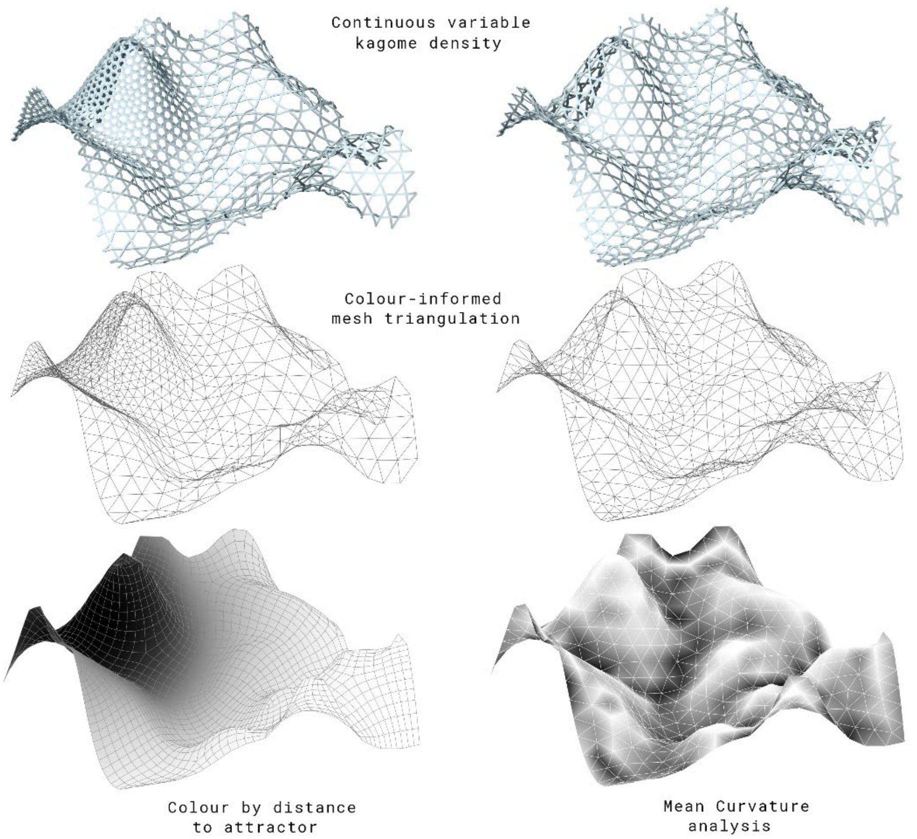

Fig. 9. Refined weave density approach for continuous change within a range parameterised by the material cross-section dimensions used. On the left, the weave density is informed by distance to an attractor point; on the right, the density is informed by mean curvature analysis of the design surface.

Fig. 10. A refined design hypothesis informed through empirical investigations, and the instrumentalisation of their findings within a digital design environment.

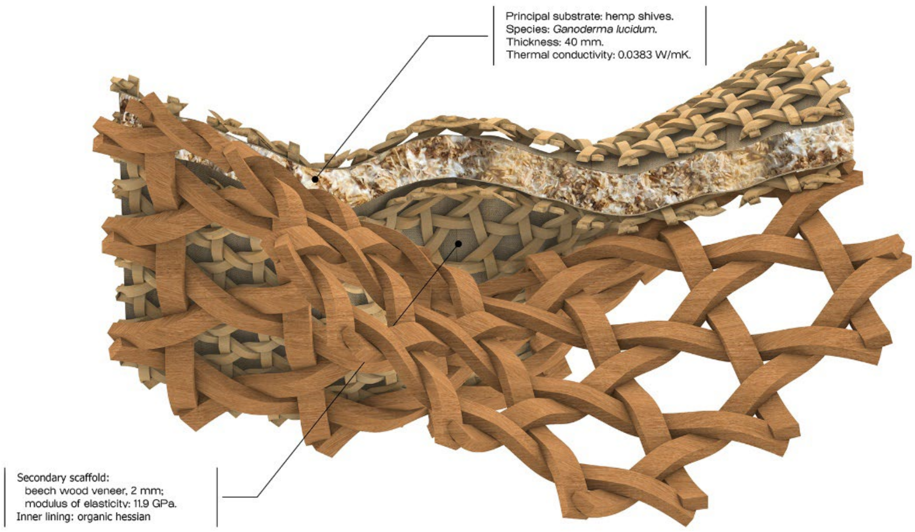

Fig. 11. Detail of the refined design hypothesis with material composition and functional performance specifications derived from design objectives. These specifications will drive further iterations of MBC material investigation.

5 Discussion

The field of MBC design research is currently flourishing, as evidenced by a burgeoning corpus of literature. The thriving community of researchers responsible for this are collectively enriching MBC practice and expanding the ’Ashby map’ of functional performance through design, engineering and cultivation strategies, productively enhancing the possible use-cases and application domains of these materials. However, where new materials offer a starting point for investigating new architectural expressions, this extended sphere of exploration remains under-explored. Where the linear design pattern of developing structural form from the proclivities of functional material performance has been productively investigated [4], the work presented here expands the design repertoire by exercising a parallel and reciprocal spatial and material inquiry. Having demonstrated that MBC functional properties can be designed and refined through, among other approaches, substrate structuring strategies, design intent can be used as a driver for designing material performance, offering enhanced and enriched modes of design engagement.

6 Conclusion

We have demonstrated the refinement of design intent through a combination of design-led hypothesis building and empirical testing that bilaterally couples material and spatial inquiry within the rapidly expanding field of MBC related to architecture. Within this work, an initial intention of developing structurally performing MBC bound by a stay-in-place Kagome weave has progressed to the contribution of a more nuanced system that integrates various MBC composition strategies with a load-bearing timber kagome gridshell. This system continues to be investigated empirically at increasing scale.

We have shown how this inquiry also results in the contribution of enhanced digital tooling, as empirical investigations provide both qualitative (weave density strategies moving from discrete to continuous) and quantitative (scaling of weave reciprocal triangles relative to material cross-section) insights that can be instrumentalised. This supports an expanded design inquiry in which speculation and development can drive material, tectonic and spatial investigation in productive, reciprocal ways. We argue that such reciprocity is a prerequisite for supporting the invention of new architectural forms, vocabularies and systems. This has been demonstrated here in the novel architectural vocabulary and construction system based on MBC in combination with Kagome weaving.

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References

1. Appels, Freek VW, Serena Camere, Maurizio Montalti, Elvin Karana, Kaspar MB Jansen, Jan Dijksterhuis, Pauline Krijgsheld, and Han AB Wösten. 2019. "Fabrication Factors Influencing Mechanical, Moisture-and Water-Related Properties of Mycelium-Based Composites." *Materials & Design* 161: 64–71.
2. Jones, Mitchell, Andreas Mautner, Stefano Luenco, Alexander Bismarck, and Sabu John. 2020. "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review." *Materials & Design* 187: 108397.
3. Nagy, Danil, John Locke, and David Benjamin. 2015. "Computational Brick Stacking for Constructing Free-Form Structures." In *Modelling Behaviour*, 203–12. Springer.
4. Heisel, Felix, Karsten Schlesier, Juney Lee, Matthias Rippmann, Nazanin Saeidi, Alireza Javadian, Dirk E Hebel, and Philippe Block. 2017. "Design of a Load-Bearing Mycelium Structure Through Informed Structural Engineering." In *World Congress on Sustainable Technologies (WCST-2017),(ss. 45-49)*.
5. Dahmen, Joseph. 2016. "Mushroom Furniture." University of British Columbia. https://doi.org/10.14288/1.0343116.
6. Dessi-Olive, Jonathan et al. 2019. "Monolithic Mycelium: Growing Vault Structures." In 8th International Conference on Non-Conventional Materials and Technologies Construction Materials and Technologies for Sustainability, Nairobi, Kenya.
7. Colmo, Claudia, and Phil Ayres. 2020. "3d Printed Bio-Hybrid Structures-Investigating the Architectural Potentials of Mycoremediation." In *Anthropologic, eCAADe Conference*, 573–82. CUMINCAD.
8. Goidea, Ana, Dimitrios Floudas, and David Andréen. 2020. "Pulp Faction: 3d Printed Material Assemblies Through Microbial Biotransformation." In *Fabricate 2020*, 42–49. UCL Press.
9. Elsacker, Elise, Asbjørn Søndergaard, Aurélie Van Wylick, Eveline Peeters, and Lars De Laet. 2021. "Growing Living and Multifunctional Mycelium Composites for Large-Scale Formwork Applications Using Robotic Abrasive Wire-Cutting." *Construction and Building Materials* 283: 122732.
10. Rigobello, Adrien, and Phil Ayres. 2022. "Compressive Behaviour of Anisotropic Mycelium-Based Composites." *Scientific Reports* 12 (1): 1–13.
11. Rigobello, Adrien, Claudia Colmo, and Phil Ayres. 2022. "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour." *Biomimetics* 7 (2): 53.
12. Rigobello, Adrien, and Phil Ayres. 2022. "Design Strategies for Mycelium-Based Composites." In *Fungi and Fungal Products in Human Welfare and Biotechnology*, edited by S. K. Satyanarayana T. Deshmukh, (in press). Springer Nature.
13. Faircloth, Billie, Ryan Welch, Martin Tamke, Paul Nicholas, Phil Ayres, Yulia Sinke, Brandon Cuffy, and Mette Ramsgaard Thomsen. 2018. "Multiscale Modeling Frameworks for Architecture: Designing the Unseen and Invisible with Phase Change Materials." *International Journal of Architectural Computing* 16 (2): 104–22.
14. Stokes, Donald E. 2011. Pasteur's Quadrant: Basic Science and Technological Innovation. Brookings Institution Press.
15. Ayres, Phil, Alison Grace Martin, and Mateusz Zwierzycki. 2018. "Beyond the Basket Case: A Principled Approach to the Modelling of Kagome Weave Patterns for the Fabrication of Interlaced Lattice Structures Using Straight Strips." In *Advances in Architectural Geometry 2018*, 72–93. Chalmers University of Technology.

16. Ayres, Phil, Ji You-Wen, Jack Young, and Alison Grace Martin. 2021. "Meshing with Kagome Singularities: Topology Adjustment for Representing Weaves with Double Curvature." In *Advances in Architectural Geometry*, 188–207. Ponts Chaussées.
17. Rasooli, Arash, and Laure Itard. 2018. "In-Situ Characterization of Walls' Thermal Resistance: An Extension to the ISO 9869 Standard Method." *Energy and Buildings* 179: 374–83.