DISCRETE ELEMENT DESIGN FOR MYCELIUM COMPOSITE USE IN CIRCULAR ASSEMBLY SYSTEMS

Strategising Geometric Treatment of Biomass Composites for Viable Assembly and Construction Systems

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Abstract. This paper presents a construction strategy for topologically interlocking mycelium composites as replaceable structural modules that could be periodically replaced, extending the lifespan while varying the architecture. Concepts of discrete fabrication would drive the methodology. The research will be carried out in two scales; (a) at the scale of the 'part' such as foundation, column, beam, joint, and floor slab component, which would be studied to form a set of interlocking geometry that allow for easy installation and de-installation process; and (b) an investigation on aggregating 'whole', whereby elements are aggregated using Wasp to generate bays of walls, flooring and cantilever roof. The elements are to be aggregated to the point of redundancy, which would support replacement of components by providing standby structural system. This will integrate repair and recondition processes as part of the building life cycle.

Keywords. Mycelium Composite; Topological Interlocking; Redundancy; Digital Fabrication.

1. Introduction

With rising urgency to reduce construction and materials waste, the built industry has been working on achieving a circular, grounded in the pursuit of closed-loop manufacturing and design systems. Under this motivation, builders and designers are urged to employ Cradle-to-Cradle (M. Braungart & W. McDonough, 2002) concepts by extending the product's lifespan through reuse, repair, and reconditioning of its parts.

A more effective circular economy system occurs when the entire loop is localized and produced out of biocompatible materials. When the resources, manufacturing, and labor are localized, the system encourages the community and site to be self-sufficient, and the energy in transportation is conserved. Using biomaterials also ensures that the system is cleaned thoroughly compared to

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a circular production system comprised of synthetic materials. Biocomposite components could be constructed quickly in low energy, zero waste, fabrication process. A circular economy built out of agricultural resources could elevate the results and effectiveness of cradle-to-cradle design research.

With this motivation, the research would focus on using Mycelium as a biocompatible building resource. Mycelium composites have stood out as a type of organic material suitable for various building and structural uses. Existing projects (Figure 1) have shown mycelium composite capabilities as a substitute for synthetic building material. Such performance is made possible by optimizing its self-standing structural ability and strategically designing the parts‘ geometry. As mycelium composites are fibrous, the structural design tends to adopt compression-only formal strategies. By carefully manipulating forces' equilibrium through the geometry design, soft materials could perform structurally while also embodying aesthetic purpose.

Figure 1. (Left) Hy-Fi Tower by The Living + Ecovative Design and (Right).

Mycotree by KIT Karlsruhe + ETH Zürich + Singapore-ETH Centre are examples of built structure using load-bearing mycelium composites.

The logistic of repair and reconditioning in this economy could be made efficient by discretizing building elements. In Digital Manufacturing, Structures made of these discrete elements are reversible; they can be re-assembled and reconfigured into other types of structures. Using these elements enables the architecture to be treated in modular parts and at the human scale. Repair and reconditioning can be done without compromising the whole structure by isolating components to assemble. The formal exploration carried out in this research would be driven towards appropriating discrete elements for disassembly and reassembly processes.

2. Evaluating Material Characteristic and the Appropriate Design and Structural Methodology

Mycelium is the root structure of mushrooms, known as hyphae, which feeds on plant-based waste to flourish. It digests the nutritious waste and grows into a network of fibres that bind the mixture compact. Through processes such as inoculation and fermentation, mycelium composite could form a durable, leather-like material that is resistant to fire, water, and harsh climate (Jones, et al. 2018).

With these capabilities, mycelium has been widely studied and used in product design. As technology develops across the years, mycelium's application has expanded from small-scale use in packaging or product design to large scale architectural implementation.

As mycelium composite possesses a relatively softer and more fibrous composition than most building materials, it requires a different attitude towards its geometric strategy to ensure structural integrity and logistic efficiency. The performance of mycelium composite, as an organic material, could be optimized with an appropriate design strategy.

2.1. INTERLOCKING GEOMETRIC DESIGN METHODOLOGY

Literature reviews done as a precedent study to this research have shown that mycelium composite holds the density of 0.1-0.4 g/cm3 varying from non-pressed, cold-pressed to heat-pressed process. Such numerical characteristic sets the material comparable in density with softwoods and forms. Wood composite has a density of about 0.5-1 g/cm3, and foams usually come in a density of 0.05-0.3g/cm3. Similarly, the bending strength, stiffness, and brittleness of Mycelium could also be comparable to that of foams, the former ranging between 0.04- 0.24 MPa in tensile strength. (Appels, et al. 2019)

Building with organic material that is considerably delicate in tension and bending requires an emphasis on achieving equilibrium through contact forces and compression only. Appropriating the geometry is essential to guarantee good transfer of loads through surfaces.

An interlocking assembly principle is adapted to develop mycelium composite geometry with lock-key ends. This design principle will ensure replaceability while also possessing structural integrity. Interlocking assemblies are capable of remaining firmly in-tact and withstand destabilizing forces (Tessman, 2012). The discrete components are force-locked onto each other's contact surface and would be kinematically compressed in place. With this system, parts of the building can be disassembled by sliding it out of its surrounding locking geometry when a replacement is required.

2.2. REDUNDANT STRUCTURAL METHODOLOGY TO ENSURE CONSISTENT STABILITY

While structural stability could be achieved through geometric optimization, it should also be considered that mycelium composite's relative brittleness would require frequent replacement. In a discrete element system, assembly and disassembly could be done in isolated sections. Carrying these out would need the rest of the structure to remain intact while repair and replacements are being carried out. Hence, it is necessary to set up a structural composition that allows redistribution of load transfers when parts of the structure are assembled and disassembled, ensuring stability during parts replacement. This can be done by having the components cluster to the point of redundancy.

The concept of redundant part refers to the idea that if the said part is detached from the structure, it will not compromise the stability of the system. The existence of the part within the structure does not directly impact the structural performance, hence rendering it ‘redundant.’ Such a point of redundancy can only be attained after achieving a certain amount of optimal density, thickness, or contact force within the structure.

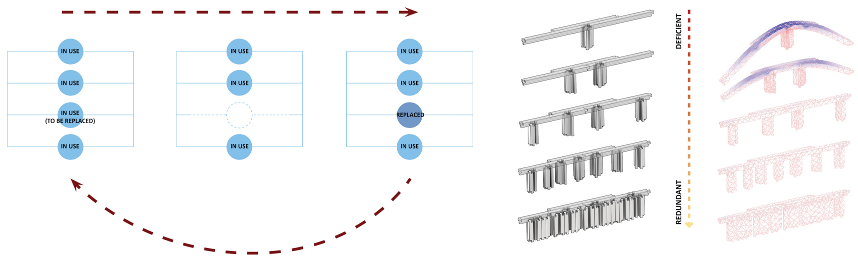


Figure 2. (Left) A system diagram that mimics a parallel circuit system, whereby the displacement of one part would not disconnect the flow of electricity flowing through the circuit and would merely make the other components perform at a higher voltage. (Right) Redundancy in structure can be represented in quantity or density.

3. Design Strategy for Disassembly and Replaceability

The ensuing geometric strategy from concepts explained above would consider the logistics of disassembly and assembly processes. Firstly, building components with an interlocking assembly system would be discretized to a human scale. Parts would possess contact forces that allow discrete elements to be kinetically interlocked without permanently binding them together. This way, the repair and replacement process could be made convenient and done in isolated sections. Secondly, the parts would be aggregated to achieve redundancy to have parts acting as standby components in the structure. By incorporating redundant elements, expected removal of parts could go on as loads are shifted onto standby parts, and the structure would remain stable.

This research would be carried out within the conventional context of building construction. A column-beam system is used due to its high flexibility, as the system is comprised of vertical and horizontal components of a building structure.

Parts would be digitally aggregated with the Grasshopper tool Wasp, which simulates the process of assembly based on contact surfaces (A. Rossi & O. Tessmann, 2019). The Grasshopper plug-in Wasp is a tool that enables designing with discrete components based on a set of rules and defined quantity of parts. It takes the information of the geometry and generates quick iterations of self-assembly using surface planes as connections. Discrete elements can be aggregated stochastically or field-driven, which direct the aggregation to be within a curve path, a region, or a volume. The tool also functions to simulate decision making on aggregating infills of walls or structures. Utilizing Wasp to create simulations helps ensure adequate and extensive aggregation results possible from designed module parts.

3.1. ASSEMBLY PROCESS BASED ON RATE OF CHANGE

The process of architectural construction is done such that the most structurally integral components are built first. The skeletal frames of the building function as the main path of loads through the building. Beyond that, elements such as plastered walls, surface tiles or veneers, window frames, and partition walls are secondary to its structure. Such parts are hence expected to hold a shorter life expectancy than that of the structure.

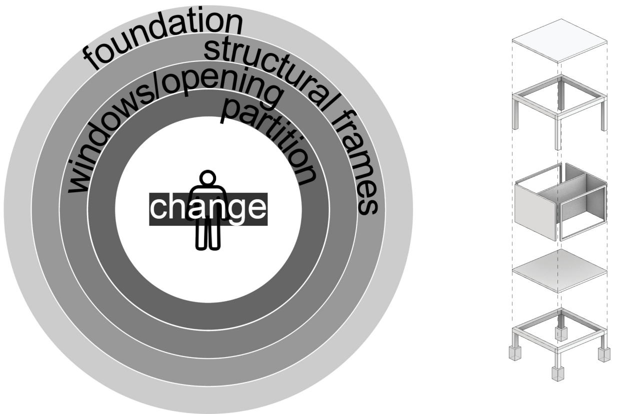


Figure 3. Sections of a building discretised according to its susceptibility to change.

According to its expected rate of change, the relationship between sections varies depending on other neighboring parts. If a part is expected to be more prone to change, its logistics for disassembly would be more straightforward. Such part might be independent of other neighboring elements in the aspect of structural performance, and its detachment would not affect the rest of the structure. The opposite could be said for parts that could be more long-lasting. These parts would probably be interlocked between neighboring parts, requiring more disassembly steps and dependent on others for structural stability.

The foundation laid out on-site would be built to form the field boundary in which spaces could create using the other parts. The foundation parts directly connect to the ground and require a more synthetic material that would be resistant to change or decay caused by natural factors.

The most transient layer in the architecture would be parts that define the program and spatial division of the spaces, both of which would be expected to change according to the user's need and future damages. In most architecture, the walls are most directly exposed to environmental factors when acting as façade or partition. In the proposed construction system, the loadbearing, insulating walls are made of aggregated discrete pieces, while partition walls are made of simple detachable boards. These parts would be made of mycelium composites.

The beams and slabs are layers directly dependent on the load-bearing vertical components and act as roof or floor components. Although it is also equally exposed to environmental factors, these parts would not be as prone to changes as the columns or partition. They do not necessarily change according to the space program. As they remain used within the architecture, they would merely shift around following the walls. The horizontal components would be made out of timber parts, which would require higher energy emission and longer time for fabrication, although it is more long-lasting.

3.2. INTERLOCKING JOINT OF PARTS

Woodworking joints were used as applied case studies of kinetically force-locked surfaces. 'Bridle' joint, 'Tongue and Groove' joint, and 'Lap' joint are traditional joint systems commonly used to overlap planar surfaces into an interlock. These joints could be assembled and disassembled from both lateral and vertical directions, hence imposing flexibility in the user interface during the construction process.

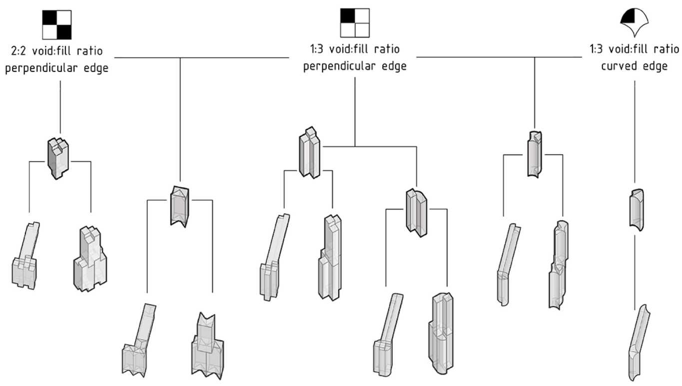


Figure 4. Exploration of tesselating and interlocking geometry, through evaluation of vertical to horizontal joinery.

Planar surfaces tend to be more versatile in creating connection planes. It possesses a more straightforward set of point data, such as straight edges, connecting points on 2-dimensional planes, and is asymmetrical in most aspects. Furthermore, working with platonic volumes give more possibilities in multi-plane aggregation.

3.2.1. DESIGN OF WALL PARTS

Loadbearing wall parts, which are expected to experience more wear and tear, are discretized into an L-base column in which the edges are either identical or exactly twice the length of the other. This relationship allows the surfaces to always overlap onto each other, edge to edge, or edge to center. With the 'L' shape as its base, the columns could be rotated and still suitable as a locking piece. The geometry offers extensive locking combinations, which would always result in exterior surfaces where an extension is possible.

The partition is discretized into panels with connecting arms on the sides, made up of male-female connections. This connection allows aggregation on a singular partitioning plane that creates a division between the load-bearing walls of column parts. It could be connected to the load-bearing walls using frames that fit in between the column parts.

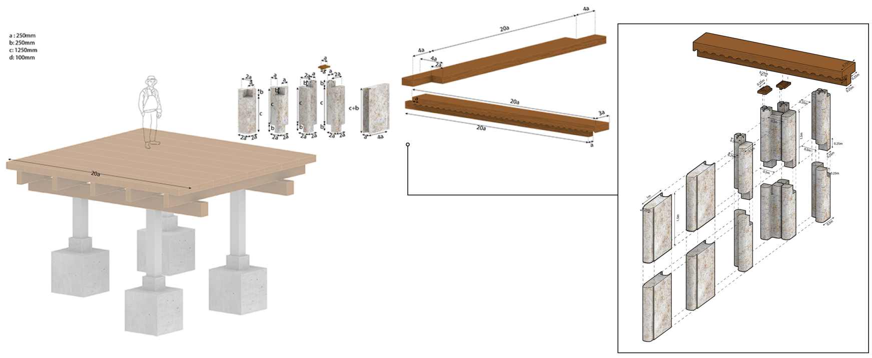


Figure 5. Parts dimensions are in increments of each other to ensure continuity at joints and are designed to be proportionate to the ground connection and human scale.

Its size was set to mimic the standard building column, usually built to be 0.75-1m thick and 3m-6m tall. It is assumed that there would at least be two 'L' shaped column stacked together at any location to form a locking part. For two beams to achieve 0.75-1m thickness, one beam should be 0.5m thick while considering overlapping. To maintain human scale in the production and construction process, the column and partition panels are discretized to components of the height of 1.5m. As mycelium composites are fibrous, there's a risk of degradation by scraping on the edges. To avoid this, the geometry is chamfered and smoothed out at its long edges.

3.2.2. DESIGN OF FLOOR AND ROOF COMPONENTS

While the columns create vertical pieces that aggregate into wall systems, the beams and slabs become horizontal part that make up the flooring/roof systems.

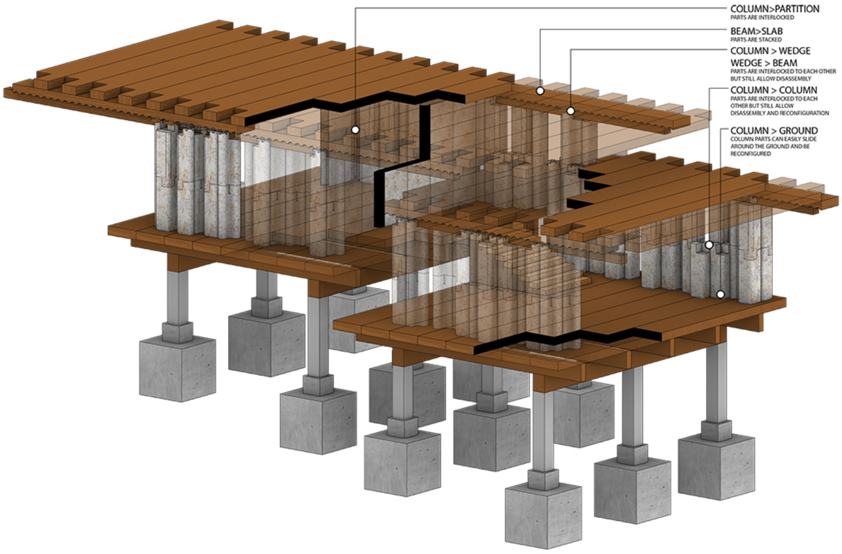


Figure 6. Configuration of parts.

The beam is a construction part supported by multiple columns at once, acting as a connecting horizontal piece to the vertical columns. Its design has to complement the top of the columns and make it so that three column pieces are required to support the beam minimally. The column pieces create valleys above it, which is complementary to the T-shaped cross-section of the beam. Columns are interlocked onto the beam from the sides and underneath while also linking onto other neighboring columns. Being in contact with the beam on its bottom surface ensures stable support against any main load-bearing forces onto the columns.

Similarly, the floor slab piece is designed to overlap onto the top surface of multiple beams at once. Instead of having large parts, the slab is further discretized into plank-like pieces. These planks are then oriented perpendicular to the length of the beam.

The horizontal parts are designed with assembly and disassembly in mind, which prompts a need for an additional joinery part that acts as a wedge that could lock the pieces in place during assembly and let the pieces be looser and quickly pulled out during disassembly. This geometry is designed to eat into the beam and column parts, interlocking onto both. It also fits onto the beams' ridges so as not to cause any sliding motion on the column parts.

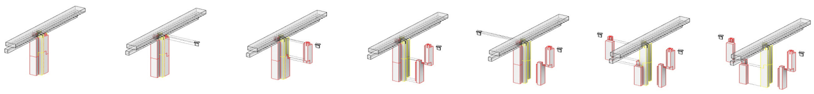
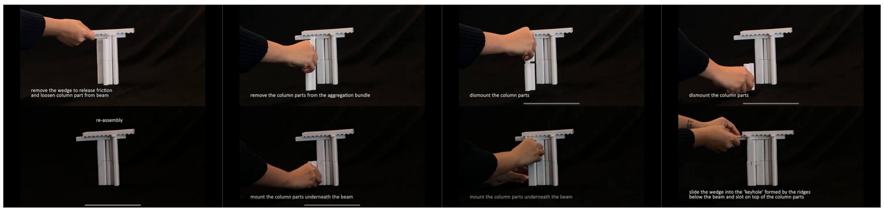


Figure 7. Assembly process of vertical to horizontal component.

ASSEMBLY/DISASSEMBLY



VERTICAL EXTENSION

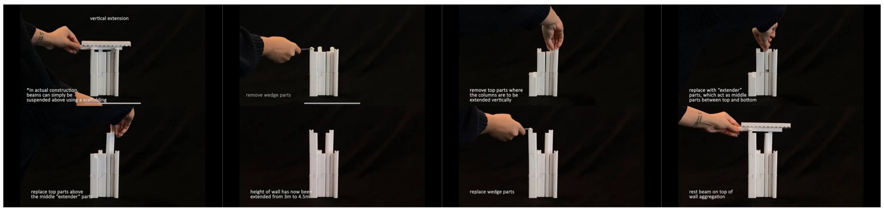


Figure 8. Assembly, Disassembly and Extension construction process.

4. Aggregation Simulation and Assembly Possibilities

As the design and connection of discrete elements are defined, they become factors that would determine possible variation in randomly aggregated massing. Different connectivity rules would offer local decisions within a field boundary, which could obtain coherent and functional configuration. In the case of the project, the potential formation would be in increments of the component dimensions.

Within the horizontal plane, spaces could be formed with depths of 4m, 8m, and their respective multiplications. This is because the beam and slabs span 8m and 12m in length. In vertical planes, the spaces' height would be multiples of 1.5m following the height of the column and partition wall parts. Hence, the room heights would be 3m, 4.5m, 6m, and 7.5m.

Space-making using the kit of parts designed in this research allow flexible iterations. The variations are only limited with a set of dimension rules that keep the parts usable, replaceable or reconfigurable on the human scale.

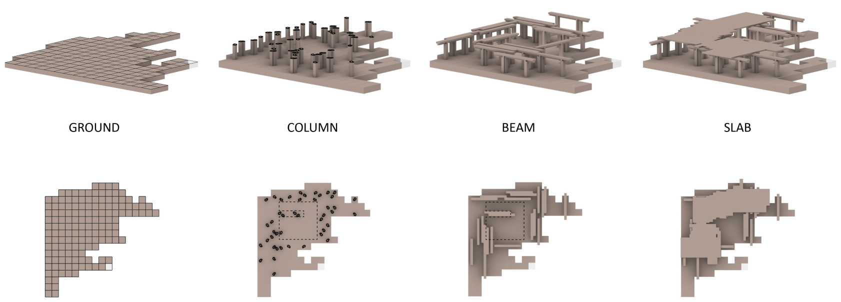


Figure 9. Space making, presented in layers.

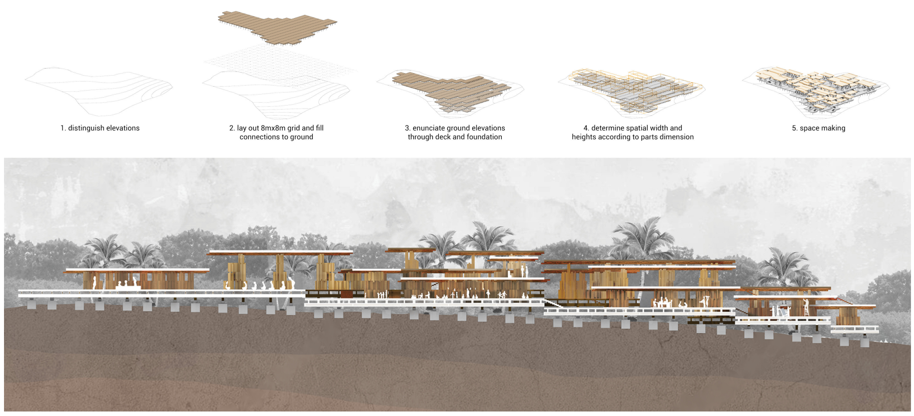


Figure 10. Implementation of modules on site allow for spaces of varying heights and widths.

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