Anatomy of a Living Joint

From Hyphal Networks to Urban Fabrics

compositi a base di micelio
materiali viventi ingegnerizzati
geometria biomimetica
giunti architettonici
stampa 3D

mycelium-based composites
engineered living materials
biomimetic geometry
architectural joints
3D printing

Errichiello, Raffaele[1]

[1] Umeå University, School of Architecture, Umeå, Sweden.
https://orcid.org/0009-0005-6327-3641
raffaele.errichiello@umu.se

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I materiali vivi possono riconfigurare il modo in cui gli edifici si relazionano e si adattano nel tempo. Le connessioni convenzionali si basano su tolleranze strette e adesivi inerti; nei compositi vivi, invece, l'interfaccia può essere progettata come un microclima, in cui geometria, materiale e biologia cooperano. Questo articolo presenta un'indagine progettuale circa un pattern biomimetico ispirato alle superfici di scambio gassoso dei coralli cervello. Attraverso corridoi di ossigeno e aree di umidità per compositi a base di micelio (MBCs) stampati in 3D, la giunzione guida le ife ad attraversare gli elementi e a saldarli. Lo studio si esprime attraverso diverse scale seguendo la logica di *Powers of Ten* di Charles e Ray Eames. Vengono illustrati pattern alla scala del centimetro, gradienti di umidità al millimetro, ife alla scala del micron, forme architettoniche alla scala del metro e reti urbane speculative. L'approccio colloca la geometria all'interno dei più ampi sviluppi nei materiali viventi ingegnerizzati (ELMs) e nelle geometrie di stampa per l'ottimizzazione di prestazioni. Alle scale maggiori, la giunzione suggerisce come gli edifici possano favorire la biodiversità e persino scambiare nutrienti attraverso reti miceliari sotterranee, riecheggiando la *Wood Wide Web*, in cui ife e micorrize connettono gli alberi e facilitano la condivisione di acqua, carbonio e nutrienti. Il focus di questo articolo è sulle implicazioni narrative del progettare con il contest vivente, mostrando come un pattern apparentemente semplice potrebbe influenzare il comportamento del materiale, lo spazio architettonico e le ecologie urbane.

Living materials may reconfigure the way buildings join and adapt. Conventional connections rely on dry tolerances and inert joints; in living composites, the interface can be designed as a breathing microclimate where geometry, material and biology co-operate. This article presents a design-led investigation into a biomimetic pattern inspired by the gas-exchange surfaces of brain corals. By carving oxygen corridors and sheltered moisture wells into 3D printed mycelium-based composites (MBCs), the joint encourages hyphae to cross between elements and weld them without glue. The narrative unfolds across scales following the logic of Charles and Ray Eames' *Powers of Ten*. Centimeter-scale patterns, millimeter moisture gradients, micron-scale hyphae, meter-scale architectural forms and speculative urban networks are illustrated. The approach situates the geometry within broader advances in engineered living materials (ELMs) and performance-aware printing toolpaths. At larger scales, the joint suggests how buildings could foster biodiversity and even exchange nutrients through underground mycelial networks, echoing the *Wood Wide Web* where mycorrhizal hyphae connect trees and facilitate water, carbon and nutrient sharing. The focus of this paper is on the narrative implications of designing with life, showing how a seemingly simple pattern may influence material behavior, architectural space and urban ecologies.

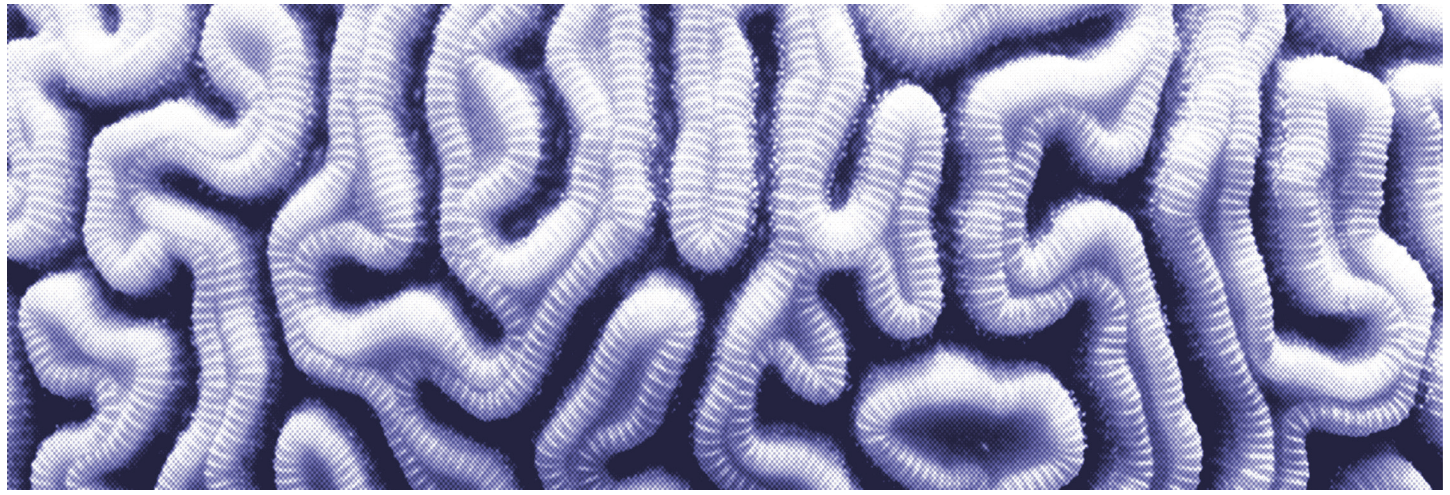

Fig.1 – Brain-coral–inspired reference pattern, showing labyrinthine ridges and channels that inform the reaction–diffusion geometry of the modular 3D-printed joint. Adapted from Adobe Stock.

INTRODUCTION

Architectural joints are typically imagined as mechanical or chemical problems: steel meets concrete through bolts, welds, and mortar; polymers are fused by heat or resin. When working with living composites, the joint can instead be imagined as a generative interface where environmental conditions are tuned so that the material's own biology consolidates the assembly (Nguyen et al. 2018; Elsacker et al., 2023). Mycelium-based composites (MBCs), lightweight solids formed when fungal hyphae bind lignocellulosic particles, are attractive for their thermal and acoustic behavior, self-healing properties and capacity to transform agricultural waste into building components (Appels et al. 2019; Elsacker et al. 2019; Jones et al. 2020; Huang et al., 2024). But their adoption faces challenges: shrinkage during drying, limited stiffness, contamination and the need for oxygenation across thick sections. Recent studies have begun to tackle these issues through material formulation and 3D-printing strategies. In a related study focusing on material behavior and fabrication, we tested biochar-mycelium composites for 3D Printing; we investigated brain coral inspired printing paths to balance porosity and strength, as well as bio-welding of printed segments (Errichiello & Diarte, 2025). Another study, explored similar geometries at pavilion scale, using digital fabrication to create vaulted shells (Errichiello, 2024).

The present investigation asks a complementary question: how does the geometry of the joint allow biological processes across multiple scales? Inspired by corals' ability to maximize surface area for gas exchange, the joint pattern carves corridors and cavities to guide airflow and moisture. In biological systems, a high surface-area-to-volume ratio increases exchange capacity; plant leaves, for example, maximize photosynthesis and gas exchange via thin surfaces, while succulent tissues lower the ratio to retain water (Mauseth, 2000). Coral colonies likewise exhibit morphologies that increase surface area relative to volume and enable efficient diffusion (Stocking et al., 2018). Translating these principles into a joint, we aim to design a functionally graded interface where oxygen diffuses along channels while pockets retain humidity longer, driving hyphal growth (Glass et al., 2000; Neira et al., 2015). Framing the topic within the broader field of engineered living materials (ELM), we use a narrative methodology inspired by the *Powers of Ten* film: the design is analyzed at centimeter, millimeter, micrometer, meter and urban scales to reveal how geometry, material and ecology interrelate (Eames & Eames, 1977).

The research questions therefore become: Can a biomimetic pattern shape the microclimate at the interface of living composites to promote biological welding? How do its implications unfold from microstructure to urban networks?

The contribution of this article is the articulation of a multiscale narrative that situates a living joint within ecological and architectural contexts, complementing technical studies with a broader conceptual lens (Benyus, 1997; Oxman, 2015).

MATERIALS AND METHODS

Biomimicry and pattern inspiration

The joint's geometry draws from *Diploria Labyrinthiformis* (brain coral), whose labyrinthine ridges and valleys increase the colony's exposed surface for respiration and nutrient uptake. Biological systems often adapt morphology to maximize surface area relative to volume for gas exchange (Stocking et al., 2018). Our pattern abstracts this principle: the material mass creates oxygen corridors that allow more oxygenation and faster drying, while in concave wells the humidity persists longer, enabling hyphae to grow a stronger network. The pattern is generated via reaction–diffusion algorithms that mimic natural morphogenesis and produces a network of regions with high and low level of moisture (Kondo & Miura, 2010).

Functionally Graded Material

Functionally graded materials (FGMs) are characterized by variations in composition or

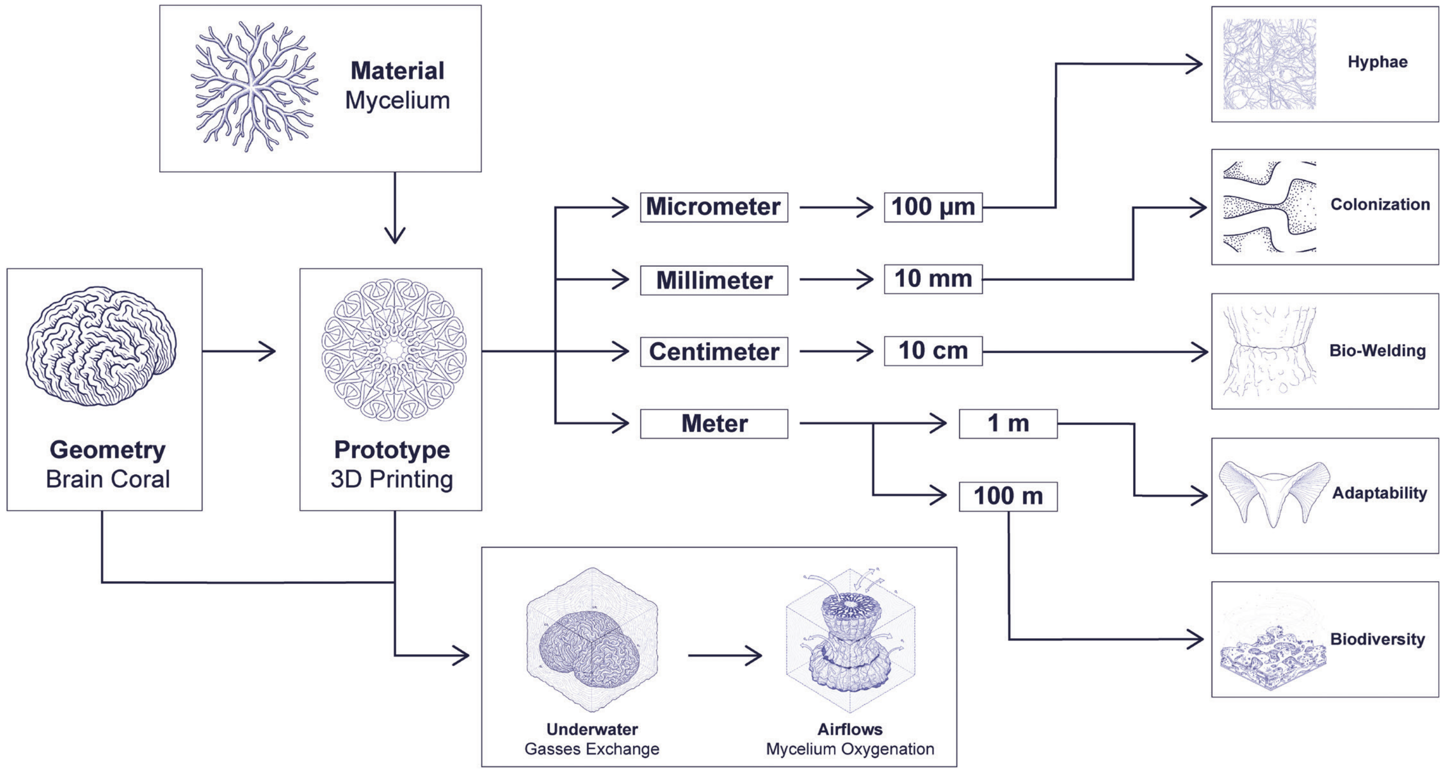

Fig.2 – Methodology inspired by *Powers of Ten*, examining the living mycelium-based joint across scales, from microscopic hyphae to architectural components and urban scenarios.

structure over their volume, producing continuous changes in properties (Suresh & Mortensen, 1998). Translating this concept into geometry, we design an interface where porosity and curvature are graded. Nested cavities keep moisture, allowing hyphae to cross and fuse; towards the edges, channels expand, facilitating airflows (Glass et al., 2000; Fricker et al. 2017). This spatial gradient is not a change in material composition but a variation in geometry that creates differentiated microclimates along the seam. Such functionally graded design echoes natural tissues like bamboo or bone, where gradients in porosity and mineralization support multiple functions (Tan et al., 2011; Rho, Kuhn-Spearing & Zioupos, 1998).

Representation and scale

To explore the joint's behavior across scales, we adopted a visualization method modelled on the *Powers of Ten* (Eames & Eames, 1977). Starting from a 30 cm square representing the joint in plan, we interpret the pattern as if viewed through radiography (centimeter scale). We then zoom in to 30 mm square samples (millimeter scale) where the effects of moisture variations are evident. At the micro-scale, electron microscopy depicts the mycelial hyphae weaving through the substrate. Moving outward, longitudinal sections at component-scale show how the joint perform bio-welding; while conceptual sketches at building-scale imagine people inhabit 3D printed vaulted space with this living composite as a prefabricated pavilion. At the urban scale, exploded axonometric drawings speculate on a cluster of buildings connected by subterranean mycelial networks. Through this methodology, the geometric and material behaviors are analyzed at different scales, as: cell, tissue, bone, body and ecosystem.

RESULTS

Centimeter scale: the pattern as bone

At the centimeter scale, the joint resembles a radiograph of a bone. Figure 3 shows a 30 × 30 cm plan where the printing path defines

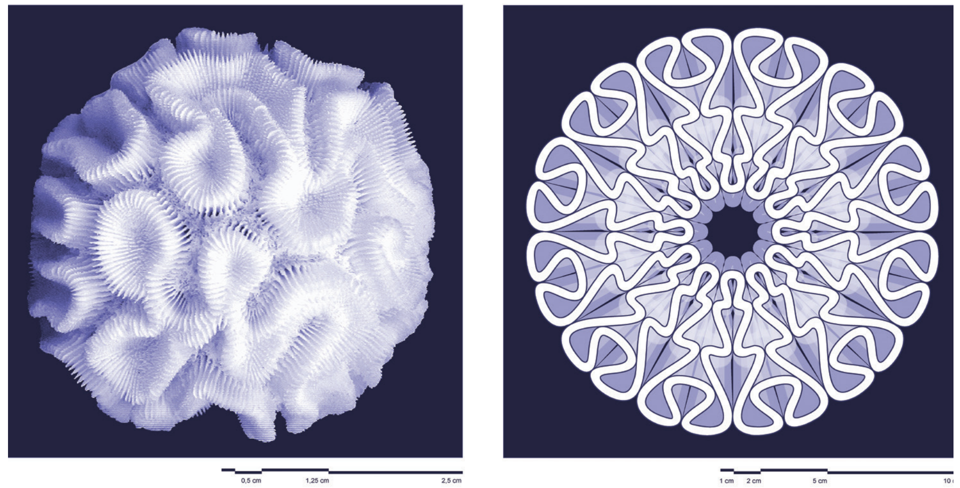

Fig.3 – (Left) Brain Coral top view, it shows its reaction-diffusion pattern. Adapted from NMITA; (Rigth) Centimeter-scale plan of the brain-coral-inspired joint pattern, where reaction–diffusion toolpaths create structural ribs and stacked cavities that increase surface area and enable oxygenation.

a maze-like geometry inspired by brain coral's reaction-diffusion pattern. The continuous white line traces the material deposition, while black areas show porosity. The design achieves multiple functions: the material path act as structural ribs that stiffen the geometry, the porosity regulate moisture, and the overall pattern increases the interface's surface area. The cross-section reveals that the cavities flow also vertically, allowing oxygen to permeate from the top and bottom faces.

Fig.4 – Thirty-millimeter square samples showing the functionally graded material and the moisture fields.

Millimeter Scale: tissue and moisture gradients

Zooming into a 30 mm square region (Fig.4), the pattern becomes a landscape of black and white zones representing porosity levels. During cultivation, mycelium grows faster in moist zones and slower in dry zones. Hyphae proliferate purely in areas more porous, while they form harder bands along the ridges. The design therefore creates a functionally graded environment: moisture and oxygen vary continuously, guiding the biological process. Each sample illustrates a different portion of the joint, to show that the gradient occurs across the geometry's entire perimeter.

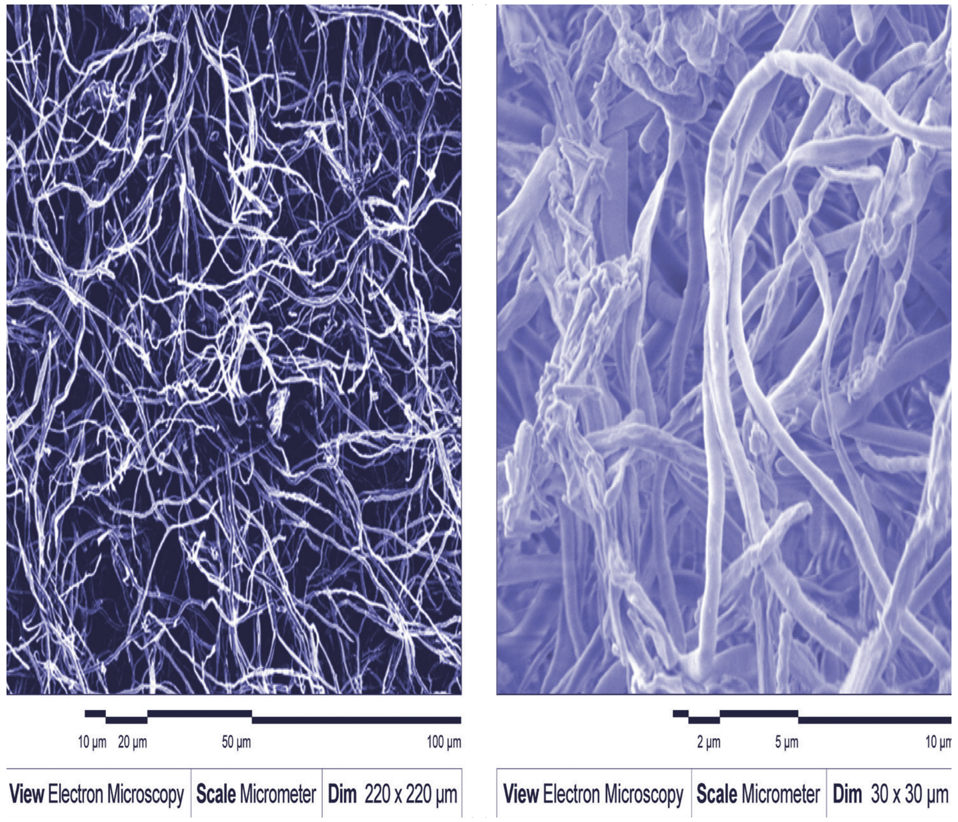

Fig.5 – Hyphae bridging pores in substrates. Adapted from Islam et al., 2017; Motamedi et al., 2025.

Micrometer scale: hyphal networks

At the micrometer scale, scanning electron microscopy (Fig.5) reveals how the intertwined network of hyphae colonizes a substrate. White threads grow across the black voids, bridging particles and weaving the joint together.

Hyphae are tip-growing filaments that fuse when genetically compatible; their *anastomosis* forms a network capable of transporting water, metabolites and signals. Intersections of hyphae mark the points where bio-welding occurs, fusing adjacent elements.

This microscopic view links back to our design objective: by shaping cavities and channels, we influence the microenvironment that hyphae encounter, encouraging them to cross the seam and reinforce the joint.

Cross-sections and biological welding

Figure 6 shows three printed elements brought together. As the composites cure, moisture evaporates from exposed ridges but lingers inside the wells, sustaining a humid microclimate.

Hyphae from both sides extend into this region, weave through the cavities and fuse, creating a continuous network. Once the joint dries, the fungi become inactive, and the seam behaves as a single element.

Longitudinal sections (Fig.7) show how this mechanism repeats along the length of a column. Such biological welding contrasts with conventional junctions: the joint self-organizes and uses the material's own growth to perform the connection.

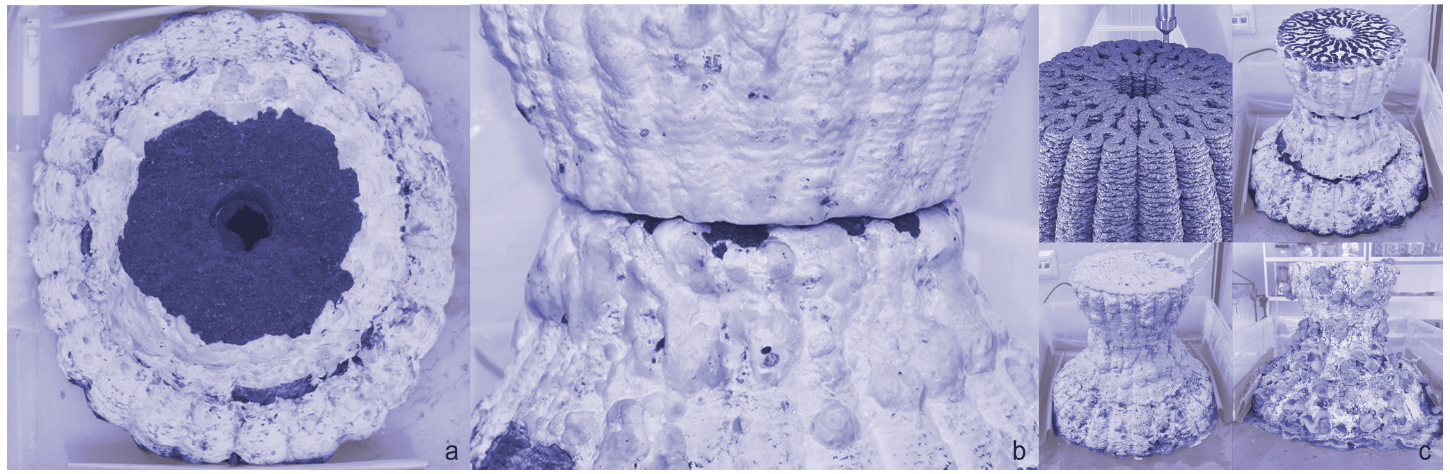

Fig.6 – Process timeline of a 3D-printed mycelium–biochar demonstrator, from fresh extrusion to colonization, biological welding of the seams, and dried element with emerging fruiting bodies.

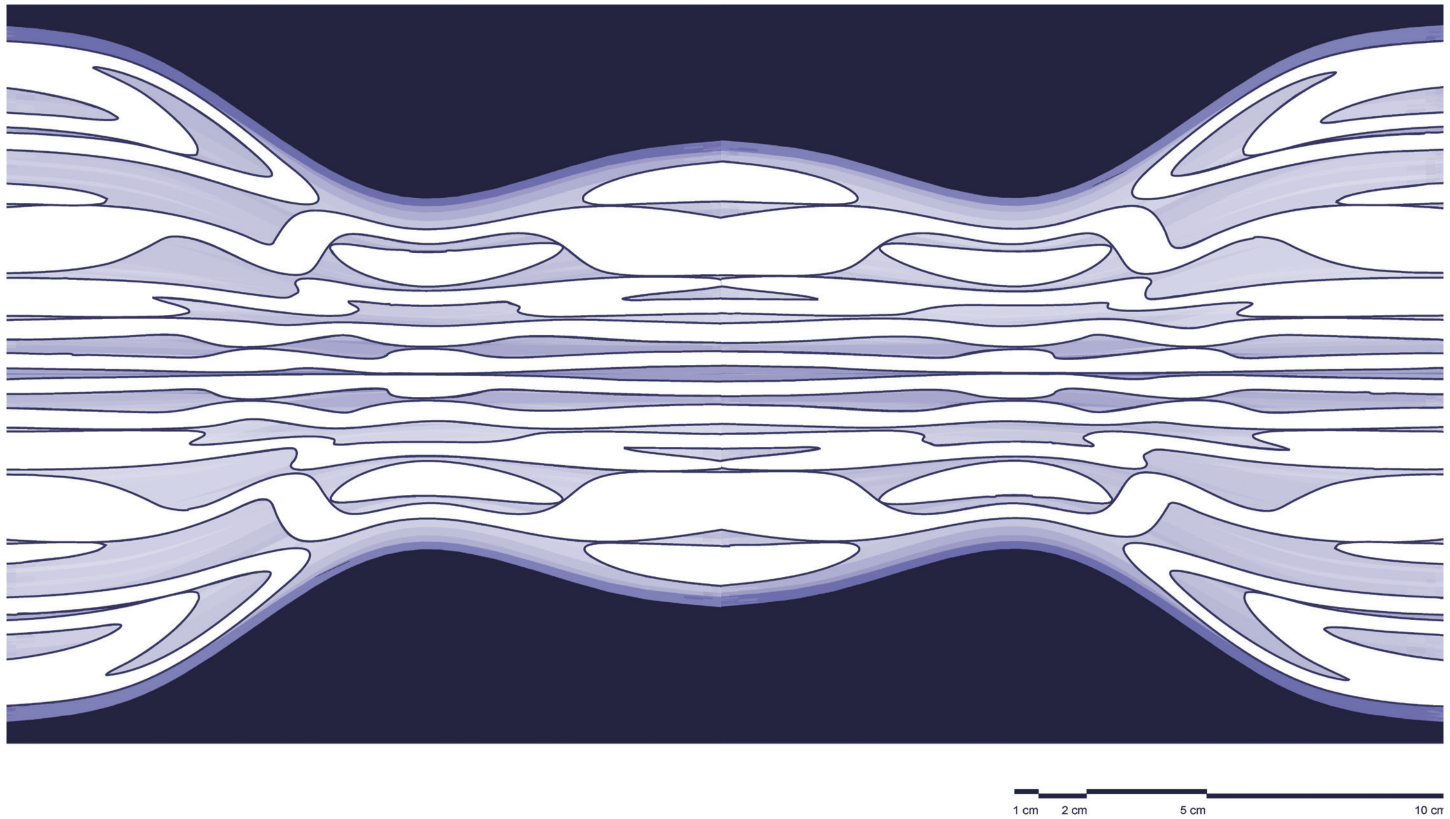

Fig.7 – Longitudinal section along a column showing the repetition of bio-welded seams, which consolidate discrete printed segments into a single structural element.

Meter scale: architectural and urban ecologies

In Figure 8 a section shows a small pavilion where the material and the pattern have been employed trough 3D printing and prefabrication. The design demonstrates the freedom offered by additive manufacturing: complex geometries can be fabricated as segments and bio-welded on site. The final step in our close up look considers clusters of buildings at

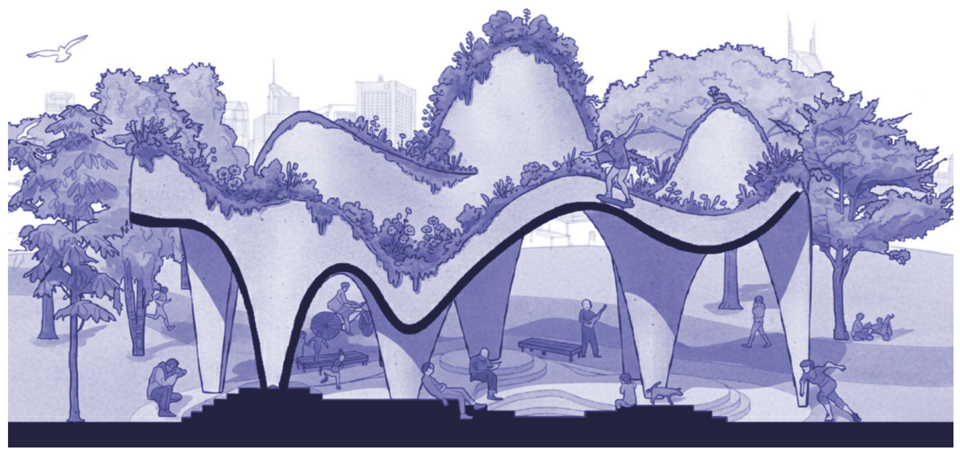

Fig.8 – Section perspective through a small prefabricated pavilion 3D-printed with MBCs, visualizing if living engineered materials may becomes part of inhabitable spaces.

the urban scale. Figure 9 speculates on a neighborhood made of engineered living materials. Each building's facade incorporates the coral pattern, providing niches for algae and cyanobacteria that may form lichens (Honegger, 1991; Cruz & Beckett, 2016; Beckett, 2023). Over time, the facades develop living patinas that photosynthesize, sequester carbon and moderate microclimates. Underground, the mycelium that binds each module extends into the soil. Research on mycorrhizal networks shows that fungal hyphae can connect trees, enabling them to exchange water, carbon and nutrients (Simard et al., 1997; Steidinger et al., 2019; Simard, 2021). If similar networks formed under a district of living buildings, they could share moisture, nutrients or even chemical signals, creating an urban analogue of the Wood Wide Web (Castro-Delgado et al., 2020). Such speculations shift the design problem from isolated components to ecosystems; buildings become nodes in a metabolic network where architecture, biology and ecology intertwine.

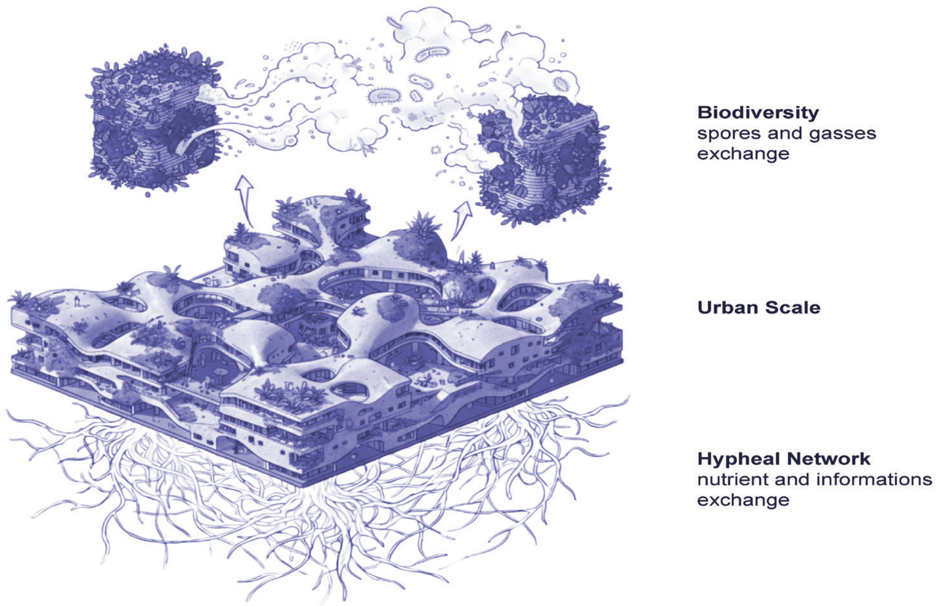

Fig.9 – Exploded axonometric of an urban block with bioreceptive façades above and interconnected mycelial networks below, speculating on buildings as nodes in a shared metabolic and ecological infrastructure.

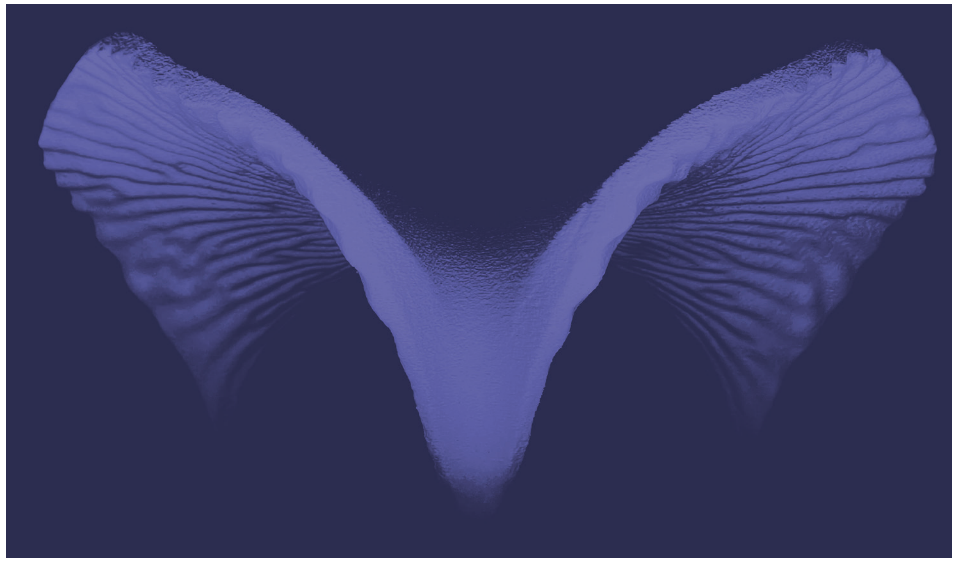

Fig.10 – Speculative modular shell for 3D printing, exploring minimal surfaces and performance-driven printing toolpaths as a prototype for future living structures.

DISCUSSION

This study aims to show how a simple biomimetic pattern may arrange material behavior, structural form and ecological speculation across scales. At the centimeter scale, the geometry manipulates surface area and moisture retention, echoing the biological principle that high surface-area-to-volume ratios enhance exchange (Stocking et al., 2018). At the millimeter and micrometer scales, the functionally graded cavities create microenvironments where hyphae grow, fuse and perform biological welding. These processes rely on the intrinsic capabilities of mycelium to bind and self-heal. At the architectural scale, the same logic could produce complex forms that can be fabricated through 3D printing and assembled via bio-welding. Such forms invite human occupation and non-human colonization, suggesting new typologies where buildings are both habitat and structure.

The urban speculation invites broader reflection. Mycorrhizal networks demonstrate that fungi can interconnect organisms and facilitate resource sharing (Simard et al., 1997; Steidinger et al., 2019; Simard, 2021). If architectural modules grown from mycelium could connect underground, they might exchange moisture and nutrients, stabilise microclimates and enhance biodiversity (Cruz & Beckett, 2016; Cruz, 2017; Beckett, 2023). Facades colonized by algae and cyanobacteria could form lichens; in lichens, fungi protect phototrophs and gather water and minerals while receiving carbon (Honegger, 1991; Nash, 2008). Such symbioses could introduce low carbon footprint construction, as living skins photosynthesize and repair themselves. The pattern also hints at economic and social implications. Using by-products and bio-welding may support local circular economies, reducing reliance on extracted materials and enabling modular prefabrication. The design invites a shift from building as static object to building as process: assemblies can be grown, disassembled and regrown, adapting over time.

While previous research, related to this study, focused on optimizing material formulations and printing parameters to control shrinkage and stiffness, our contribution here is narrative and conceptual: we articulate a multiscale imagination that frames living joints within ecological and cultural contexts. The methodology aims to encourage designers to consider how decisions at one scale ripple across others. The results suggest that carefully designed geometry can harness biological processes not only at the microscale but also at the scale of buildings and cities.

CONCLUSION

The coral-inspired joint shows how geometry can arrange the microclimate at the interface of living composites. By combining oxygen corridors with sheltered moisture wells, the pattern drives hyphal growth to fuse printed segments, turning bio-welding into a spatial design problem rather than an added adhesive. Read through the lens of *Powers of Ten*, the same configuration becomes cell, tissue, bone, body and ecosystem, linking microscopic hyphae to architectural shells and speculative districts woven by fungal networks.

This multiscale narrative complements ongoing technical work on engineered living materials by foregrounding their ecological, spatial and cultural implications. As architecture responds to climate breakdown and resource scarcity, such living joints suggest an alternative paradigm in which buildings are grown from by-products, heal through biological processes and participate in metabolic networks as intricate as those found in forests and reefs.

WORKS CITED

Appels, Frederik V. W., Simone Camere, Maurizio Montalti, Elvin Karana, Kaspar M. B. Jansen, Jan Dijksterhuis, Paul Krijgsheld, and Han A. B. Wösten. 2019. "Fabrication Factors Influencing Mechanical, Moisture- and Water-Related Properties of Mycelium-Based Composites." Materials & Design 161:64–71.

Beckett, Richard. 2023. Probiotic Cities: Rewilding the Built Environment with Microbes. London: UCL Press.

Benyus, Janine M. 1997. Biomimicry: Innovation Inspired by Nature. New York: William Morrow.

Castro-Delgado, Ana Lucía, Stephanie Elizondo-Mesén, Yendri Valladares-Cruz, and William Rivera-Méndez. 2020. "Wood Wide Web: Communication through the Mycorrhizal Network." Tecnología en Marcha 33 (4):114–25.

Cruz, Marcos. 2017. "From Anthropocene to Biocene: The Architecture of Symbiosis." In Fabricate 2017: Rethinking Design and Construction, edited volume. London: UCL Press.

Cruz, Marcos, and Richard Beckett. 2016. "Bioreceptive Design: A Novel Approach Towards Biodigital Materiality." Architectural Design 86(2):90–95.

Eames, Charles, and Ray Eames. 1977. Powers of Ten: A Film Dealing with the Relative Size of Things in the Universe and the Effect of Adding Another Zero. Los Angeles: Eames Office / IBM.

Elsacker, Elise, Simon Vandelook, Joost Brancart, Eveline Peeters, and Lars De Laet. 2019. "Mechanical, Physical and Chemical Characterisation of Mycelium-Based Composites with Different Types of Lignocellulosic Substrates." PLOS ONE 14(7):e0213954.

Elsacker, Elise, Mingxuan Zhang, and Martyn Dade-Robertson. 2023. "Fungal Engineered Living Materials: The Viability of Pure Mycelium Materials with Self-Healing Functionalities." Advanced Functional Materials 33(29):2301875.

Errichiello, Raffaele. 2024. "Aurora: Adaptive Units for Rational, Organic and Resilient Architecture: Form Finding of Biomimetic Minimal Surfaces." In XXVIII Conference of the Iberoamerican Society of Digital Graphics (SIGraDi 2024): Biodigital Intelligent Systems, 2383–2394.

Errichiello, Raffaele, and Julio C. Diarte Almada. 2025. "Biobased Material Confluences: Investigating Material Formulation and 3D Printing Parameters for Biochar-Mycelium Building Composites" In: 7th International Conference on Computational Design and Robotic Fabrication (CDRF 2025): Transindividual Intelligence, Springer Nature, 2025, article ID 355.

Fricker, Mark D., Luke L. M. Heaton, Eliza Jones, and Lynne Boddy. 2017. "The Mycelium as a Network." Microbiology Spectrum 5(3):FUNK-0033-2017.

Glass, N. Louise, Daniel J. Jacobson, and Patrick K. T. Shiu. 2000. "The Genetics of Hyphal Fusion and Vegetative Incompatibility in Filamentous Ascomycete Fungi." Annual Review of Genetics 34:165–186.

Honegger, Rosmarie. 1991. "Functional Aspects of the Lichen Symbiosis." Annual Review of Plant Physiology and Plant Molecular Biology 42:553–578.

Huang, Zicheng, Yaning Wei, and S. Ali Hadigheh. 2024. "Variations in the Properties of Engineered Mycelium-Bound Composites (MBCs) under Different Manufacturing Conditions." Buildings 14(1):155.

Jones, Mitchell, Thomas Huynh, Martin Dekker, et al. 2020. "Mycelium Composites: A Review of Engineering Characteristics and Growth Kinetics." Journal of Bionic Engineering 17(5):1003–1022.

Kondo, Shigeru, and Takashi Miura. 2010. "Reaction–Diffusion Model as a Framework for Understanding Biological Pattern Formation." Science 329(5999):1616–1620.

Mauseth, James D. 2000. "Theoretical Aspects of Surface-to-Volume Ratios and Water-Storage Capacities of Succulent Shoots." American Journal of Botany 87(8):1107–1115.

Nash, Thomas H., ed. 2008. Lichen Biology. 2nd ed. Cambridge: Cambridge University Press.

Neira, José, Mauricio Ortiz, Luis Morales, and Edmundo Acevedo. 2015. "Oxygen Diffusion in Soils: Understanding the Factors and Processes Needed for Modeling." Chilean Journal of Agricultural Research 75(S1):35–44.

Nguyen, Peter Q., Zachary R. Courchesne, Anurag Duraj-Thatte, Patrick Praveschotinunt, and Neel S. Joshi. 2018. "Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials." Advanced Materials 30(19):1704847.

Oxman, Neri. 2015. "Material Ecology." Computer-Aided Design 60:1–21.

Rho, Jae Young, L. Kuhn-Spearing, and Peter Zioupos. 1998. "Mechanical Properties and the Hierarchical Structure of Bone." Medical Engineering & Physics 20(2):92–102.

Simard, Suzanne W., David A. Perry, Melanie D. Jones, David D. Myrold, Daniel M. Durall, and Randy Molina. 1997. "Net Transfer of Carbon between Ectomycorrhizal Tree Species in the Field." Nature 388:579–582.

Simard, Suzanne W. 2021. Finding the Mother Tree: Discovering the Wisdom of the Forest. New York: Alfred A. Knopf.

Steidinger, Christian E., et al. 2019. "Climatic Controls of Decomposition Drive the Global Biogeography of Forest–Tree Symbioses." Nature 569:404–408.

Stocking, James B., Lindsey H. Rippe, Christopher M. Reidenbach, and Stephen G. Monismith. 2018. "The Role of Turbulent Hydrodynamics and Surface Morphology on Heat and Mass Transfer in Corals." Journal of the Royal Society Interface 15:20180448.

Suresh, Subra, and Andreas Mortensen. 1998. Fundamentals of Functionally Graded Materials. London: IOM Communications.

Tan, Ting, Nima Rahbar, Seyed M. Allameh, Samuel Kwofie, Derek Dissmore, Kentaro Ghavami, and Wole Soboyejo. 2011. "Mechanical Properties of Functionally Graded Hierarchical Bamboo Structures." Acta Biomaterialia 7(10):3796–3803.

NOTES

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