

# Design of a load-bearing mycelium structure through informed structural engineering

The MycoTree at the 2017 Seoul Biennale of  
Architecture and Urbanism

Felix Heisel<sup>1</sup>, Karsten Schlesier<sup>1</sup>, Juney Lee<sup>2</sup>, Matthias Rippmann<sup>2</sup>, Nazanin Saeidi<sup>3</sup>, Alireza Javadian<sup>3</sup>,  
Adi Reza Nugroho<sup>4</sup>, Dirk Hebel<sup>1</sup>, and Philippe Block<sup>2</sup>

<sup>1</sup>Sustainable Construction, Faculty of Architecture, KIT Karlsruhe, Karlsruhe, Germany

<sup>2</sup>Block Research Group, Department of Architecture, ETH Zürich, Zurich, Switzerland

<sup>3</sup>Alternative Construction Materials, Future Cities Laboratory, Singapore-ETH Centre, Singapore

<sup>4</sup>Mycotech, PT Miko Bahtera Nusantara, Indonesia

**Abstract—** MycoTree is a spatial branching structure made out of load-bearing mycelium components. Its geometry was designed using 3D graphic statics, utilizing compression-only form to enable the weak material to perform structurally. Using only mycelium and bamboo, the structure represents a provocative vision of how one may move beyond the mining of our construction materials from the earth's crust to their cultivation and urban growth; how achieving stability through geometry rather than through material strength opens up possibilities to use weaker materials structurally and safely; and ultimately, how regenerative resources in combination with informed structural design have the potential to propose an alternative to established building materials for a more sustainable construction industry.

*mycelium; bamboo; alternative building materials; closed-loop; circular; prototypology; 3D graphic statics; compression-only*

## I. INTRODUCTION

As populations and urban aspirations grow, so does the demand for materials and resources to support them. Although such demands were once satisfied by local and regional hinterlands, they are becoming increasingly global in scale and reach. This phenomenon has generated material flows that are trans-continental in scope and has profound consequences for the sustainability, functioning, sense of ownership and identity of future cities. However, the focus of the global construction industry on only a few established building materials results in a high consumption of specific and limited natural resources [1]. In this respect, the built environment of the future city demands the utilization of new resources.

The 21st century will face a radical paradigm shift in how materials are produced for the construction of future habitats. The linear concept of “produce, use, and discard” has proven itself unsustainable in the face of scarce resources and exponentially growing urban populations [2]. Instead, to achieve a cycle of production, use, and re-use, we must explore

alternative materials and approaches to construction. Materials that were previously considered unwanted and low-strength may present possibilities to end this undesirable state of affairs.

MycoTree, the prototypological structure described in this paper, consists of organic building components made from agricultural waste, which are stabilized only by the grown matrix of mushroom mycelium. Its geometry was designed using 3D graphic statics, utilizing compression-only form to enable the weak material to perform structurally. The resulting expressive and provocative structure demonstrates that the combination of newly developed building materials – which can be effectively grown locally or even on-site – with informed structural design and engineering may bring about the changes that are desperately needed.

## II. ARCHITECTURAL INNOVATION THROUGH INFORMED STRUCTURAL DESIGN

The Professorship of Sustainable Construction at the Karlsruhe Institute of Technology (KIT), the Block Research Group (BRG) at the Swiss Federal Institute of Technology (ETH) Zürich and the Future Cities Laboratory (FCL) in Singapore are combining their expertise in construction, structures, geometry and materials to discover new design opportunities of cultivated materials and to challenge the status quo. While the teams at KIT and FCL investigate the cultivation of natural, regenerative materials and their applicability in the built environment [3], the BRG develops novel structural design techniques to explore compression-only, spatial structures. The advent of advanced computational tools, in conjunction with state-of-the-art research in cultivated materials, has the potential to significantly improve the relevance and applicability of humble, “low-strength” materials in designing of efficient and expressive structures.

### III. MYCELIUM-BOUND BUILDING COMPONENTS

*Mycelium* is the root network of fungi, a fast-growing matrix that can act as a natural binder. It consists of individual *hyphae* which grow from mycelium fungal strain spores and consume feedstock containing carbon and nitrogen. Digesting plant-based waste products, such as sawdust, mycelium's dense network binds the substrate into a structurally adequate material composite. The advantages of such materials are significant. As mycelium-bound building components are organic in matter, they can, following a metabolic cycle, simply be composted after their original use. The material can be grown locally, reducing both the energy and time required for transportation. Furthermore, mycelium-bound building components can act to reverse carbon emissions through the absorption of carbon.

Research activities at KIT and FCL focus on developing mycelium-bound building components using agricultural waste products as substrates. In this study, the mycelium strain *Ganoderma Lucidum*, commonly known as *Lingzi* mushroom was chosen for the development of the mycelium-bound elements. This particular strain grows quickly and sturdily in typical tropical climate. Material engineering and production of building elements for the MycoTree were conducted in collaboration with the company Mycotech in Indonesia. The recipe for the substrate was developed to maximize its structural strength and rigidity while minimizing the growth and production time.

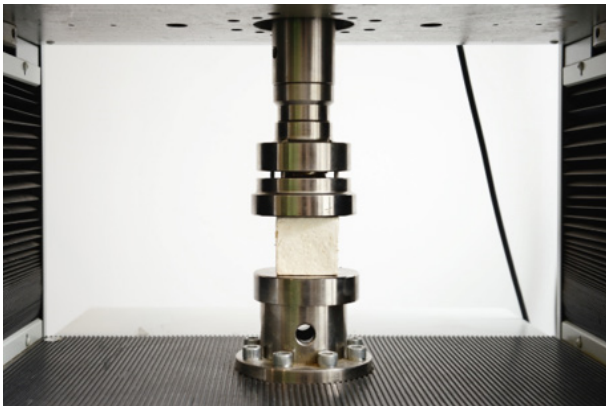


Figure 1. Mycelium specimen in compressive strength test.

Wood chips, sawdust and fibrous waste products from the regional food industry such as sugarcane and cassava root were used as substrates. Mycelium with various substrate recipes were grown under varying conditions, and were subjected to compressive tests (according to ASTM D3574) using a uniaxial testing machine. Mycelium-bound material grown on a mix of sugar cane and cassava root showed comparatively favorable performance and was chosen for the structural application. The material has a density of  $440 \text{ kg/m}^3$  with  $0.61 \text{ MPa}$  of compressive strength at 5% strain.

To ensure clean connections and even load transfers from one element to another in the final structure, the ends of each individual mycelium-bound components are capped with plates of bamboo composite material. These plates are also used for compacting the mycelium mixture into the mold, and are eventually secured to the mycelium-bound components with dowels.



Figure 2. Production: substrate collection and processing; bag logs with mycelium in first growth stage; preparation of second growth stage; final growth in mould.



Figure 3. Mycelium-bound building element of the MycoTree structure.

### IV. STRUCTURAL GEOMETRY FOR “LOW STRENGTH” MATERIALS

The development of engineered materials, such as concrete or steel, is largely focused on making these materials stronger, on increasing their allowable stress. Mycelium-bound materials offer significant ecological advantages over established engineered materials on the one hand but comparably low structural strength on the other. To build with materials that are weak in tension and bending and to overcome their structural limitations the use of good geometry is essential to guarantee equilibrium through contact only, i.e., through compression. Achieving stability through geometry rather than through material strength opens up the possibility of using weak materials.

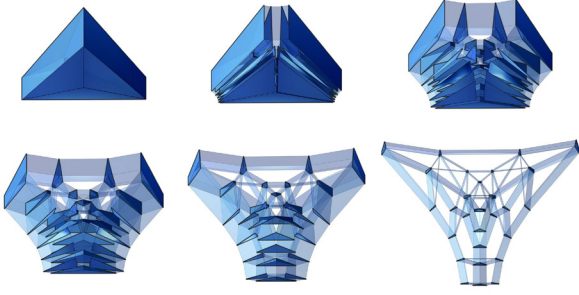


Figure 4. Exploration of structural geometry through manipulation and interactive visualisations of force polyhedra used in 3D graphic statics.

The geometry of the structure was designed using 3D graphic statics, a novel method developed by the Block Research Group at ETH Zürich that extends the traditional 2D structural design technique to fully spatial systems [4]. Using polyhedral form and force diagrams, it allows exploring and discovering efficient but expressive structural forms, going beyond the arch or vault in compression [5] [6], such as the compression-only branching geometry of MycoTree. While the mycelium portion of the structure is a metaphor for a load-bearing component of a building, the grid at the top of the structure represents a floor or a ceiling of a building that applies load to the mycelium structure.

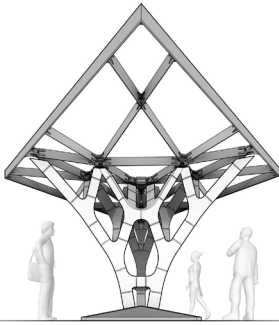


Figure 5. MycoTree is a spatial branching structure whose discrete elements are loaded in compression only.

The form-finding of the structural geometry was guided by several key constraints. First, in order to minimize the geometric complexity while maximizing fabricability, all nodes were limited to a valency of four, meaning there are no more than four mycelium elements coming together at any of the nodes. Second, the dihedral angles between any two mycelium members were constrained to be larger than 30 degrees. In addition, the center-to-center distances between any pair of nodes were constrained to be at least 40 cm such that smooth transitions could be made between any two directly adjacent nodes. Lastly, the maximum length of any linear mycelium member was limited to 60 cm in order to avoid potential buckling.

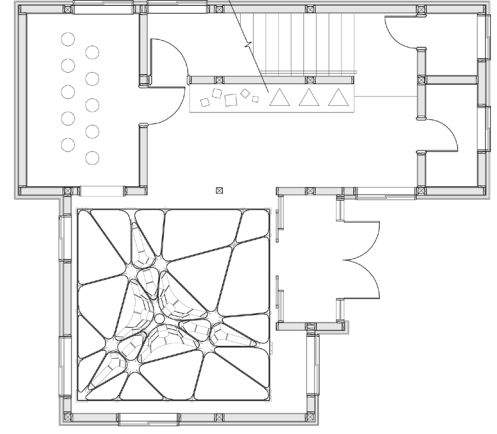


Figure 6. Plan view of MycoTree as part of the exhibition layout.

## V. FABRICATION PROCESS

One of the most rewarding benefits of using 3D graphic statics to design spatial structures, is that the geometry of the structure is polyhedral by construction. Without the need for additional optimization processes, the massing of the complex nodes of the structure can be developed through polyhedral transformations that only use planar and flat surfaces. As a result, the geometry of the molds for the nodes could be materialized using only developable surfaces, which can be laser cut from readily available and easy-to-recycle sheet materials. In order to reduce the number of mechanical connections and adhesives, teeth-and-slit joints are used for the walls of the mold for efficient assembly and clean expressions of the curved edges after demolding. Once the mold has been assembled, it can be filled with the mycelium mixture, which requires incremental compacting and additional filling as the mixture gradually densifies.

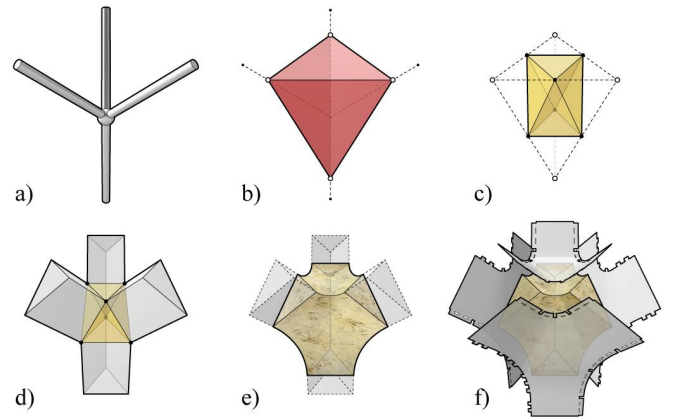


Figure 7. Development of the mould geometry: a) the orientation of linear members at a node; b) convex hull of points that are equidistant along each of the members from the center of the node; c) dual transformation of the convex hull; d) extrusion of the dual hull faces along the orientation of the corresponding members; e) filleting of the edges, and; f) the subsequent, developable surfaces of the node mould.



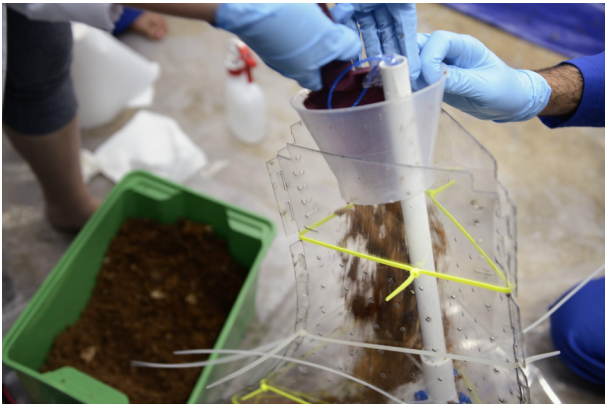


Figure 8. Digitally fabricated moulds are being filled with inoculated substrate for the 2nd stage growth process under compression.

While the mycelium components are designed to carry their self-weight plus the weight of the grid through compression, the grid itself is acting primarily in tension; it holds the branching linear elements at the top together and prevents them from falling over. For this reason the grid is constructed out of CNC-cut, eight mm thick bamboo composite boards, a material which has been developed and optimized throughout the past five years at FCL in order to withstand high tensile and bending forces [7]. For ease of assembly and for minimization of steel connections, all joints of the grid are designed with slit-and-slot connections that can be easily assembled on-site and secured using simple locking elements and wooden dowels.



Figure 9. Assembly of CNC-cut grid components through jointless, slit-and-slot connections and wooden dowels.

## VI. DATA AND FACTS

The structure supports a four by four meter bamboo grid at a height of three meter over ground. It consists of 36 linear members of maximum 60 cm length as well as 15 nodal elements of mycelium-bound material. The bamboo grid weighs 134 kg in total, the overall weight of mycelium-bound members amounts to 182 kg.

The structural triangular sections of the mycelium-bound members are sized for a limit stress value of 0.1 MPa. The self-weight of the structure was considered with a safety factor of 1.35 during design. The structure can withstand an accidental horizontal point load of 0.7 kN at a height of 1.27 m (arm height) from the ground at a single node. However, because the structure is designed to be primarily in compression-only, any type of horizontal loading should be avoided.

## VII. CONCLUSION AND OUTLOOK

MycoTree is the result of a collaboration between the Professorship of Sustainable Construction at Karlsruhe Institute of Technology (KIT) and the Block Research Group at the Swiss Federal Institute of Technology (ETH) Zürich. It is the centerpiece of the “Beyond Mining – Urban Growth” exhibition at the Seoul Biennale of Architecture and Urbanism 2017 in Seoul, Korea curated by Hyungmin Pai and Alejandro Zaera-Polo, and will be on display in Pavilion i7 at the Donuimun Museum Village from September 1st to November 5<sup>th</sup> 2017.



Figure 10. MycoTree is the centrepiece of the “Beyond Mining - Urban Growth” exhibition at the 2017 Seoul Biennale of Architecture and Urbanism in Korea.

The structure represents a provocative vision of how we may move beyond the mining of our construction materials from the earth's crust to their cultivation and urban growth; how achieving stability through geometry rather than through material strength opens up the possibility of using weaker materials structurally and safely; and, ultimately, how regenerative resources in combination with informed structural design have the potential to propose an alternative to established, structural materials for a more sustainable building industry.

## ACKNOWLEDGMENT

We would like to thank all team members who designed, produced and assembled MycoTree:

Sustainable Construction, KIT Karlsruhe: Karsten Schlesier, Felix Heisel, Dirk E. Hebel;

Block Research Group, ETH Zürich: Juney Lee, Matthias Rippmann, Tomás Méndez Echenagucia, Andrew Liew, Noelle Paulson, Tom Van Mele, Philippe Block;

Alternative Construction Materials, Future Cities Laboratory, Singapore-ETH Centre: Nazanin Saeidi, Alireza Javadian, Adi Reza Nugroho, Robbi Zidna Iman, Erlambang Adjidarma, Ronaldiaz Hartantyo, Hokie Christian, Orion Tan, Sheng Yu, Kelly Cooper.

We would further like to extend our thanks to production partner Mycotech, PT Miko Bahtera Nusantara, Indonesia.

## REFERENCES

- [1] Frondel, Manuel et al. (2007) : Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen: Endbericht. Forschungsprojekt Nr. 09/05 des Bundesministeriums für Wirtschaft und Technologie (BMWi), RWI Projektberichte
- [2] Hebel, Dirk E., Marta H. Wisniewska and Felix Heisel (eds.) (2014). *Building from Waste, Recovered Materials in Architecture and Construction*. Berlin: Birkhäuser.
- [3] Hebel, Dirk E. and Felix Heisel (2017). *Cultivated Building Materials: Industrialized Natural Resources for Architecture and Construction*. Berlin: Birkhäuser.
- [4] Akbarzadeh M., Van Mele T. and Block P., On the equilibrium of funicular polyhedral frames and convex polyhedral force diagrams. *Computer-Aided Design*, 2015a; 63; 118-128.
- [5] Akbarzadeh M., Van Mele T. and Block P., Three-dimensional compression form finding through subdivision. *Proceedings of the IASS Symposium 2015, Amsterdam, Netherlands, 2015b*.
- [6] Lee J., Van Mele T. and Block P., Form-finding explorations through geometric transformations and modifications of force polyhedrons. *Proceedings of the IASS Symposium 2016, Tokyo, Japan, 2016*.
- [7] Hebel, Dirk E., Alireza Javadian, Felix Heisel, Karsten Schlesier, Dragan Griebel and Mateusz Wielopolski (2014). 'Process-Controlled Optimization of the Tensile Strength of Bamboo Fiber Composites for Structural Applications', *Composites Part B: Engineering Journal*, Elsevier.