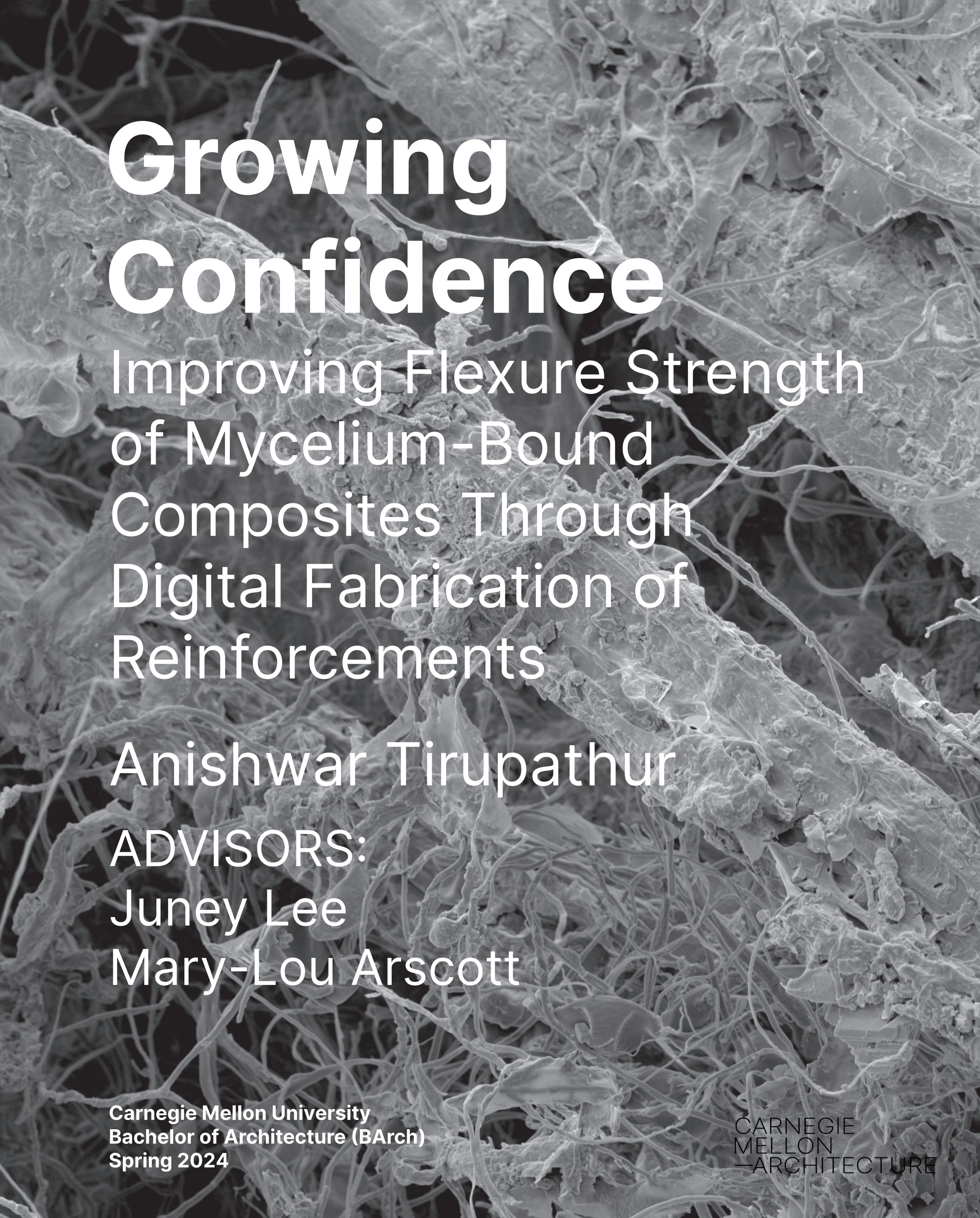

Growing Confidence

Improving Flexure Strength of Mycelium-Bound Composites Through Digital Fabrication of Reinforcements

Anishwar Tirupathur

ADVISORS:
Juney Lee
Mary-Lou Arscott

Carnegie Mellon University
Bachelor of Architecture (BArch)
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Acknowledgements

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The Frank-Ratchye STUDIO for Creative Inquiry

Abstract

The application of mycelium-bound composites as load-bearing elements within architecture offers opportunities to develop more sustainable ways of building. These organic materials are capable of consuming agricultural waste and are biodegradable, making mycelium an exemplar of a cradle-to-cradle material cycle. However, the use of these composites is limited by their relative weakness and lack of consistency in production. In its current state, these materials are largely limited to the creation of compression-only structures.

In order to reliably increase the flexure strength of mycelium-bound composites, this thesis proposes to use 3D-printed Polylactic Acid (PLA) filament to produce reinforcements that will help compensate for the material's weakness in tension. Finite Element Analysis (FEA) was used to help design the layout of reinforcements for the test samples. The strength of these samples was then evaluated through compression and three-point flexure testing. Additionally, scanning electron microscopy (SEM) was used to help evaluate the bond between the mycelium and the PLA.

Based on the results of the experiments conducted, new speculative architectural applications are presented and discussed and areas of further research are identified.

Keywords: mycelium-bound composites, substrates, PLA, 3D-printing, compression strength, Finite Element Analysis (FEA), flexure strength, architectural structures, cradle-to-cradle, sustainability

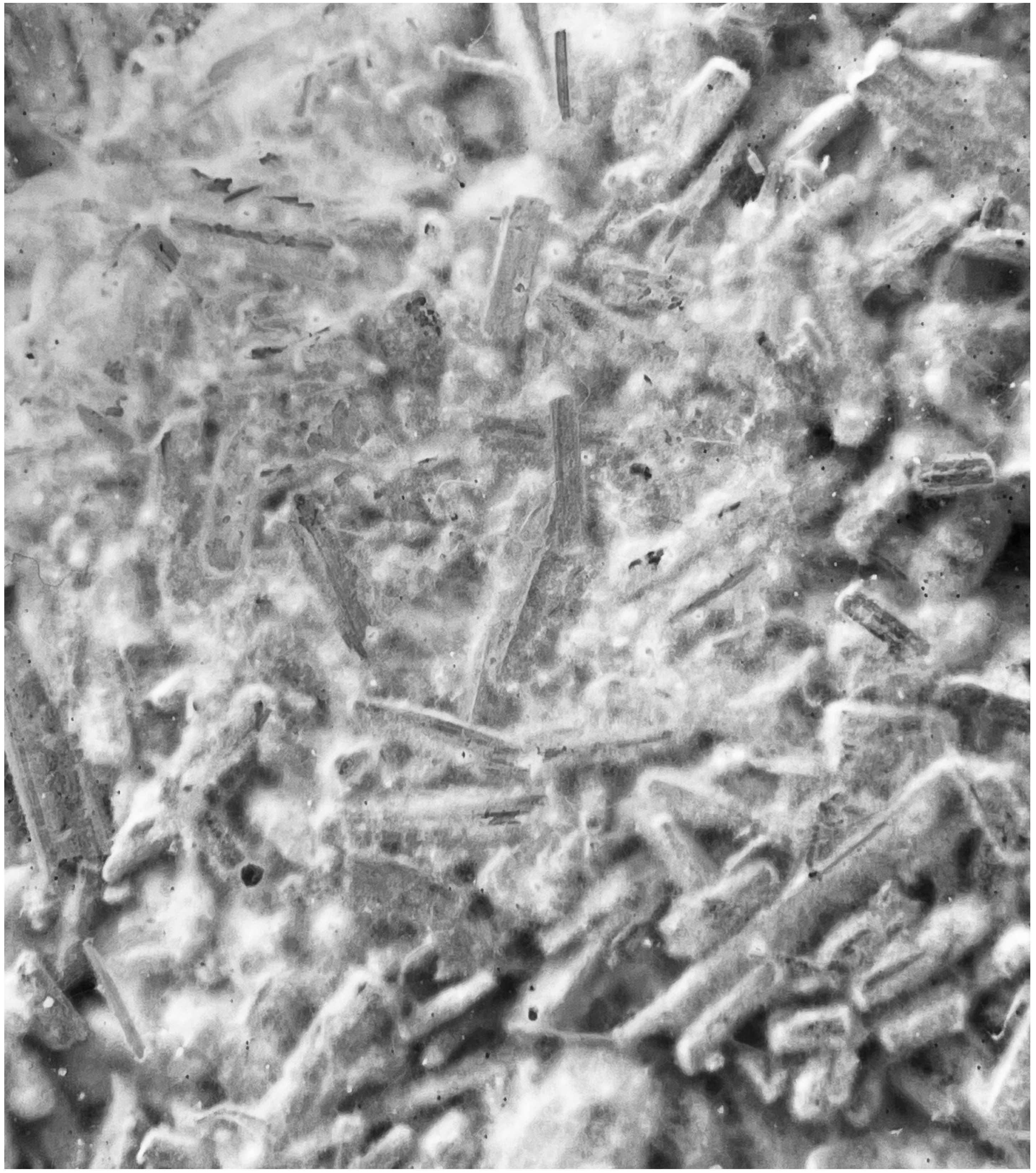


FIGURE 1: Mycelium growing on hemp substrate

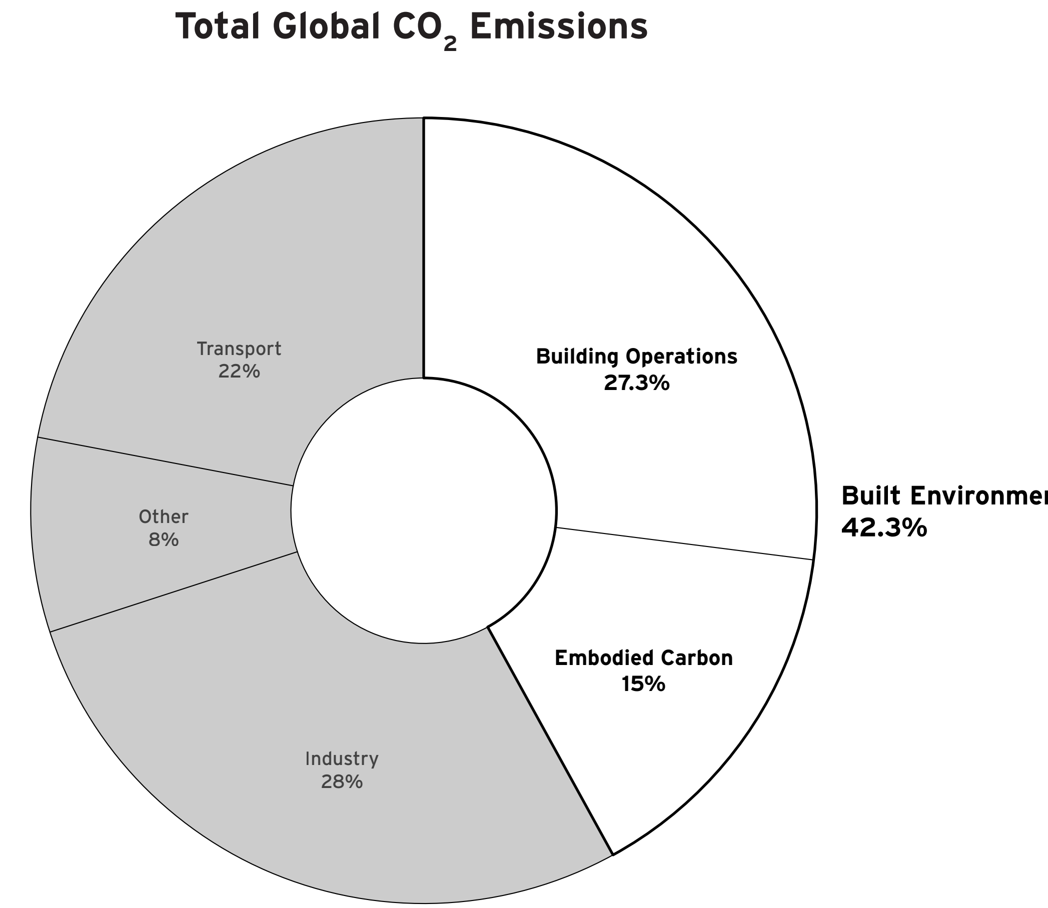
Introduction

Structures and Embodied Carbon

As the threats of climate change loom ever closer, the discipline of architecture is forced to grapple with its role in designing the built environment, one of the largest contributors to carbon emissions globally. About 42% of global carbon emissions are attributed to the built environment.[1] A significant portion of these CO_2 emissions are sourced from the embodied carbon connected with the structural mass of buildings due to the creation of "cement, iron, steel, and aluminum."[2] The heavy usage of these materials makes structures of the built environment one of the biggest contributors to climate change. The continued use of cement, iron, steel, aluminum, and other materials with high amounts of embodied carbon, implicates architecture heavily as part of the impending climate crisis, and it puts a significant onus on the discipline to develop new strategies and alternatives to existing practices of design and construction in order to address its relationship with global environments and ecosystems.

Shift towards Biomaterials

In large part due to the growing call for sustainable and environmentally friendly construction within the built environment, there has been a push within both academia and industry to explore structures made out of biological materials. Most notably, mass timber has arisen as a more sustainable structural alternative to the aforementioned high-embodied carbon materials in recent years. Mass timber is a sequester of carbon, has lower greenhouse gas emissions, and is a consumer of "15% less energy compared to concrete over the life cycle of a building."[3] However, there are shortcomings with mass timber, most notably the use of toxic adhesives (like phenol-resorcinol formaldehyde, emulsion polymer isocyanate, and melamine formaldehyde) in the creation of cross-laminated timber (CLT) and glue-laminated timber.[4] The use of these adhesives in particular mitigates sustainability of mass timber because it reduces recyclability, biodegradability, and reusability of the wood. As such, this growing push towards the use of biologically sourced materials for structural applications is a step in the right direction; however, for them to truly be effective and actionable, biological materials should have a low impact on the ecosystem; utilize environmentally-friendly methods of construction and production; be low cost; and be fully recyclable or biodegradable.



Mycelium-Bound Composites

Bearing these steps and concerns in mind, in the attempt to discover new and better biological materials for structural and building applications, the exploration of mycelium as a material for use within structures has captured the attention of researchers in architecture and engineering in recent years. Mycelium is raw, natural, and widely abundant. In the wild, it often grows discretely underground, only revealing itself through the fruiting bodies that belie the vast organic network that exists beneath the soil. It breaks down organic waste and reintroduces nutrients into the ecosystem, allowing new life to emerge and develop.

This ability to break down organic waste of mycelium and fungal systems is a large part of what makes them so intriguing within architecture material research. Mycelium-bound composite materials are particularly attractive to

1. "Why The Built Environment – Architecture 2030." n.d. Accessed April 7, 2024. https://www.architecture2030.org/why-the-built-environment/.

2. Refer to 1.

FIGURE 2: Pie Chart showcasing the CO_2 emissions and embodied carbon associated with the built environment annually. Statistics sourced from Architecture 2030

those seeking more sustainable ways of building because of their organic nature and ability to process agricultural waste materials. The hyphae, the "dense network of micro-filaments" that make mycelium "have the capacity to bind food, agricultural and industrial waste that have very little or no commercial value and convert them into higher-value composite materials with a wide range of potential applications."[5] These composites bring value to waste materials because they are taking something that was discarded, that most likely required labor and natural resources to create, and giving it use and worth as a viable and desirable building material.

These capabilities offer architects and engineers opportunities to design with a material that embodies the principles of cradle-to-cradle design. Cradle-to-cradle is a system of design that is predicated on the creation of "cyclical material flows" that "like the earth's nutrient cycles, eliminate the concept of waste."[6] Mycelium-bound composites are a biological material, and accordingly, develop in line with biological cycles. As a building material, mycelium composites can grow around organic waste from natural and agricultural processes, perform as a structural material, and biodegrade at the end of the building's lifespan. This biological lifecycle allows buildings to use mycelium composites as a structural material to avoid the embodied carbon associated with the creation of steel and cement and reduce the waste generated by buildings at the ends of their lifespans.

Beyond its benefits in reducing the embodied carbon within the built environment, fungi grow around the world and can develop on a wide variety of organic substrates. In their study "Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates," Elsacker, et al. compare the results of using wood, straw, hemp, and flax, concluding that while the type of organic fiber used to grow mycelium has some effect on its compressive strength, "the fibre condition (loose, chopped, tow, pre-compressed)" of the substrate is much more significant. This research into substrates demonstrates the robust variety of substrates that mycelium can grow on while emphasizing the importance of their preparation.[7] This opens the possibility for creating these biocomposites to leverage agricultural and other organic wastes to create a sustainable and accessible structural material.

3. Ahmed, Shafayet, and Ingrid Arocho. 2020. "Mass Timber Building Material in the U.S. Construction Industry: Determining the Existing Awareness Level, Construction-Related Challenges, and Recommendations to Increase Its Current Acceptance Level." Cleaner Engineering and Technology 1 (December): 100007. https://doi.org/10.1016/j.clet.2020.100007.

4. "Mass Timber Adhesives." University of Toronto. Accessed April 30, 2024. https://academic.daniels.utoronto.ca/

5. Bitting, S., et al.(2022). Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. Biomimetics, 7(2), 44. https://doi.org/10.3390/

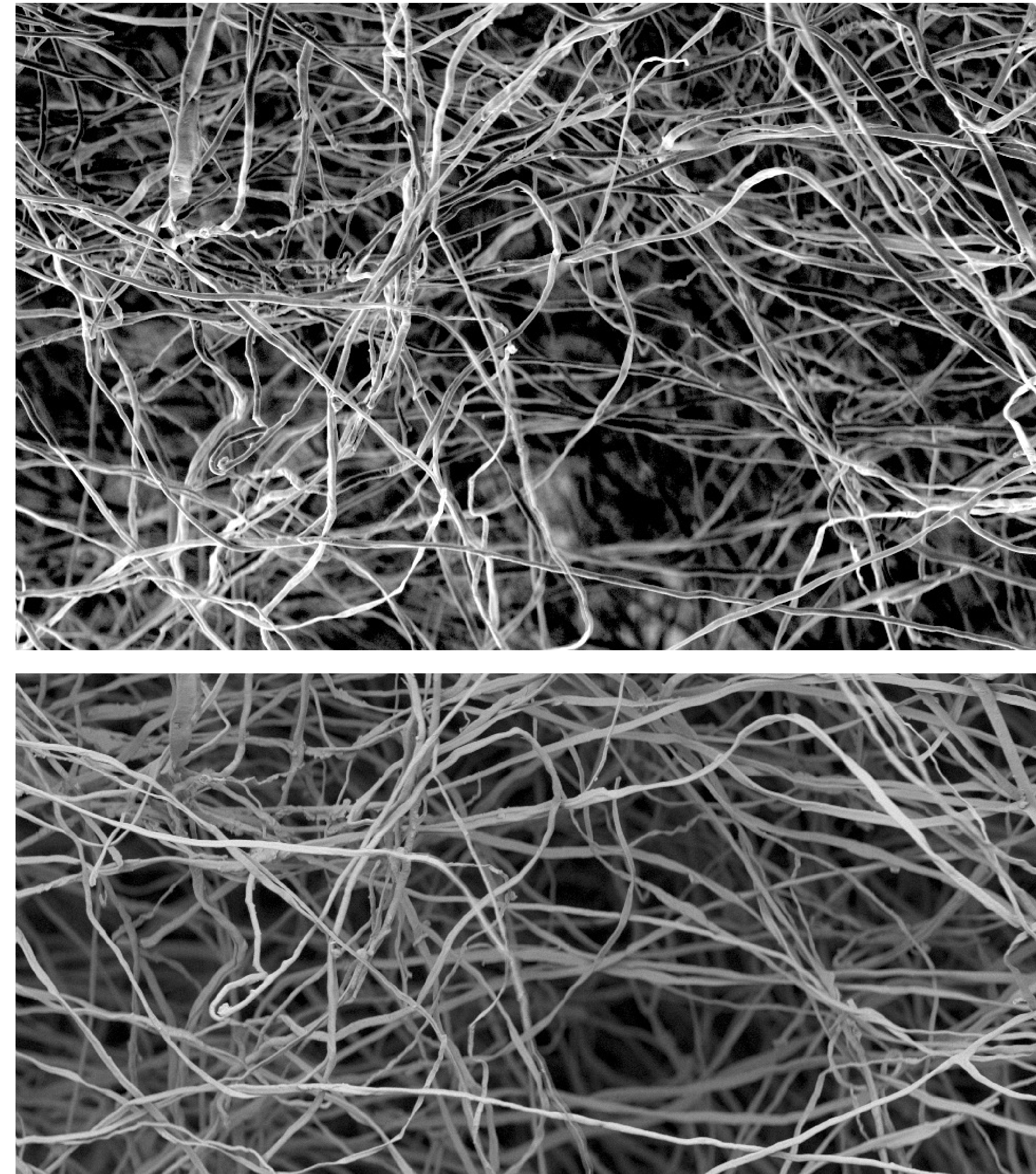


FIGURE 3: Mycelium hyphae network from mycelium-hemp composite sample, imaged with Scanning Electron Microscope (SEM). (Top) Primary electron beam. (Bottom) Backscatter electrons

Challenges with Load-Bearing Mycelium-bound Composites

Despite mycelium's popularity within architectural material research and its potential applications on developing sustainable structures, the applications of mycelium as a load-bearing material within architectural practice has largely been limited to academia and experimental pavilions. A major factor preventing mycelium composites from being used in contemporary structural applications is their weakness relative to more conventional building materials, being strong only in compression. In comparison to cement, iron, steel, and aluminum, mycelium-bound composites are lacking in stiffness and are incredibly lightweight. While these factors have the advantage of making building components made from mycelium easy to carry and work with, it also means that they cannot withstand high loads.

In the current state of research, mycelium-composites can only be used structurally if used in the creation of compression-only structures. Projects from the Block Research Group at ETH Zürich have demonstrated that "compression-only structures can empower weak materials to become load-bearing elements at an architectural scale" because "compression-only structures significantly reduce the amount of internal stresses, and subsequently reduce the amount of material required to carry the applied loads."[8] Although this finding introduces opportunities for the creation of mycelium structures, compression-only structures, like shells and vaults, are expensive and difficult to build and as such, relegate mycelium to a small niche of applications, limiting its effectiveness and impact.

The largest barrier to the use of mycelium composites within the AEC industry is the post-industrial distrust of organic and natural materials. Francesca Hughes highlights the shift towards man-made, engineered materials like aluminum and steel within architecture and engineering in The Architecture of Error. In particular, she references Le Corbusier's desire for the Industrial Revolution to lead to "'the replacing of natural materials by artificial ones, heterogenous and doubtful materials by homogenous and artificial ones (tried and proved in the laboratory) ... Natural materials which are infinitely variable in composition must be replaced by fixed ones.'"[9] This sentiment of Le Corbusier's was a harbinger of the material shift that led to the accumulation of embodied carbon within

6. "Design Challenge for E-Commerce Shipping Packaging and Logistics Cradle to Cradle Design Guidelines." n.d. https://web.stanford.edu/class/me221/readings/C2C_Design_Guidelines_PKG.pdf.

7. Elsacker, E., et al. (2019). Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates. PLOS ONE, 14(7), e0213954. https://doi.org/10.1371/journal.pone.0213954

8. Heisel, F., et al. 2017. "Design, Cultivation and Application of Load-Bearing Mycelium Components: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism." International Journal of Sustainable Energy Development 6 (1): 296–303. https://doi.org/10.20533/

a)

b)

FIGURE 4: Process of mycelium growing on hemp substrate. a. Loose inoculated hemp substrate in petri dish b. Mycelium is developing visibly. It is consuming the hemp substrate and binding the fibres together

the built environment and reflects the distrust that still exists within practice of constructing with organic materials. Due to their relative novelty within architectural material research, mycelium-bound composites have yet to overcome this stigma against organic materials. They are highly variable; are in the early stages of lab testing and development; and have many undiscovered properties.

Goals of this Thesis

Bearing these challenges in mind, this thesis aims to make a small but important step towards making mycelium-bound composite materials more reliable within architectural and structural applications. Throughout the course of this exploration, this project intends to investigate and document the processes and challenges of growing mycelium composites for structural applications. Primarily, intending to broaden the range of applications of mycelium-composite materials, this project attempts to answer the following question– *How can we develop a strategy for increasing the flexure strength of mycelium-bound composites?* This question reflects the need for mycelium to increase and diversify its capacity to carry loads to become more applicable and robust as a structural material. By increasing and diversifying the loads that building components made of mycelium-bound composites can carry, this thesis aims to make a step towards opening mycelium to a wider variety of structural applications and growing confidence in these materials' ability to be implemented within contemporary building practices.

9. Hughes, Francesca. The Architecture of Error: Matter, Measure, and the Misadventures of Precision. Cambridge, Massachusetts: The MIT Press, 2014.

FIGURE 5: MycoTree by Block Research Group (2017). Photo: © Carlina Teteris

State of the Art

The following selection of well-known projects exploring mycelium structures reflects the potentials and current limitations of building and fabricating with this material. To better understand the work that has already been done regarding improving and designing load-bearing mycelium-bound composite structures, as well as the work that still needs to be done, this thesis highlights and analyzes efforts to design and build mycelium structures, alternative ways of constructing with mycelium, and current research into improving the strength of these materials.

Load-bearing Mycelium Structures

An early example of applying mycelium-bound composites within architecture is the Hy-Fi Tower built in the Summer of 2014 for MoMA PS1's Young Architects competition. Designed by architecture firm The Living in collaboration with structural engineers at Arup, this pavilion is built of mycelium-bound composites grown into the form of a brick. The use of this brick system introduces a component-based logic for mycelium construction. The form of the overall tower leverages a double curve structure which "offered maximum strength with a stiff, wide base resistant to wind loads" and addressed the fact that the mycelium bricks the designers were utilizing were "10,000 times less stiff than a typical housing brick." As a result, the overall form of the structure had to be designed to compensate for these weaknesses.[10] This strategy to form and structure demonstrates that although this material's relative weakness places restrictions on the structural forms that mycelium-bound composites are capable of creating, it does not diminish its value or potential as a viable structural material. However, to maintain these structures for a long time, they must be designed with strategies that accommodate maintenance, replacement, and renewal. The Hy-Fi tower elucidates that working with mycelium-bound composites requires special consideration of the relation between the form of the structure, how it addresses the forces acting upon it, and the durability of the material.'

Developing these strategies of mycelium construction is the MycoTree project which uses mycelium-bound composite materials to develop a prototype for a load-bearing branching structure. Similar to the Hy-Fi Tower, the logic of the branching form in which the mycelium is deployed is a result of optimizing for the strengths and weaknesses of these composites. As mentioned in the introduction, research at ETH Zürich has demonstrated that weaker materials are capable of performing structurally in the form of compression-only structures. This branching structure was designed using 3D graphic statics, "using polyhedral form and force diagram" to discover "efficient and expressive spatial structures that are in compression-only." The system that went into the creation of the resulting structure is constructed out of a series of discrete mycelium-composite components joined together with laminated bamboo plates. These plates help "[compact] the mycelium mixture into the moulds" and facilitate the assembly system.[11] MycoTree reinforces the current paradigm of building mycelium-bound composites into the form of compression-only structures through the assembly of discretely cultivated components.

FIGURE 6: Hy-Fi Tower, The Living (2014)
Photo: © Amy Barkow, Barkow Photo

10. Abrams, M. (2014, October 22). Construction Materials Made from 'Shrooms'. The American Society of Mechanical Engineers. https://www.asme.org/topics-resources/content/Construction-Materials-Made-from-Shrooms

11. Refer to 8.

Alternative Ways of Constructing with Mycelium

Although both the aforementioned projects used component-based aggregation strategies, developing methods of assembling inert mycelium pieces, many projects leverage the way mycelium grows to join them together while they are still alive. The work of Jonathan Dessi-Olive and the MycoMatters Lab at UNC Charlotte often leverages this method. Dubbed "bio-welding" or "myco-welding," this technique involves taking still-living mycelium components, placing them together, and growing them together in this final configuration. While this process reduces the need for other materials within the joinery of the mycelium, it introduces challenges concerning "maintaining necessary sanitary and environmental conditions." Additionally, this method requires a longer growing time which can result in variations to the final product including "thick [layers] of pure mycelium [growing]" on the object's surface and "changes in color to the formation of fruiting bodies." This method has the advantage of developing stronger mycelium skin on these composites, which would increase the material's durability, but it also increases variability in the color, texture, and amount of fruiting bodies in the final product.[12] Additionally, while this method can allow for the fabrication of larger-scale mycelium structures, larger mycelium objects would require larger equipment to dry out the material before installation, which would limit the ultimate size of components made with this strategy due to the cost and accessibility of users to large-scale ovens or dehydrators.

12. Dessi-Olive, Jonathan. 2022. "Strategies for Growing Large-Scale Mycelium Structures." Biomimetics 7 (3): 129. https://doi.org/10.3390/

13. Refer to7.

Efforts to Improve Composite Strength

These three research endeavors engage with mycelium at the architectural and structural scale, primarily engaging with questions about fabrication, assembly, and the relationship between form and structure. However, in parallel to these explorations, much of the research into mycelium-bound composites is addressing ways of improving the strength and stiffness at the material scale. As mentioned in the introduction, research conducted by Elsacker et al. into the effects of substrate choice and distribution demonstrates that "the mechanical performances of the mycelium-based composites depend more on the [substrate] condition, size, processing" but establishes that there is a need to establish more standardized practices of growing and fabrication to reduce variability.[13] The findings of this investigation open up the possibility for mycelium to be grown on substrates that

are sourced locally from agricultural waste, as long as they are chopped. However, the overall strength of mycelium-bound composites grown on well-prepared substrates is still much weaker when compared to conventional building materials, and the systems for growing these reliably with uniform standards have not been adequately developed.

While Elsacker et al.'s study focuses on substrate choice and preparation to improve the compressive strength of mycelium-bound composites, the work of Rigobello et al. in their paper "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour," explores methods of using fiber-reinforcement to improve bending strength. In this study, the authors explore reinforcing mycelium composites with internally placed hessian, hessian jacketing, and five parallel rattan fiber rods. Mimicking the strategy of reinforcing concrete with steel rods, the rattan fiber-reinforced mycelium performed the best in bending compared to the base case and both types of hessian reinforcement.[14] This finding was particularly informative for my thesis because it introduced a strategy of reinforcement through the embedding of reinforcements in the form of rods within the mycelium. However, this finding also invites further investigation into questions of the ultimate geometry of

14. Rigobello, et al. 2022. "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour." Biomimetics 7 (2): 53. https://doi.org/10.3390/

FIGURE 7: La Parete Fungina, Jonathon Dessi-Olive. Project made at University of Virginia using Myco-welding technique. Photo: © Dessi-Olive.

the rod, the optimal placement within differently-formed mycelium components, the potential reinforcement materials, and the methods for manufacturing these reinforcements.

In addition to substrate preparation and reinforcement strategies, post-processing has been tested to improve the structural properties of mycelium-bound composites. One of the most successful methods of improving the strength of mycelium is cold-press or hot-press mycelium into panels. This compression strategy has the advantage of "[improving] the tensile strength and elastic modulus" of these composites and significantly increasing their final density. This strategy also helps reduce variability in the final density and thickness of the material.[15] The increased strength and standardization of these mycelium panels is a major step forward toward improving the material strength; however, compressing the mycelium reduces the forms and structural strategies that mycelium-bound composites can be built into. Additionally, it reduces the lightweight aspect of the composites which makes them easier to work with.

Takeaways

All in all, the aforementioned investigations into mycelium-bound composites reveal that with our current knowledge, these materials perform best structurally when grown into components that are then aggregated together to build forms that carry loads solely in compression. Mycelium can grow on a variety of organic substrates which opens these structures to provide a use for a variety of agricultural waste products (as long as they are prepared properly). However, there are still many gaps that need to be addressed to make mycelium a more robust and reliable structural material. Primarily, mycelium-bound composites need to be stronger overall and able to better withstand non-compressive loads. In particular, this thesis is concerned with increasing the flexure or bending strength of mycelium composites. Although Rigobello et al.'s work makes an important step towards improving flexural strength in mycelium composites, there is still work to be done to develop better ways of reinforcing these materials in bending. What other materials perform similarly or better than rattan fibers? How do the ultimate geometry and placement of these reinforcements within the composite affect flexure strength? Additionally, what systems of design can be developed to design reinforcements for differently formed, sized, and loaded mycelium components?

14. Rigobello, Adrien, Claudia Colmo, and Phil Ayres. 2022. "Effect of Composition Strategies on Mycelium-Based Composites Flexural Behaviour." Biomimetics 7 (2): 53. https://doi.org/10.3390/

15. Refer to 5.

FIGURE 8: Fibre-reinforcement strategies from Rigobello et al. (Left to right) Rattan fibre, Hessian Jacketing, Hessian Interior, Base Case Photo: © Rigobello et al.

Chapter 1: Research Set-up

Critical Questions and Hypothesis

To take steps towards making mycelium-bound composites a stronger and more reliable material for use in structural applications, this thesis asks the following questions:

- How can we improve the flexure strength of mycelium-bound composites?
- What systems can be developed to design optimal reinforcement for mycelium composites?
- How can we more reliably create reinforcements for mycelium composites?

To address these questions, this thesis hypothesizes that if we reinforce mycelium-bound composites with 3D-printed reinforcements, then these materials will be able to withstand higher bending loads because the reinforcements will help compensate for mycelium's weakness in tension.

FIGURE 9: Mycelium-bound composite sample growing in cylindrical mould (top-view)

Methodology

Growth Process
This project approaches growing the mycelium-composite samples used in testing through practical means while ensuring as much as scientific control as possible. To achieve this balance, I will control for the mycelium species and substrate by using Ecovative's "Grow-it-Yourself" bags which consist of a proprietary mycelium strain inoculated on a chopped hemp-fiber substrate. Following the instructions of the product, I will use the same growth process for each sample, starting with hydrating the substrate with a slurry consisting of 4 tbsp of flour (in the case of this thesis, corn flour) and 3 cups of water. After the mycelium has started growing in the original bag for 3 - 4 days, I will break up the substrate, add 4 additional tbsp of corn flour, and transfer the mycelium into moulds. If the sample is reinforced, wood dowels will be placed temporarily to support the reinforcement and the substrate will be packed around them. Once the reinforcements are fully surrounded by the inoculated hemp, the dowels will be removed and the mould will be packed with substrate as normal. Lastly, the samples will be left to grow in an air-filtered box for a period of 5-6 days and then baked until dry in an oven for 4-6 hours.[16]

Workflow
Method 1: Finite Element Analysis
To locate and design the reinforcements for the mycelium samples, I will use Finite Element Analysis (FEA) to visualize the principle lines of stress within the sample using the Grasshopper plug-in Karamba3D. This analysis will guide the form and placement of the reinforcements within the sample.

Method 2: Material Testing
For compression testing, the samples will be grown into 101.6 mm x 203.2 mm (4" x 8") cylinder in reference to the ASTM C39 standard for concrete compression testing. This is one of the standard size and shaped samples for compression testing, with the diameter-to-height ratio of the cylinder being 1:2. For the three-point flexure testing, the mycelium composites will be grown into 100 mm x 100 mm x 200 mm (3.94" x 3.94" x 7.87") rectangular prism, which references a standard sized cross-section of 100 mm x 100 mm for testing bending strength in

concrete beams. The use of the 200 mm length is in response to size limitations from the 3D printers that were accessible to this study.

Method 3: 3D Printing
To fabricate the reinforcements, a model will be created within CAD software and 3D-print them out of PLA, specifically PolyMaker PolyWood PLA.

Method 4: Scanning Electron Microscopy
Lastly, to evaluate the bonding capacity of mycelium on the PLA reinforcement, a scanning electron microscope (SEM) will be used to image the sample.

16. "GIY Mycelium Step by Step Instructions." n.d. Grow.Bio. Accessed April 22, 2024. https://grow.bio/pages/instructions.

FIGURE 10: Mycelium growing in a filtered bag

Initial Challenges and Investigations

Growth on PLA and Sterilization of Substrate

Before I could begin my study, I first had to develop a reliable system for growing mycelium composites and investigate how they grow upon 3D-printed PLA. To conduct this initial set of experiments I 3D-printed three identical boxes out of PLA, leaving one box plain, brushing one box with corn flour, and filling another box with black locust wood dust mixed with corn flour. These samples would be injected with Pink Oyster Mushroom liquid culture (a species of fungus that develops quickly) to inoculate them with mycelium. The purpose of these experiments was to help understand and visualize the ability of the mycelium to grow upon the PLA with and without the presence of the substrate.

The use of the corn flour was to provide a "food source" for the mycelium that encourages growth on the filament and substrate. The use of black locust wood dust was out of a desire to use a local waste stream, sawdust from a design-build studio taught in the same semester, as a growth substrate. The wood dust was boiled in hot water, in an attempt to reduce the impact of contaminants, and cooled before its placement in the PLA box. The environment was cleaned with 80% isopropyl alcohol, the liquid culture syringe was sterilized with a flame in between injections, and the samples and materials were only handled while I was wearing nitrile gloves in order to reduce the risk of contamination.

Both the box with the corn flour and the box with the black locust wood dust were successful at allowing mycelium to grow on PLA; however, contamination proved to be an issue with this method. As one can see in Figure 13, both of these boxes started growing undesirable molds in addition to the mycelium desired. The presence of these molds could be a result of an unsterilized substrate or exposure to airborne contaminants. Sterilization of the black locust wood proved difficult as this thesis did not have access to an autoclave or other reliable means of substrate sterilization. As a result of these initial studies, I elected to grow my samples using Ecovative's "Grow-it-Yourself" material because the hemp substrate

FIGURE 11: (From top to bottom) PLA box inoculated with Pink Oyster mycelium; PLA box with corn flour inoculated with Pink Oyster mycelium; PLA box with black locust wood dust and corn flour inoculated with Pink Oyster mycelium

they provide comes sterilized and pre-inoculated with the mycelium culture. Using these greatly reduces concerns about introducing contamination and sterilization from my working environment. In addition to this change of substrate, the process of transferring the mycelium from the growth bags to the final moulds was moved on campus and performed under a laminar flow hood to reduce the impacts of airborne contamination.

PLA-Composite Interaction

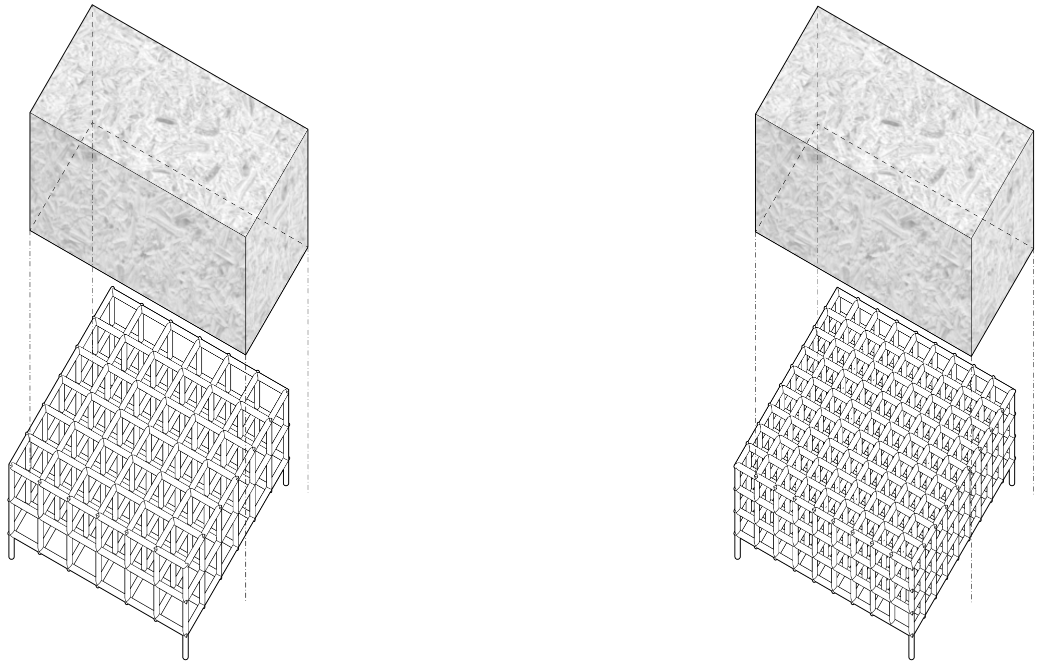
Following the switch to using the hemp-mycelium composite, I wanted to undergo a series of experiments to understand how the PLA would interact with the new mycelial strain and the spacing required for packing the hemp fibre around the reinforcements. To evaluate these variables I printed two "cages" that defined a 75 mm x 75 mm x 35 mm box. One cage had wider spacing dividing the box into a 2x6 grid; whereas, the cage with the tighter spacing divided the box into a 3x9 grid. Each "bar" of the cage was printed as a 2mm thick pipe, and each cage was half-packed with the mycelium-hemp composite and left to grow for several weeks inside of a Tupperware container while under observation.

The wider-spaced PLA cage proved to be better for packing the mycelium composite due to the relatively large size of the chopped hemp substrate material. Both pieces demonstrated the mycelium growing along the PLA cages away from the initial location of the packed mycelium. This visually confirmed that the mycelium would grow along the PLA; however, it should be noted that this growth away from the hemp took several weeks longer than the growth process used for the samples.

Issues with Contamination

After completing these initial tests and investigations, I began to grow a set of three unreinforced mycelium composite cylinders for an initial round of compression testing. These cylinders were intended to be tested to understand the initial compressive strength of this hemp-mycelium composite to evaluate the reinforced samples against. One of these cylinders was grown in a cylindrical mould with a lid meant

FIGURE 12: (Top) PLA box with corn flour inoculated with Pink Oyster mycelium contamination; (Bottom) PLA box with black locust wood dust and corn flour contamination



for casting concrete samples of the same dimension for compression testing, the other two were packed into two sections of PVC pipe with an internal diameter of 101.6 mm (4").

Unfortunately, all three of these samples failed to grow. When the samples were ready to be demoulded, the sample grown in the mould with the lid had only developed in the lower half of the mould. The samples grown in the sections of pipe had grown more thoroughly in the mould than the previous sample; however, they did not develop as well in the middle resulting in the cylinders breaking apart after the samples were dried in the oven. As a result of these failures, subsequent mould were made to include small airholes throughout the mould to encourage the growth of the mycelium throughout the entirety of the formwork.

This inclusion of airholes resulted in subsequent mycelium composite cylinders which had developed through the entirety of the mould. While this demonstrated the effectiveness of introducing additional airflow into the mould, the additional airflow also allowed for airborne contaminants to take hold within the composite despite their being grown in a enclosed, air-filtered box. The proliferation of contamination within

FIGURE 13: (Left) 2×6 Grid Cage; (Right) 3×9 Grid Cage

FIGURE 14: PLA cages with mycelium composite. (Left) 2×6 Cage top and side-views; (Right) 3×9 Cage top and side-views

these samples reflected a lack of humidity in the samples which is needed for proper development of the mycelium on the substrate. As a result, to balance the need for proper airflow throughout the mould and the need for a humid environment for the mycelium to grow in, I covered the top and bottom of the pipe sections with plastic wrap sprayed with 80% isopropyl alcohol. This helped retain humidity within the mould while allowing for airflow through the sides of the formwork. Additionally, a 3% hydrogen peroxide solution was sprayed on future samples if they exhibited contamination.

These three rounds of investigation helped me to identify, understand, and develop strategies for addressing the challenges associated with growing mycelium composites and introducing PLA reinforcements.

FIGURE 15: Trichoderma contamination in mycelium composite

FIGURE 16: Failed unreinforced mycelium composite cylinders. (Left and middle) Grown in section of PVC pipe; (Right) Grown in mould with lid

Chapter 2: Experiments

Synopsis

Following the initial investigations, experiments were undertaken in order to evaluate the validity of the hypothesis. First, a set of compression tests were done on cylindrically shaped samples to develop and better understand the system for designing reinforcements based off of Finite Element Analysis. These tests were done on two sets of two samples, each consisting of an unreinforced and reinforced specimen.

The results of the compression test informed the execution of three-point bending tests on a set of 5 samples in order to evaluate whether or not the reinforcements increased the flexural strength of these materials.

Lastly, to draw a more informed conclusion regarding the results of the bending tests, the samples were analyzed and imaged using a scanning electron microscope.

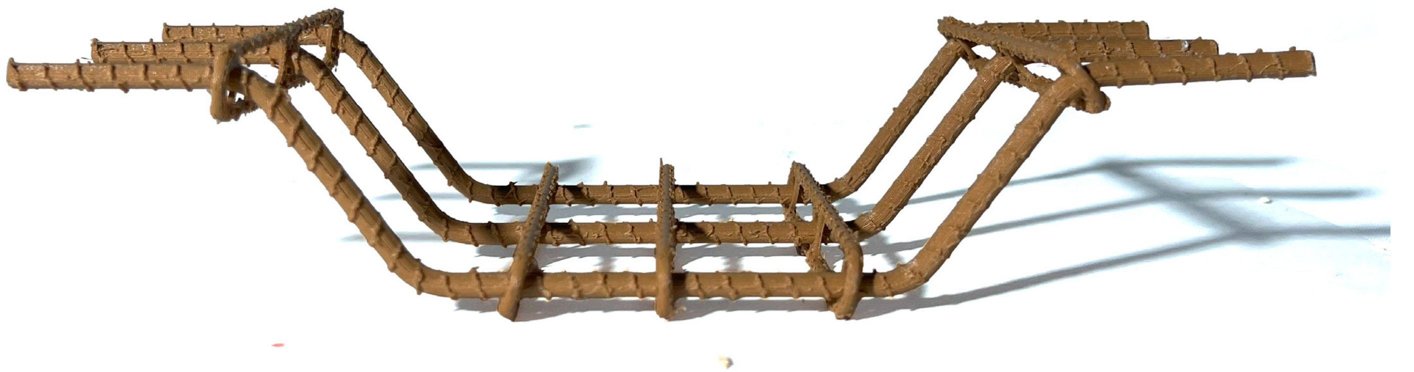


FIGURE 17: Reinforcement design for flexure testing

Initial Reinforcement Study

Goals
My goals for the first round of reinforcement testing were to develop a strategy for translating the results of Finite Element Analysis into a 3D-printed reinforcement design. Additionally, these tests provided an opportunity to develop a method for packing the mycelium composite into a mould while making sure that the PLA reinforcements are evenly spaced and embedded within it.

Although current knowledge of mycelium composites indicates that they perform best under compressive loads, the four cylinders studied will be evaluated for their compressive strength. The intent of the PLA reinforcement is primarily to address mycelium's weakness in tension; however, it is also important to evaluate the impacts of the reinforcement on the overall strength of the material. The purpose of conducting this series of compression tests was to better understand the effects and impact of the reinforcements on the strength of the mycelium.

Developing the Reinforcements
Initial studies of the principle lines of stress through FEA, indicate that the principle lines of tensile stress in the cylinder form run vertically from the top face to the bottom face. The principle lines of compressive stress are circular and are in line with the circular cross-section of the sample. These principle lines of stress indicated that the reinforcement geometry would primarily need to consist of a set of vertical continuous reinforcements and horizontal rings.

Having visualized the principle lines of stress within the cylinder, a set of diagrams was developed to understand how to translate and rationalize the flow of forces into a grid of reinforcements. The grid developed in the set of drawings shown in the figure above are intentionally intense to reflect the output from the analysis tools; however, for this reinforcement grid to be reasonable to fabricate and embed within the mycelium-bound composite, the geometry needed to be greatly simplified.

The resulting kit-of-parts for reinforcing the cylindrical samples consists of a set of seven vertically-oriented rods and five horizontally-oriented rings that connect the rods together. In reference to the grooves in steel reinforcements used in concrete

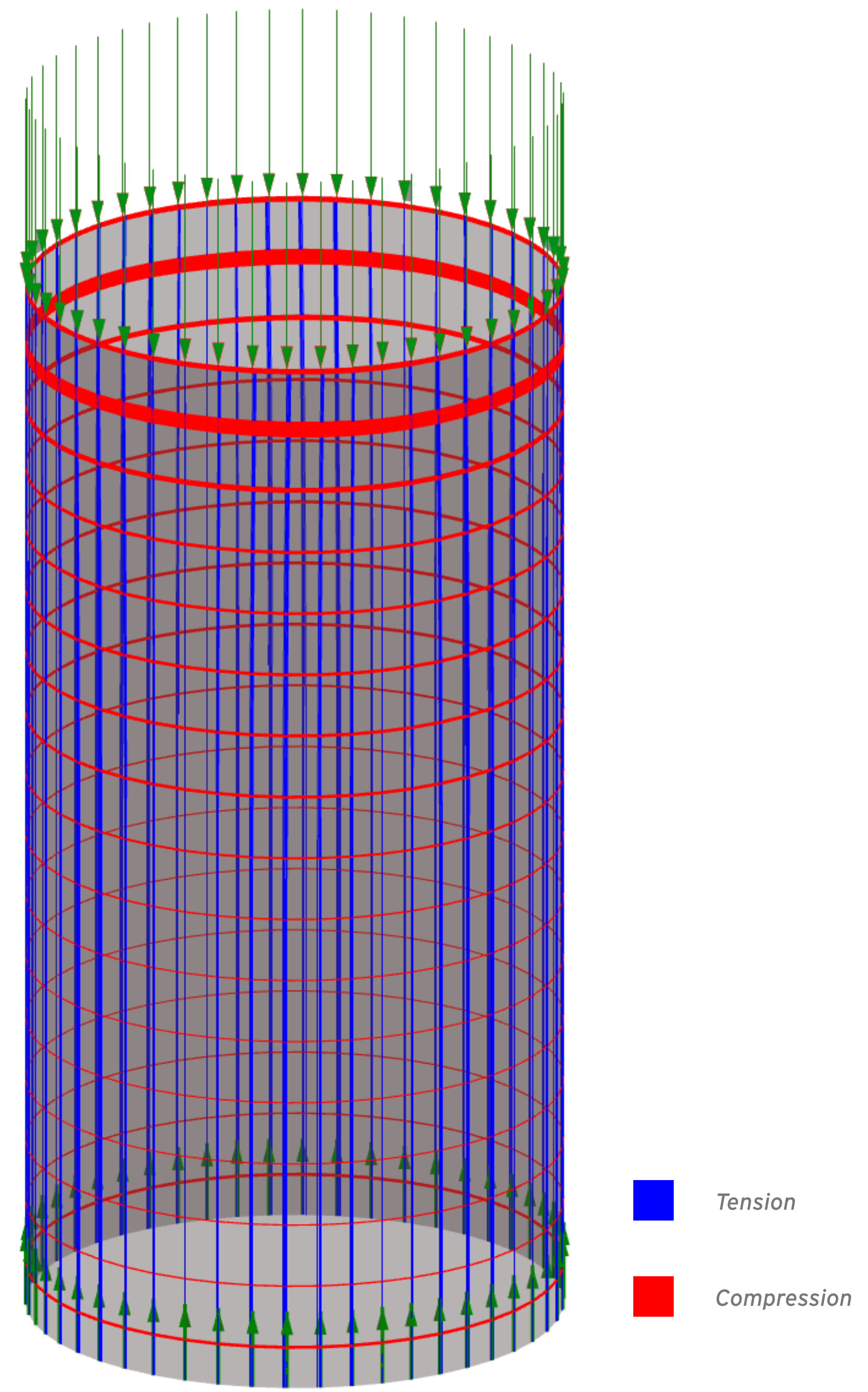
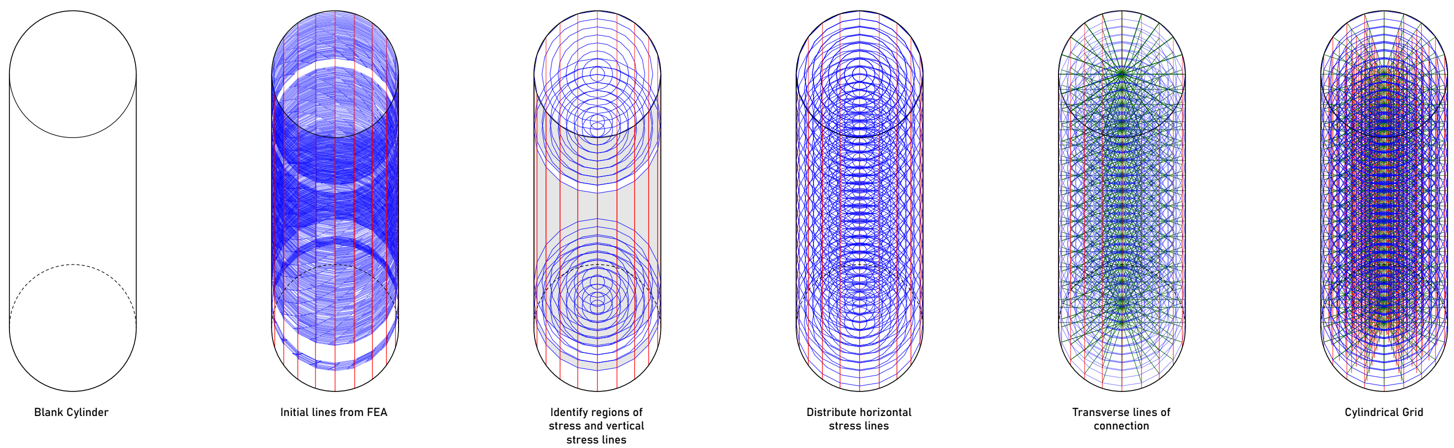


FIGURE 18: Finite Element Analysis of sample cylinder



composites, each component of the kit-of-parts was printed with “teeth” to theoretically help the 3D-prints stay bonded to the mycelium as it dries. Both the rings and the rods were printed with a 2 mm thickness. To allow for tolerance and working room for placing the mycelium into the moulds, the geometry of the rings was offset 12.5 mm from the interior edge of the mould. Additionally, to ensure even spacing of the horizontal rings within the composite, the airholes in the mould were drilled so that the tops of each hole aligned with the bottom of the rings. After an initial layer of mycelium-inoculated hemp fibres were packed into the mould, a set of wood dowels was temporarily inserted into the airholes to support the rings while more substrate is packed around them. After a sufficient amount of hemp fibre is packed around the ring to support it, the dowels are removed.

FIGURE 19: FEA geometry rationalization diagram

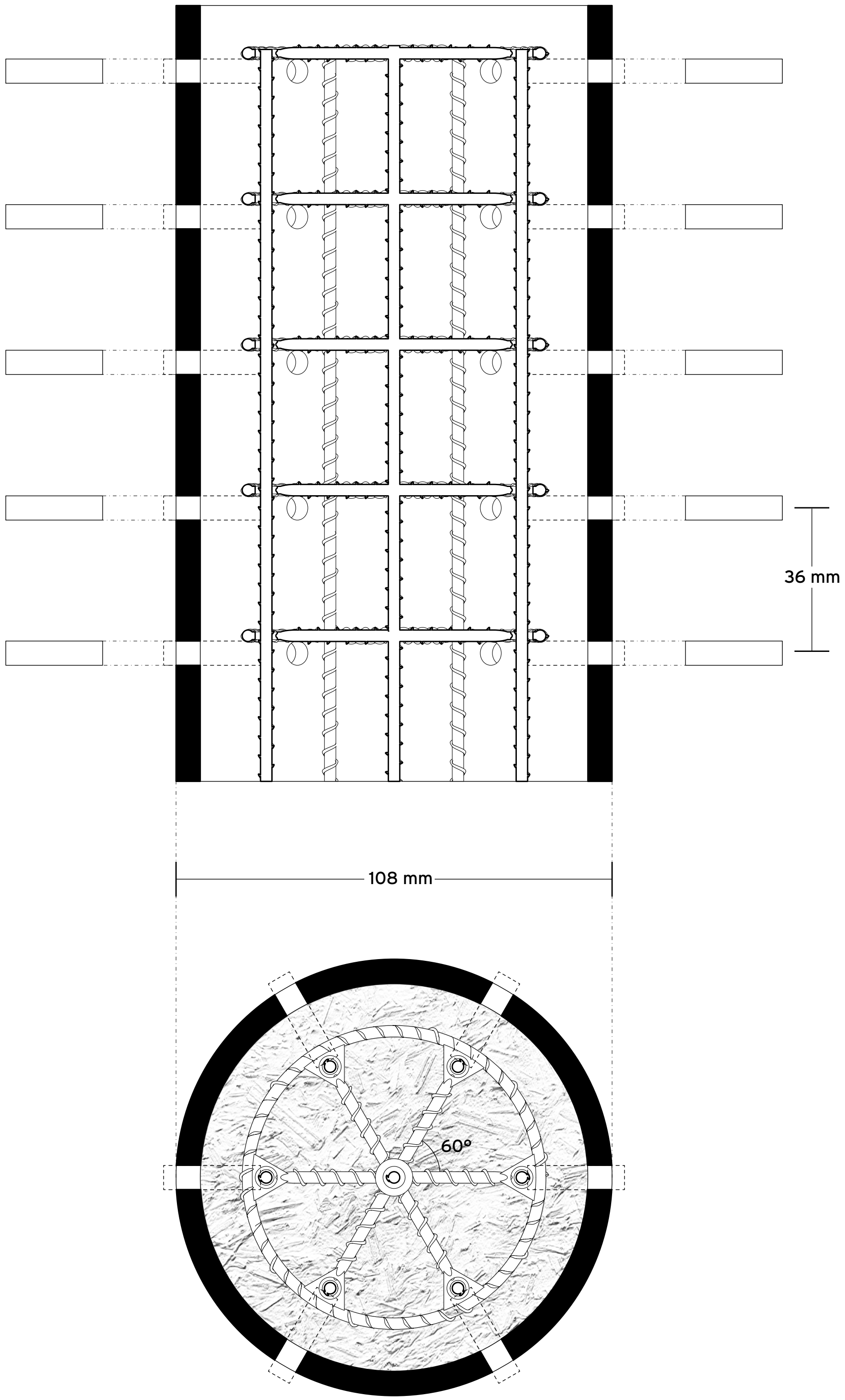


FIGURE 20: Reinforcement assembly diagram

FIGURE 21: (Top) Reinforcement ki-of-parts; (Bottom) Testing reinforcement assembly

Compression Testing Results

To evaluate the performance of the mycelium-bound composites in compression with the reinforcements, two rounds of compression testing were conducted. Each round of tests consisted of an unreinforced sample and a reinforced sample. The samples were displaced at a rate of 15 mm/s with the force applied increasing at a rate of 0.05 kN/s. Each sample was evaluated for Young's Modulus (MPa) and through Force-Displacement and Stress-Strain graphs.

Young's Modulus First Round of Testing:

- Unreinforced: 6.117 MPa
- Reinforced: 3.768 MPa

Young's Modulus Second Round of Testing:

- Unreinforced: 7.459 MPa
- Reinforced: 4.197 MPa

FIGURE 22: Mycelium-bound composite cylinder in Instron compression testing equipment

FIGURE 23: (Left) Round 1 testing cylinders before and after; (Right) Round 2 testing cylinders before and after (images need to be edited)

Conclusions

Both rounds of testing show that the unreinforced mycelium-composite cylinders performed better under compression than their reinforced counterparts. During the test, the unreinforced samples compressed at a relatively constant rate. In comparison, while testing the reinforced samples, the testing head stalled temporarily whenever it encountered the horizontal reinforcements; however, instead of slowing down the overall rate of compression, these starts and stops resulted in an uneven rate of displacement. As one can see in Figure 24, this is reflected in the Force-Displacement and Stress-Strain curves for specimens two and four as the curves are less smooth in comparison to specimens one and three which were unreinforced. The results of loading the reinforced mycelium composites in compression indicate that the PLA is compromising the existing compressive strength of the material. As mycelium performs better in compression, future testing of this reinforcement strategy should be applied solely to areas in which mycelium is experiencing tensile loads. Consequently, for the next round of testing, this thesis moves towards improving the flexure strength of mycelium-bound composites, solely reinforcing the areas where the sample experiences tension.

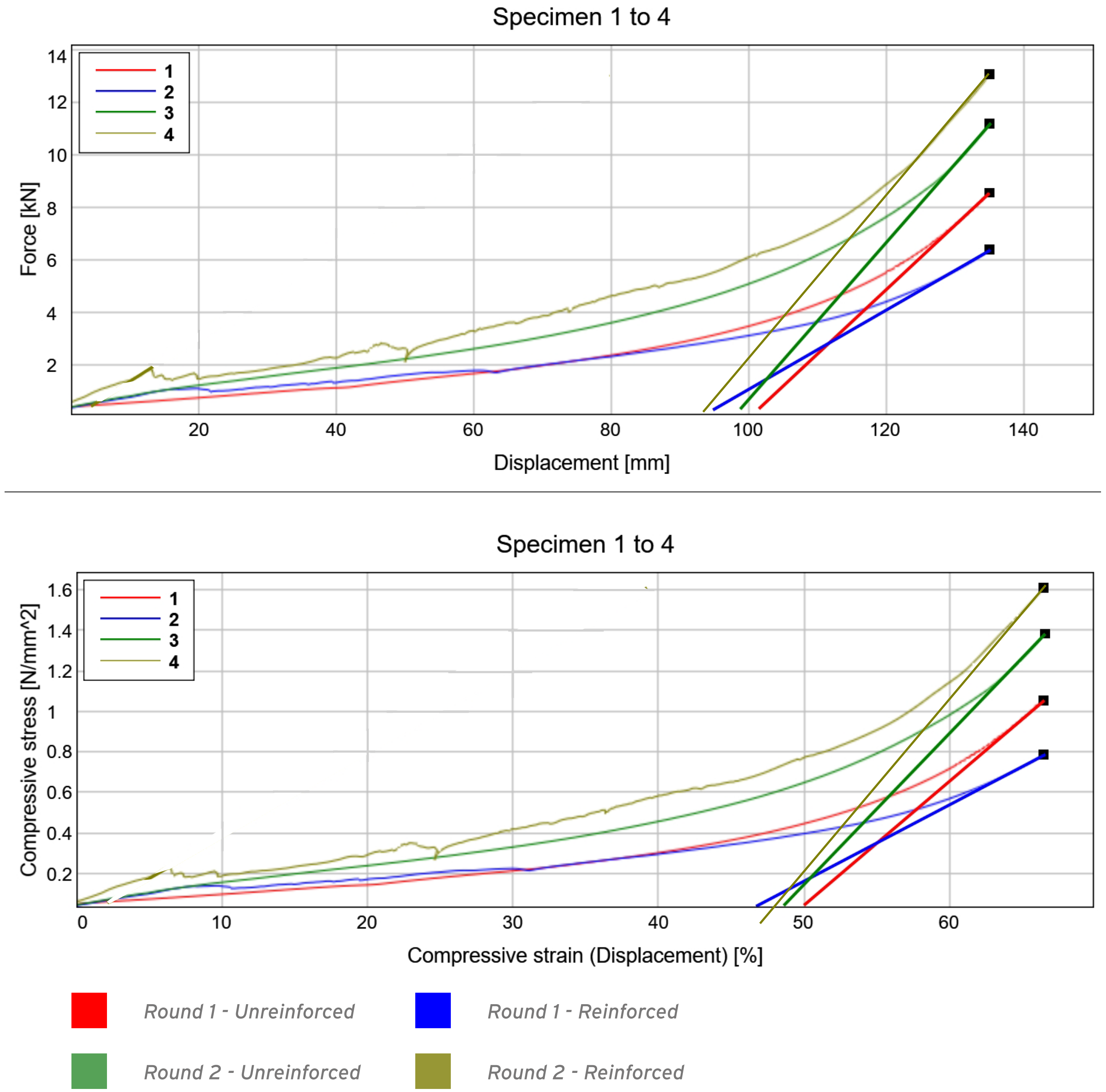


FIGURE 24: Force-Displacement and Stress-Strain graphs

Flexure Testing

Goals

After evaluating the results of compression testing, this project moved towards the goal of improving the flexure or bending strength of mycelium-bound composites. During this round of testing, the goal was to increase the flexure strength of mycelium composites by reinforcing the samples below the neutral axis, where the material experiences tensile forces when undergoing bending loads. Additionally, these tests helped evaluate and compare the performance of straight reinforcements versus reinforcements with FEA-derived geometry, as well as, the impact of the effective depth.

Test Parameters

Borrowing from the conventions of concrete composite testing, the samples changed from cylinders to rectangular prisms that would undergo three-point flexure testing. In a three-point flexure test, the sample is supported on both ends by two rollers and loaded across the middle of the material by a metal bar. It should be noted that all mycelium composite specimens were grown in moulds that measured 100 mm x 100 mm x 200 mm; however, due to shrinkage from the drying process, the average final measurement of the samples was 95 mm x 95 mm x 190 mm which was used in the final calculations.

The main variables for testing were the geometry and effective depth (offset from the bottom of the sample) of the 3D-printed reinforcements. The first reinforcement geometry tested was a straight rod, and the second reinforcement geometry tested was derived from the principle lines of tensile strength as shown in Figure 25. The two offsets used for determining the effective depth were 12.5 mm, the nominal offset used for tolerance in the previous experiment, and 16.67 mm, which is calculated based on the centroid of the tension curve below the neutral axis. Three threaded PLA rods were embedded in each sample, Two sets of rings, corresponding to each offset, were also fabricated to evenly space the reinforcements apart.

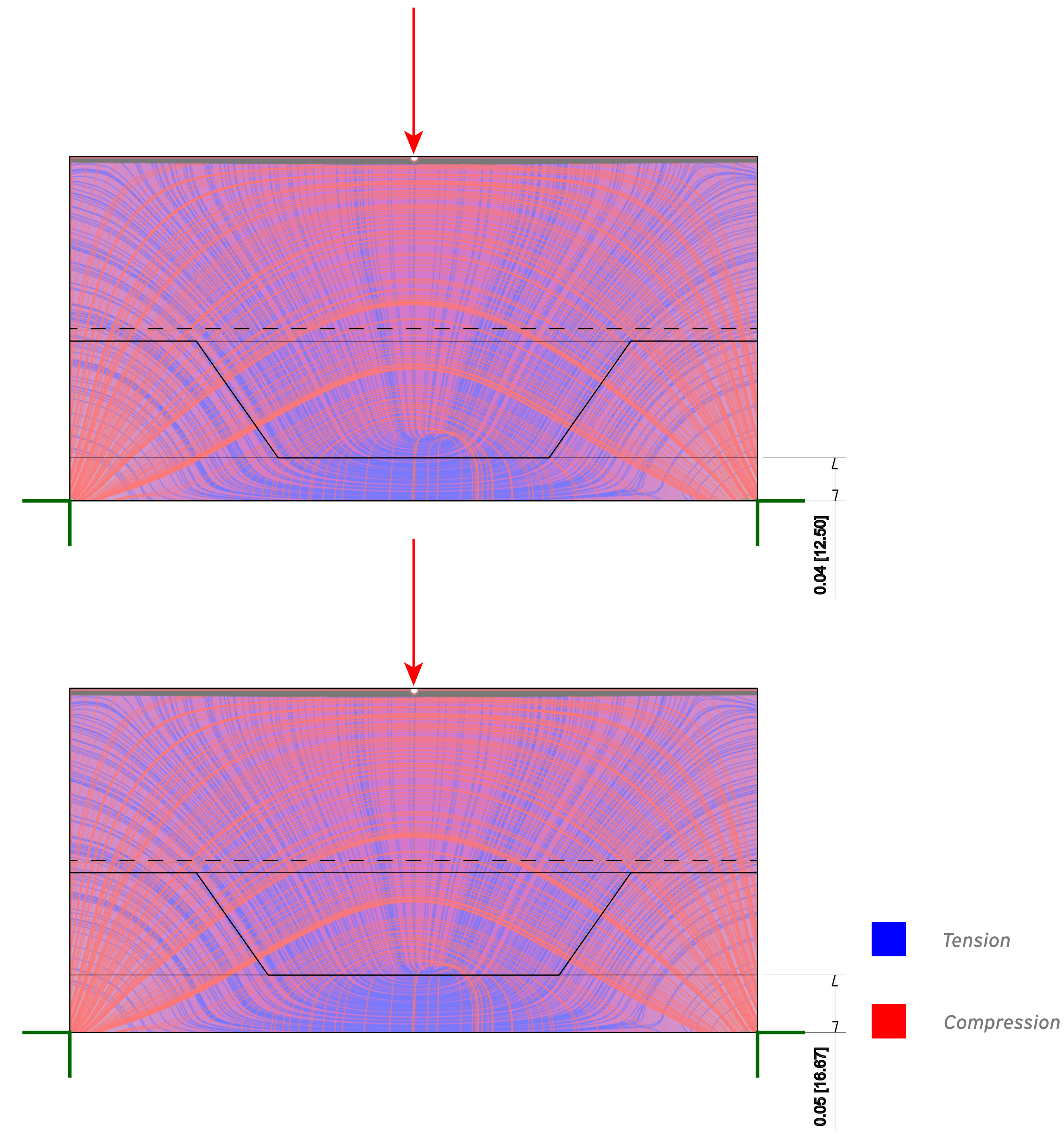


FIGURE 25: Design of reinforcements from Finite Element Analysis

FIGURE 26: Mycelium sample in 3-point flexure testing apparatus

Three-Point Flexure Testing Results

To evaluate bending strength, five samples, including an unreinforced control, were tested on the Instron. All five mycelium composite specimens were displaced at a rate of 15 mm/s, with the load increasing by 0.5 kN/s. Each sample was evaluated for Flexure Modulus (MPa) and through Force-Displacement and Stress-Strain graphs. The five samples were tested in the following order:

1. Unreinforced
2. Straight reinforcement, 12.5 mm offset
3. Straight reinforcement, 16.67 mm offset
4. FEA reinforcement, 12.5 mm offset
5. FEA reinforcement, 16.67 mm offset

Flexure modulus was calculated for each of the samples using the displacement and the force applied to the mycelium at the breakpoint. The results are as follows:

1. Unreinforced:
   a. Breakpoint: 22.53 mm, .8550 kN
   b. Flexure Modulus: 0.795 MPa

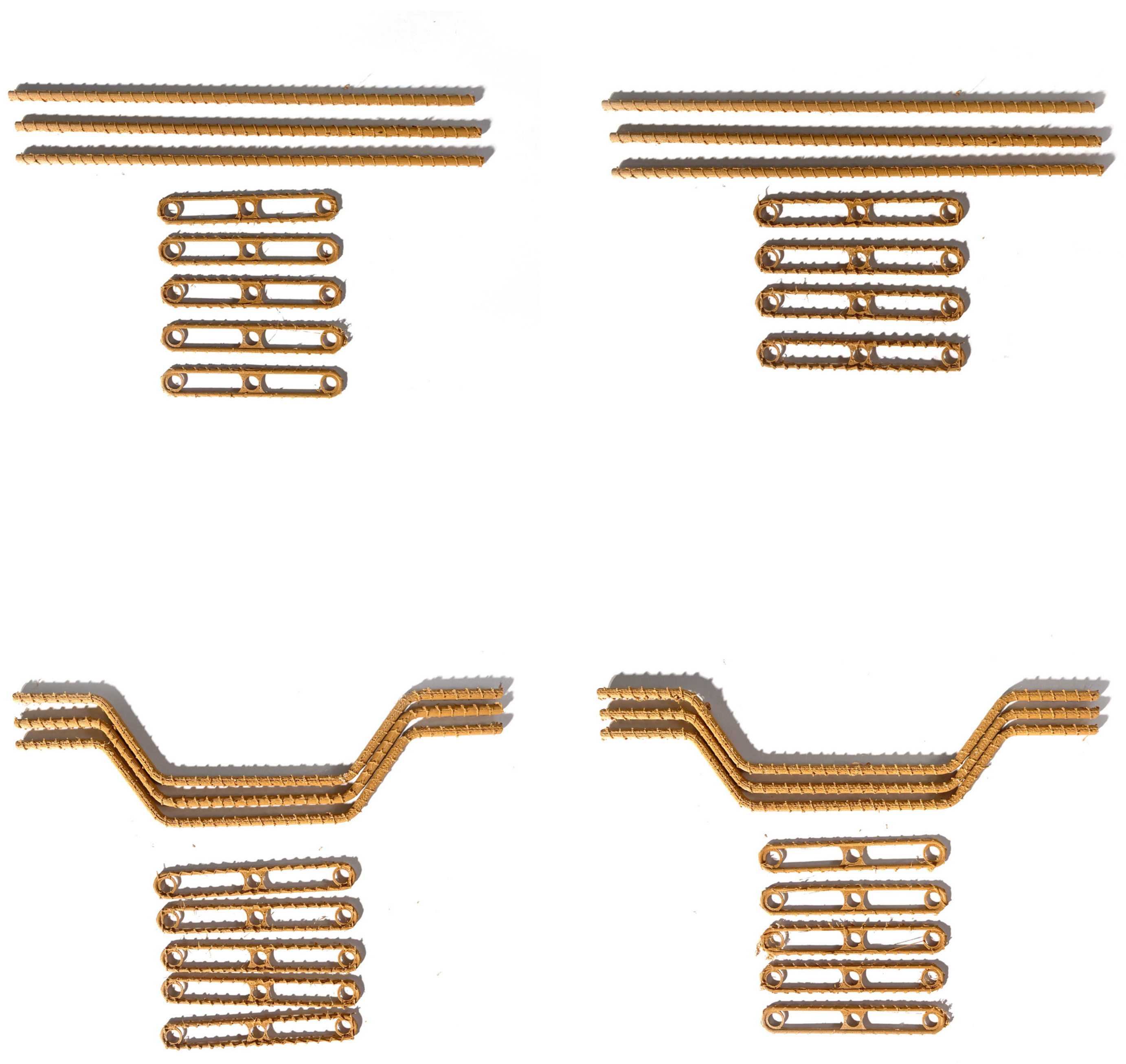
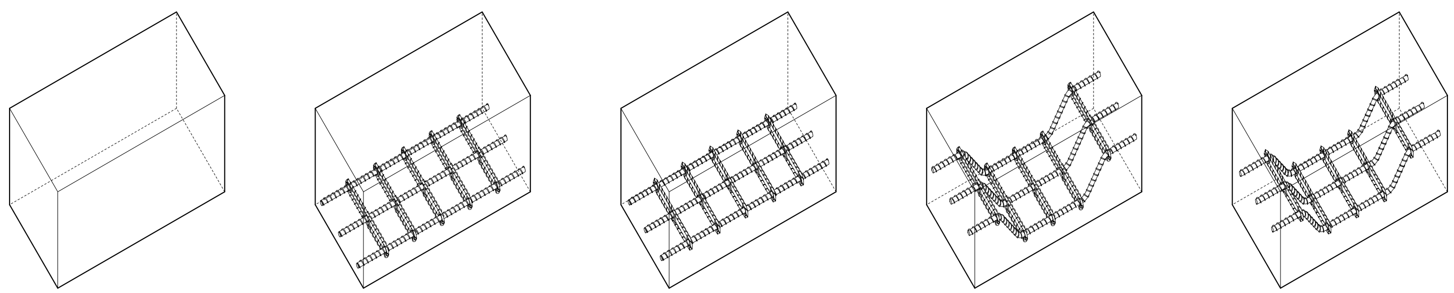


FIGURE 27: Four reinforcement designs. (Top-left) Straight 12.5 mm offset; (Top-right) Straight 16.67 mm offset; (Bottom-left) FEA 12.5 mm offset; (Bottom-right) FEA 16.67 mm offset



2. Straight reinforcement, 12.5 mm offset:
   a. Breakpoint: 28.10 mm, .9014 kN
   b. Flexure Modulus: 0.675 MPa
3. Straight reinforcement, 16.67 mm offset:
   a. Breakpoint: 27.16 mm, .9944 kN
   b. Flexure Modulus: 0.771 MPa
4. FEA reinforcement, 12.5 mm offset:
   a. Breakpoint: 54.07 mm, 1.090 kN
   b. Flexure Modulus: 0.424 MPa
5. FEA reinforcement, 16.67 mm offset:
   a. Breakpoint: 56.58 mm, 1.178 kN
   b. Flexure Modulus: 0.438 MPa

Conclusions

Across the board, the reinforced mycelium-bound composites broke under a higher load and displaced farther than the base case. Although these samples broke under a higher load, for samples of the same size, the ratio between the force applied and the displacement at the breakpoint is the key factor in evaluating the flexural stiffness of the specimen. As such, despite being able to carry a larger load, the reinforced composites had a much lower flexural modulus than the unreinforced mycelium.

Comparing the different reinforcement geometries, one can see that the straight reinforcements performed far better than the FEA-derived reinforcement designs. For reinforcements of the same geometry, the ones designed for

FIGURE 28: 5 Samples. (From left to right) Unreinforced; Straight reinforcement, 12.5 mm offset; Straight reinforcement, 16.67 mm offset; FEA reinforcement, 12.5 mm offset; FEA reinforcement, 16.67 mm offset

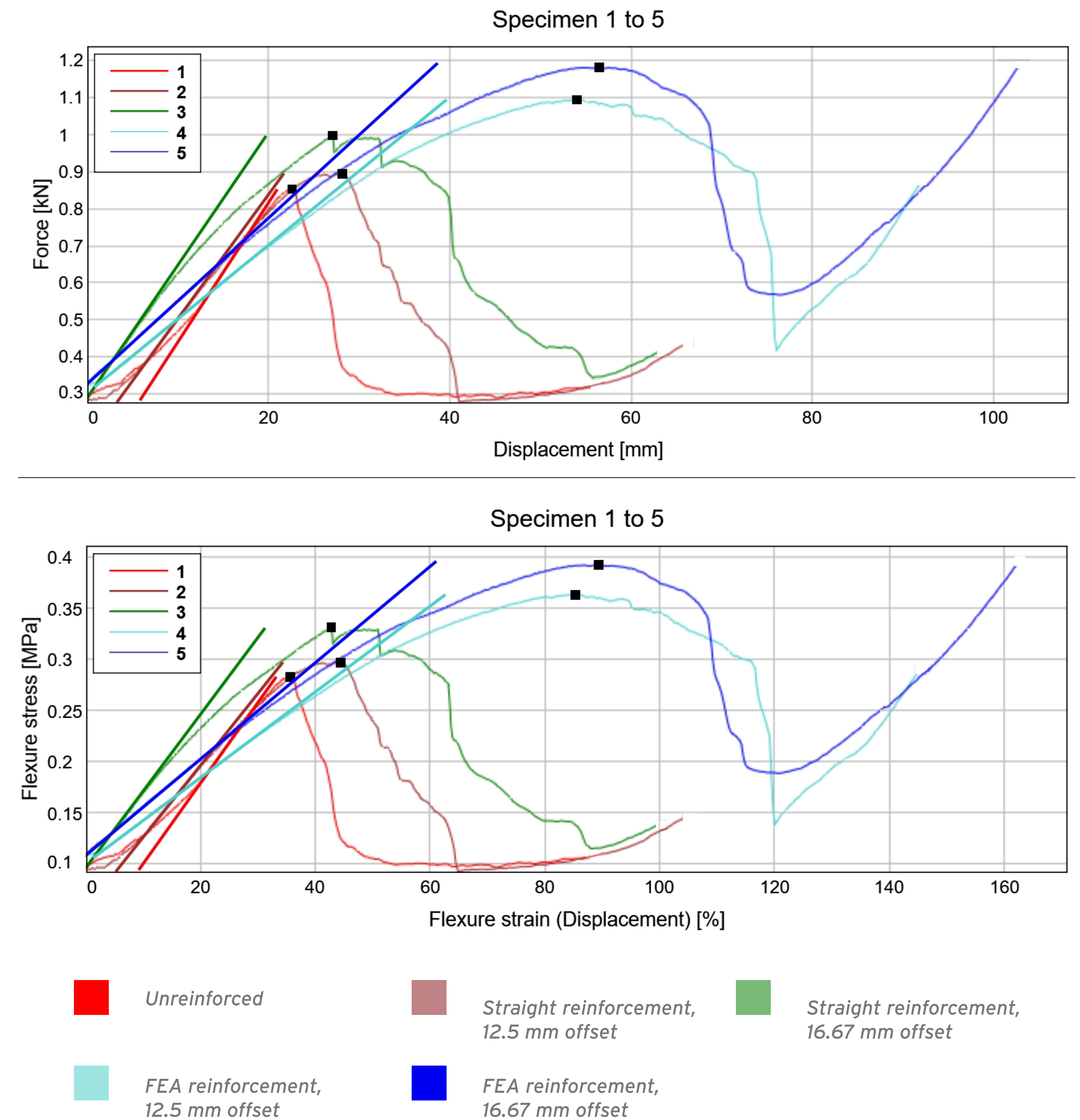


FIGURE 29: Force-Displacement and Stress-Strain graphs

an effective depth of 16.67 mm performed better than those designed with an effect depth of 12.5 mm. These results potentially indicate that using an effective depth based on the centroid of the tension curve below the neutral axis of a mycelium component results in improved performance. However, the superior performance of the straight reinforcements raises more questions than answers. Is the reason that the straight reinforcements performed better than the FEA-derived components a result of the bond, or lack thereof, between mycelium and PLA? Could the potential weakness of this bond explain why the reinforced samples had a lower flexural modulus than the base case? To answer these questions, the bond between mycelium and PLA needs to be interrogated.

FIGURE 30: 5 samples post-flexure testing (Organized from left to right in testing order)

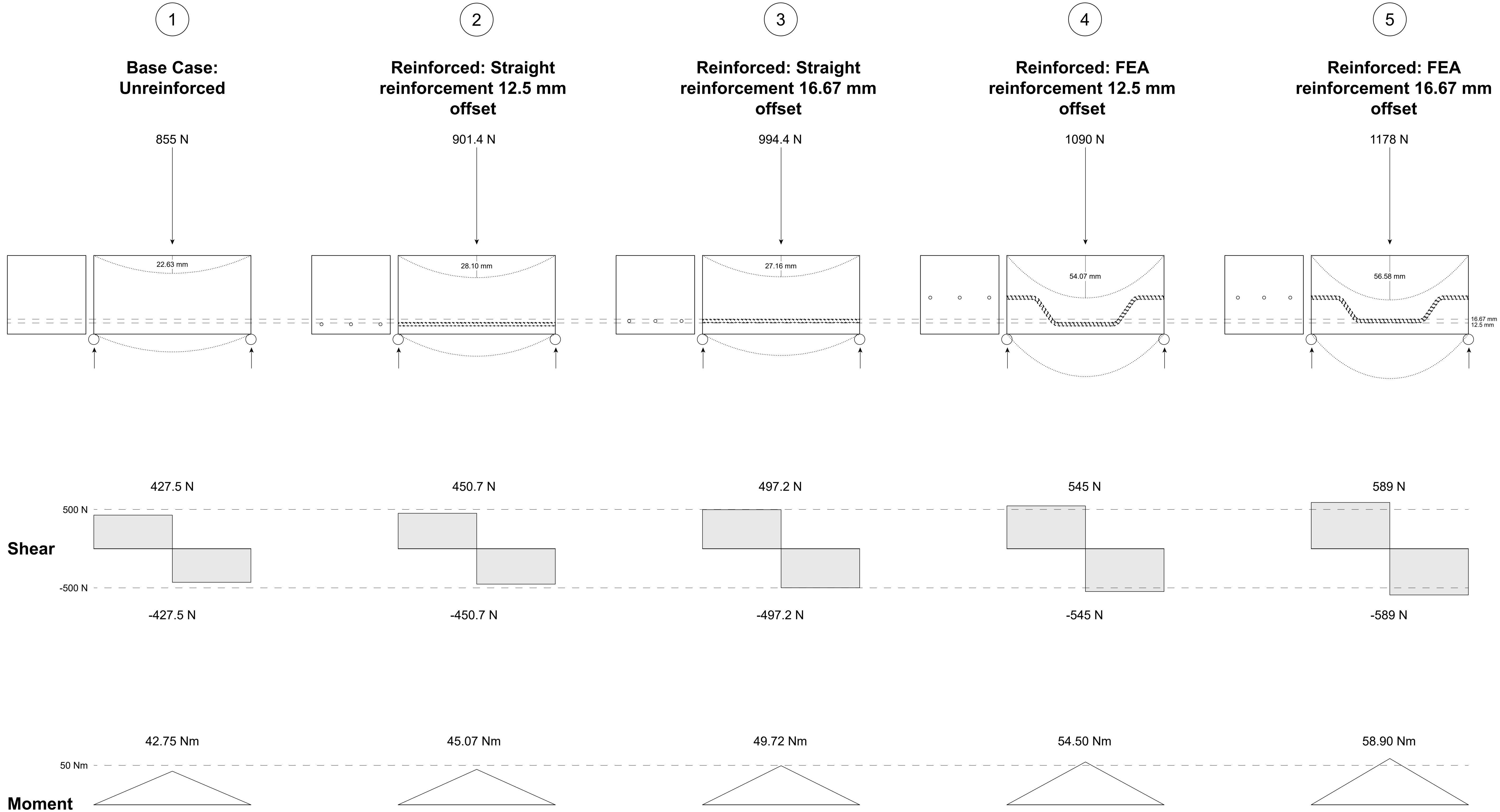


FIGURE 31: Shear-Moment diagrams of mycelium flexure tests at the breakpoint

Evaluation of PLA-Mycelium Bond

Both the compression and flexure tests of the reinforced mycelium composites invite questions about the nature of the bond between mycelium and the PLA. To better understand the relationship between these two materials, a scanning electron microscope (SEM) was used to image two samples of mycelium composites at varying scales. The first sample imaged consists solely of the mycelium-hemp composite, and the second sample imaged includes the mycelium bonded to both hemp and PLA. Both SEM samples were sourced from fragments that resulted from the second round of the compression testing phase.

Mycelium-Hemp Bond

To first understand how mycelium bonds to hemp, images were taken of the hyphae interacting with a group of hemp fibres. Figure 32 showcases how the hyphae grow along and link the hemp together. In the center of the image, one can see how the hyphae emerge from the network below and "hook" around the substrate above it. This image demonstrates how the mycelium grows along, around, and in between the substrate material to form the fungal network that binds the composite together.

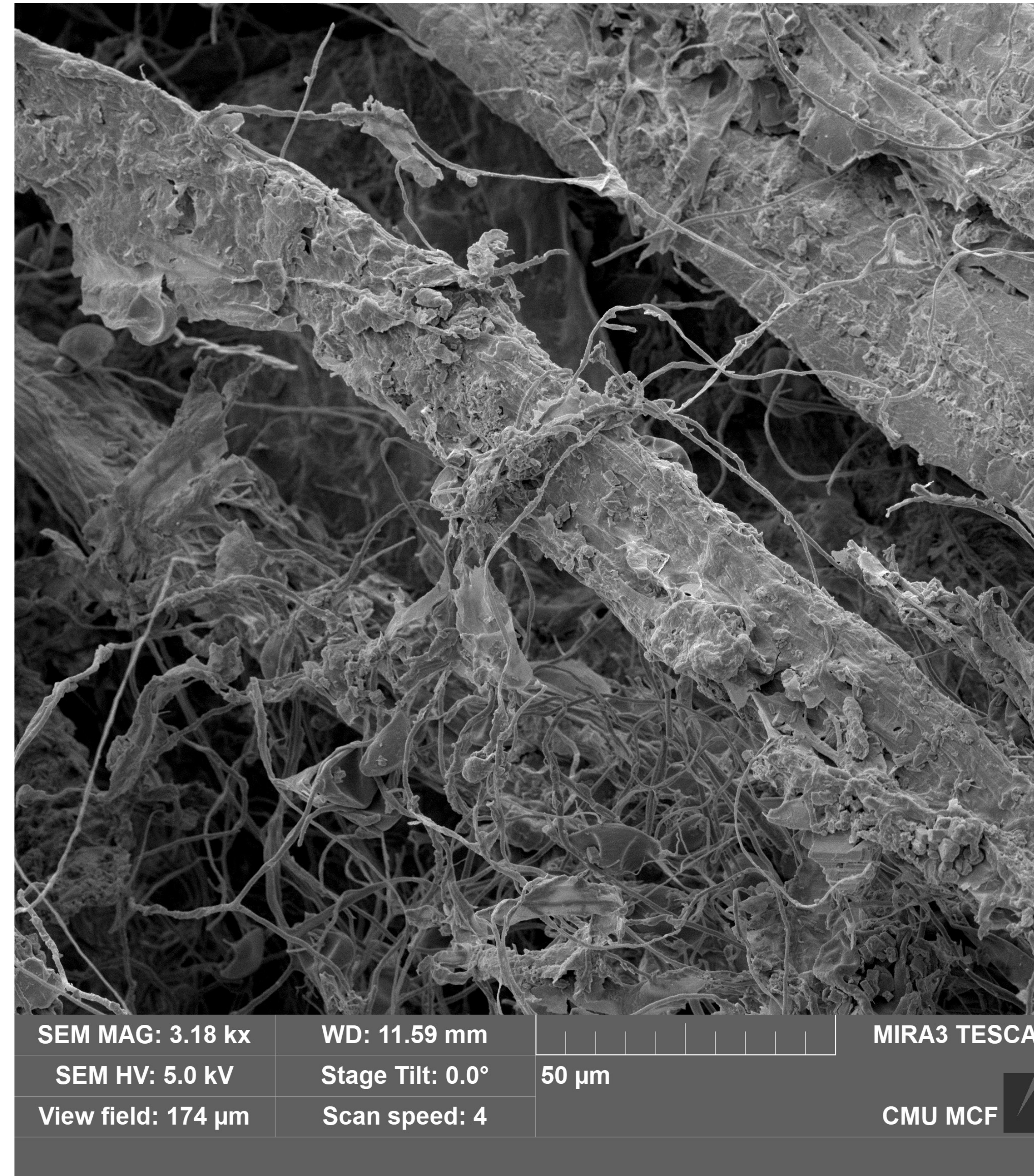


FIGURE 32: Mycelium hyphae network growing around hemp fibres

Mycelium-PLA Bond

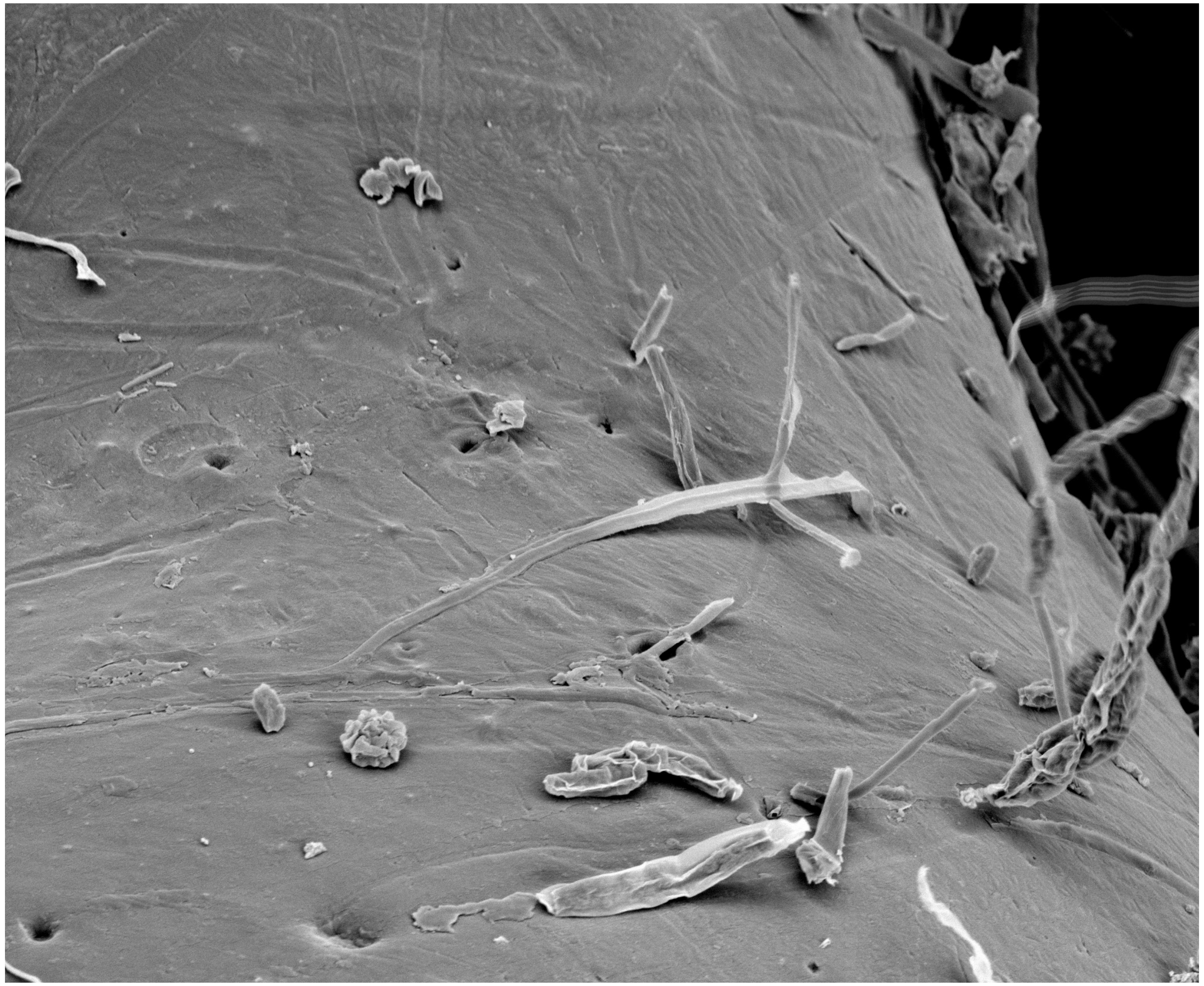
In contrast to the network created by the mycelium and hemp, the bond between the hyphae and the PLA is much more fragmented. Figure 33 shows the mycelium growing along the "teeth" of the reinforcements. The hyphae are growing together disorderly and fragmented. Unlike in the hemp imaging, where the mycelium was weaving around the substrate to link and bind it together, the hyphae are much less successful, with undeveloped spores scattered across the surface of the PLA.

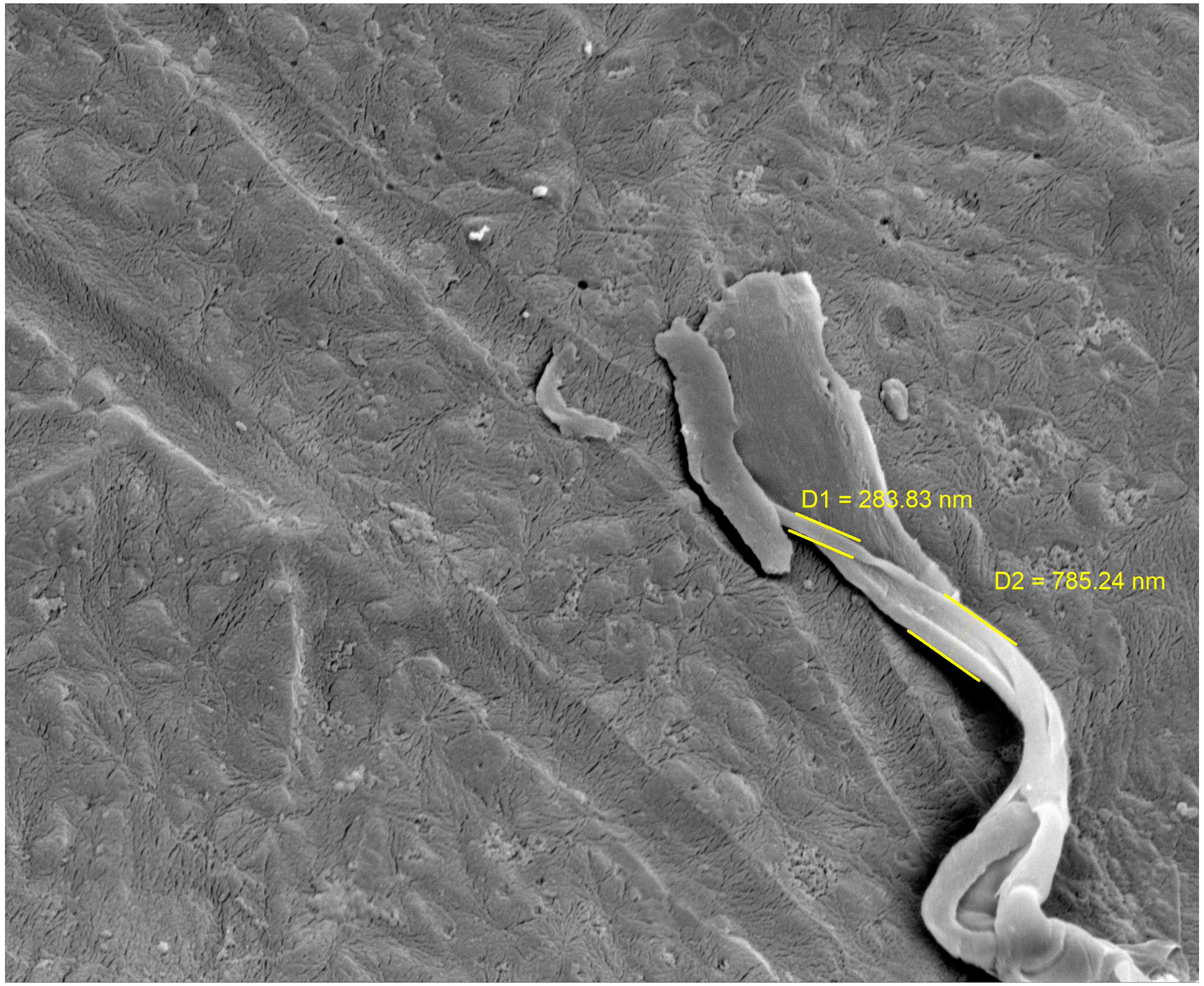
FIGURE 33: Mycelium hyphae growing on PLA reinforcements

Comparing Material Bonds

This next image highlights the differences in growth patterns between the mycelium on hemp versus on the reinforcements. On the top right, the hyphae are growing in an orderly and linear fashion along the hemp substrate. However, as in the previous image, the mycelium grows irregularly and fragments as it approaches the PLA. The spacing between the hyphae is also much wider as it approaches the PLA in comparison to the hemp.

FIGURE 34: Mycelium hyphae growing on hemp fibres and PLA





Zooming in on the PLA

Looking closer at the PLA, there is a series of microscopic holes and tracks that are present over the surface. Similar impressions of the PLA can be seen around the mycelium that has grown onto the reinforcements. These holes and tracks on the PLA seem to indicate that before the compression test, the mycelium had attempted to dig into and bond with the PLA. However, these impressions are extremely shallow with the depth of the tracks being less than a micron. These images suggest that some of the mycelium bonded with the PLA; however, since relatively fewer hyphae were able to penetrate the surface of the reinforcements, and the bond was much weaker, the mycelium was ripped off the reinforcements when the composite experienced high loads.

FIGURE 35: Close-up view of impressions made on PLA by hyphae

FIGURE 36: Measurement of hyphae in relationship to impressions made on the reinforcement's surface

Conclusions

Imaging of the samples at a microscopic level helps elucidate the difference in mycelial growth on hemp versus PLA. Mycelium grows much more orderly, tightly, and interconnectedly on hemp fibres; whereas, the mycelium grows much more disorderly, loosely, and fragmented on the PLA. Where the mycelium was able to take hold of the PLA, the bond was much too shallow and weak, potentially resulting in the mycelium readily pulling off of the reinforcements when it experienced significant loads. As such, for PLA to be an effective reinforcement material for mycelium, the surface would need to be designed and fabricated in such a way that it allows for the hyphae to embed itself deeper and more securely into the reinforcements.

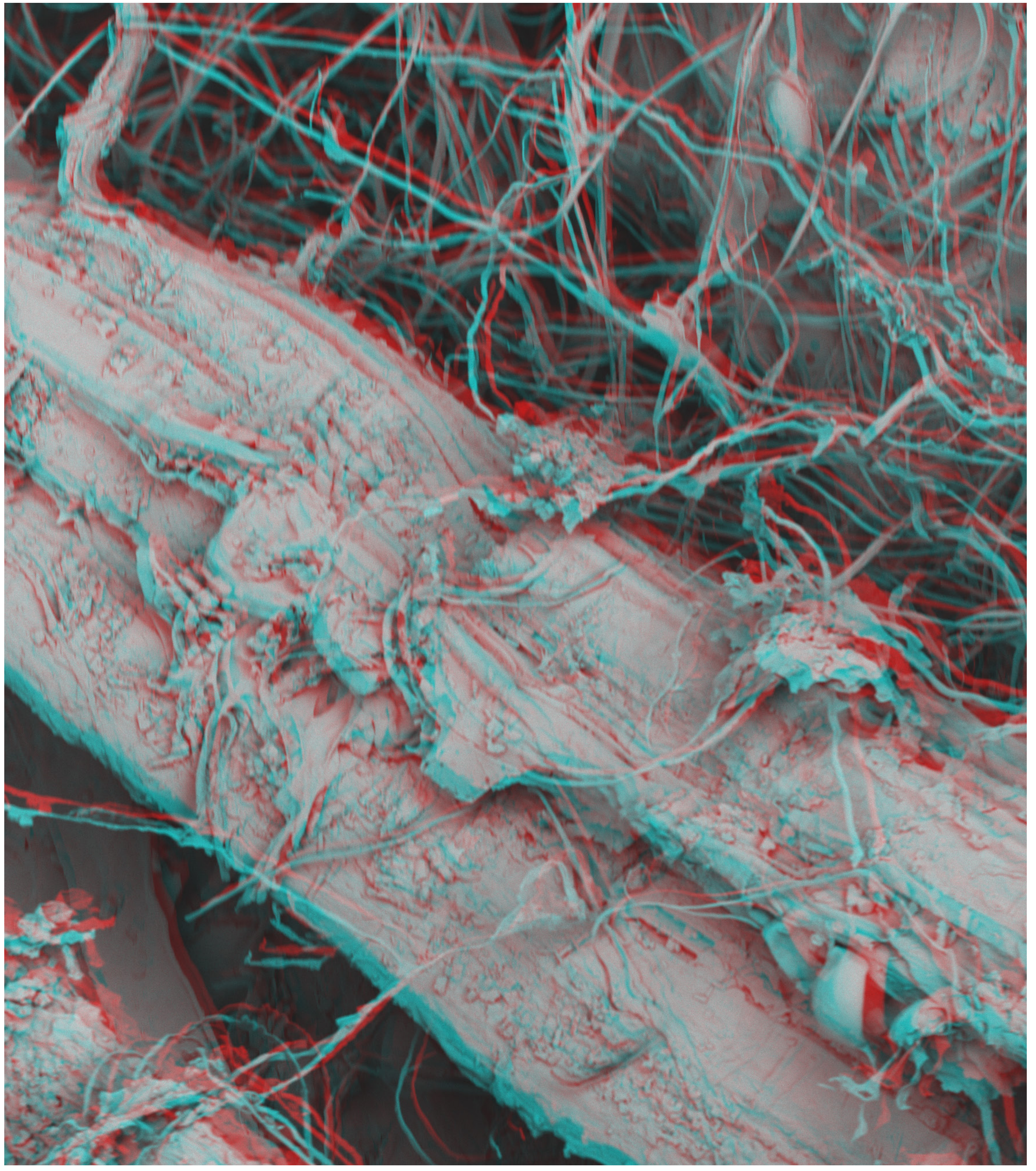


FIGURE 37: 3D imaging of mycelium-hemp composite bond and growth pattern

Chapter 3: Potential Architectural Applications

Summit Pavilion

In its current state, the most reliable way of strengthening mycelium-bound composites is through compressing the material into a panel.[17] Utilizing this strategy, this Summit Pavilion projects a future where mycelium panels are used to create folded-plate structures. This structure is situated at the top of Mt. Tammany, a mountain in New Jersey famous for its trail which leads to the Delaware Water Gap. Creating a shelter that extends the view of the summit of Mt. Tammany, the Summit Pavilion takes advantage of mycelium's light weight and natural biodegradability to showcase a new paradigm of architecture that exists in harmony with the natural environment.

Mycelium-bound composite panels are a lightweight material that is easy to carry and is less strenuous on workers' bodies during construction. This light weight makes these composites apt for construction in remote and hard-to-reach environments. Furthermore, by its organic nature, the mycelium composite used in the Summit Pavilion crafts a better ecological relationship between building and nature than other load-bearing materials. Unlike inorganic load-bearing materials which often leave behind toxic and harmful waste, mycelium-bound composite panels that become worn can be removed and decomposed naturally into the environment, without fear of harming the ecosystem. If designed and fabricated with a joinery system that allows for the easy removal and addition of panels, newly created panels are easily installable to restore the structure to its original state and offer new shapes and typologies for mycelium-bound composites.

FIGURE 38: Mycelium folded-plate Summit Pavilion extending the view from the peak of Mt. Tammany. A worn panel is removed and left to biodegrade

FIGURE 39: Two hikers admiring the view from the Summit Pavilion

Braddock Farmer's Market

17. Refer to 5.

This thesis is primarily concerned with improving the flexural strength of mycelium load-bearing elements because it expands the structural typologies that these materials can be built into. Most notably, this includes beam-girder structures as used in this vision of a Farmer's Market across the road from Grow Pittsburgh's Braddock Farms community garden.

Operating in a notorious food desert, the Braddock Farms community garden provides produce and community-centered programs for residents of Braddock and surrounding neighborhoods. The proposed Farmer's Market not only helps provide a place for residents to buy food but also helps educate volunteers and the community about sustainable agriculture and building practices. Constructing this structure out of a column-beam system would help workers who are more familiar with more traditional building materials learn how to work with mycelium-bound composites. To enable the creation of this Farmer's Market, a refined version of the reinforcement strategies investigated in this thesis would be used to improve the flexural strength of the beams and girders, enabling the creation of a safe, sound, and sustainable space for the community.

FIGURE 40: People gathering around the Braddock Farmer's Market. The mycelium-bound composite takes the form of a column-beam structure that invites the community in

Pedestrian Bridge

This vision of a Pedestrian Bridge in Schenley Park uses a shell structure to help visitors traverse the topography of the park. Underpasses are created underneath the bridge to preserve the existing paths and provide shelter during rain. As with the folded-plate pavilion on Mt. Tammany, the use of mycelium-bound composites as a structural material within Schenley Park helps demonstrate the possibilities of a built environment that works with ecological systems instead of being separate from it.

Shell structures are a type of compression-only structure, which mycelium-bound composites are currently good at; however, due to the increase in live loads from real-scale applications, like pedestrians and bikers walking on top of the bridge, reinforcement of the composite will be necessary to ensure the safety and stability of the structure. The use of the reinforcements to improve the performance of this shell structure against live loads, demonstrates how developing strategies to increase the flexural strength of these materials is an important step towards expanding the capacity of mycelium in load-bearing applications.

FIGURE 41: Visitors to Schenley Park using the mycelium Pedestrian Bridge to get around

FIGURE 42: Bikers riding along the top of the Pedestrian Bridge

Summary

The ability to increase the flexure strength of mycelium-bound composites opens up new possibilities for its use as a load-bearing structural material. Current strategies of compressing mycelium composites into panels can allow for the creation of stronger folded plate structures, but the use of successful reinforcement strategies expands mycelium composites to be built as column-beam structures and increase the capacity of compression-only structures like shells to carry live loads. These structures are significantly more sustainable than conventional structural materials due to their biodegradability and ability to consume agricultural waste products as part of their development. Most importantly, mycelium composite structures offer a future in which the built environment has a more harmonious relationship with the natural environment, offering new paradigms of architectural design and engineering.

Chapter 4: Conclusions

Conclusion

The use of mycelium-bound composite materials within structural applications is an important strategy for developing more sustainable ways of building and cultivating a more harmonious relationship between natural systems and the built environment. Growing Confidence attempts to make a step towards this future by interrogating three critical questions:
How can we improve the flexure strength of mycelium composite materials?
What systems can be developed to design optimal reinforcement for mycelium composites?
How can we more reliably create reinforcements for mycelium composites?
Operating under the hypothesis that if we reinforce mycelium-bound composites with 3D-printed reinforcements, then these materials will be able to withstand higher bending loads because the reinforcements will help compensate for mycelium's weakness in tension, this thesis project endeavored to develop systems using digital tools and fabrication to improve the performance of mycelium structural components.

Reinforcements for the samples created during this investigation were designed using Finite Element Analysis to visualize the principle lines of stress within composites. These lines of stress were translated into the geometry of reinforcements that were embedded into mycelium-hemp composites. Additionally, these analysis tools helped inform the placement and distribution of the reinforcements within the test samples. To create a replicable product, the designs for the reinforcements were digitally modeled and 3D-printed with PLA to ensure consistency amongst the parts.

These lines of stress were translated into the geometry of reinforcements that were embedded into mycelium-hemp composites. Additionally, these analysis tools helped inform the placement and distribution of the reinforcements within the test samples. To create a replicable product, the designs for the reinforcements were digitally modeled and 3D-printed with PLA to ensure consistency amongst the parts.

Utilizing three-point flexure testing, the samples were loaded until they failed to evaluate the impact on the bending strength of each reinforcement strategy.

As each reinforced specimen had a lower flexural modulus than the unreinforced samples, the reinforced composite was imaged with a scanning electron microscope to understand how mycelium was bonding to the PLA. The use of both of these techniques allowed for the evaluation of this reinforcement strategy at a macroscopic and microscopic level.

While Growing Confidence did not succeed in increasing the flexural strength of mycelium-bound composites, it developed and showcased a strategy for designing reinforcements for these materials. This strategy of using FEA to generate reinforcement geometry based on the principle lines of stress within the component applies to a wide variety of shapes and sizes, making it a flexible and effective strategy for design. Additionally, the tests this thesis conducted of different offsets during the flexure testing phase strongly suggest that the optimal effective depth for mycelium composite reinforcements is the centroid of the tension curve below the neutral axis of the specimen. Lastly, this series of investigations used graphs, calculations, and microscopic imaging to understand and characterize the effectiveness of using PLA to reinforce mycelium-bound composites. The visualization of the interaction between mycelium and PLA at the microscopic level helps to characterize the challenges for future research into improving the bond between these two materials.

Finite Element Analysis and 3D printing support the digital design workflow this research uses to design and fabricate reinforcements for improving bending strength within mycelium composites.These strategies did not prove effective because of the weakness in the bond between mycelium and PLA. Although we are still a long way from improving the flexural strength of mycelium composites with PLA reinforcement, this research marks a step forward in developing this and other strategies. If these, or other, techniques of reinforcement can be further developed and refined, it opens mycelium composites to a wider range of structural applications which will improve its ability to make an impact on the built environment as an exemplar of sustainable building strategies.

Future Work

Future work is needed to create effective strategies for improving the flexural strength of mycelium-bound composites. The decrease in flexural and compressive stiffness in the reinforced specimens highlights how the weakness of the mycelium-PLA bond is one of the primary factors compromising the effectiveness of this strategy. To do this in the future, if PLA was able to be fabricated in a way that is more microscopically porous, that potentially could allow the mycelium to better penetrate the 3D prints and develop a better bond with the reinforcements.

Additionally, the challenges of bond with PLA prevented a more robust evaluation of the effectiveness of the FEA-derived reinforcement geometries. To evaluate the effectiveness of these strategies, the ability to fabricate the reinforcements out of a material with a higher level of organic content should be tested. Furthermore, beyond 3D-printing, experiments other digital fabrication methods should be conducted to compare other methods of producing these geometries reliably and out of more organic materials.

The ultimate goal of this research is to enable and encourage the use of mycelium composites within large-scale structural applications within the built environment. These structures are at a much larger scale than the samples used in this thesis and other similar research projects. This disparity begs the question– how do these reinforcement strategies scale up? Additionally, if we are able to scale up mycelium structural components, it is important to question at what point does it become to impractical to be a viable solution. It is established that part of mycelium's appeal from a sustainability standpoint is its ability to provide a use for agricultural waste products. However, if the depth-to-span ratio of bending active mycelium structures is too large to effectively grow, or the production of these building components expands to a high level, the manufacturing of mycelium-composites may be too resource-intensive to truly be sustainable.

Lastly, constructing with mycelium requires a different mindset towards replacement, renewal, and active maintenance as part of extending the lifespan of a building or other structure. How can we educate and encourage adoption of new strategies of building component renewal and replacement to facilitate the longevity of mycelium structures?

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Figures

FIGURE 39: Two hikers admiring the view from the Summit Pavilion

FIGURE 40: People gathering around the Braddock Farmer's Market. The mycelium-bound composite takes the form of a column-beam structure that invites the community in

FIGURE 41: Visitors to Schenley Park using the mycelium Pedestrian Bridge to get around

FIGURE 42: Bikers riding along the top of the Pedestrian Bridge