# Expanding Academic Boundaries

*Research-to-Practice Pathways in Hybrid Flax-Timber System Design and Construction*

Tzu-Ying Chen[1], Harrison Hildebrandt[2], Otto Lindstam[3], Quentin Chef[4], Rebeca Duque Estrada[5], Oriol Carrasco[6], Christoph Zechmeister[7], Fabian Kannenberg[8], Yanan Guo[9], Achim Menges[10] and Jan Knippers[11]
[1,3,4,9,11]*Institute of Building Structures and Structural Design (ITKE), University of Stuttgart*
[2,5,7,8,10]*Institute for Computational Design and Construction (ICD), University of Stuttgart*
[6]*The Institute for Advanced Architecture of Catalonia (IAAC)*
[1]*tzu-ying.chen@itke.uni-stuttgart.de, 0000-0002-1993-6306*

**Abstract.** Flax fibre-polymer composites (FFPC) present significant potential for sustainable construction, yet adoption remains limited despite advantages in renewability, regional availability, and favourable mechanical properties. This paper examines knowledge dissemination mechanisms through three FFPC-timber hybrid projects of increasing scale: an indoor exhibition installation, a temporary outdoor pavilion, and a permanent structure employing FFPC as primary load-bearing elements. Through material morphology theory and stakeholder integration analysis, the research demonstrates how bidirectional knowledge transfer expands the collective design morphospace. Each project introduced distinct parameters at different stakeholder interfaces: design workshops tested the feasibility of established computational tools for general designers, a collaborative framework development unlocked experimental morphologies, and academia-industry integration translated coreless filament winding methodologies from robotic platforms to conventional industrial machinery. The realisation—validated through full-scale structural testing and long-term monitoring—demonstrates technological readiness while establishing reciprocal opportunities: diversified portfolios for fibre producers, broadened construction market access for composite manufacturers, and regulatory framework influence. These complementary dissemination pathways collectively advance FFPC-timber hybrids from research prototypes toward established architectural practice, shaping the trajectory of bio-based materials in construction.

*HUMANISTIC COMPUTATION AND INTELLIGENCE, Proceedings of the 31st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2026*, Volume 2, 595-604.

**Keywords.** Fibrous Architecture, Flax Fibre-Polymer Composites, Bio-Material Systems, Knowledge Dissemination, Integrative Design Method

## 1. Introduction

Flax has played a pivotal role in the economic and industrial development of Central Europe since the late Middle Ages, primarily through the textile industry and associated trade networks (Keller, 1990). Its historical prominence declined following the introduction of cheaper cotton, which largely supplanted flax in textile production (Kampp, 1939). In the early 20th century, however, flax re-emerged in a novel context, with the first structural applications of flax fibre-polymer composites (FFPC) in aeronautical composites (Baley et al., 2021). Today, although synthetic fibre composites such as carbon fibre-reinforced polymers exhibit superior specific strength and have become the predominant materials in the aerospace sector (Xu et al., 2025), flax fibres offer notable advantages in terms of low cost, renewability, and regional availability (Akhil et al., 2023). Due to their favourable mechanical performance relative to other plant-based fibres, flax fibres have demonstrated potential as load-bearing reinforcements in composite systems and have consequently attracted increasing interest within the automotive industry (Barbhuiya et al., 2025).

Despite its adoption in transportation industries, applications within the construction sector—one of the largest contributors to global carbon emissions—remain limited. Within this context, such materials are predominantly employed in non-structural components, including doors, furniture, and interior acoustic panels (Yan et al., 2014). Recent research on FFPC has demonstrated their potential for application in the built environment through the integration of computational design and fabrication methods (Gil Pérez et al., 2022). Nevertheless, widespread adoption in construction practice has been hindered by limited material and technological familiarity, and as a result, the development and application of these composite systems have largely remained confined to academic research settings. This paper, therefore, investigates the mechanisms of knowledge dissemination embedded within a series of experimental projects, examining how such research-to-practice pathways might be strengthened to facilitate broader implementation of FFPC technologies in the construction industry.

## 2. Coreless Filament Winding in Architecture

Coreless filament winding (CFW), a robotic manufacturing process for filament materials, builds on established industrial filament winding techniques, adapting them for architectural applications that enable material-efficient and geometrically versatile structures. Advancements in the architectural application of FPCs are exemplified by research at the University of Stuttgart. Some examples of CFW include the BUGA Fibre Pavilion (2019) (Zechmeister et al., 2020) and the Maison Fibre (2021) (Dambrosio et al., 2021), both of which employed synthetic materials such as carbon and glass fibres. Subsequent developments have transitioned toward bio-based composite systems, incorporating natural fibres such as flax. Flax offers regional availability in Europe and a significantly reduced environmental footprint. The

LivMatS Pavilion (2020) marks the instance in which FFPC was applied as a structural building component (Gil Pérez et al., 2022).

The three projects examined in this study represent a new approach for FFPC in architecture, in which FFPC is combined with timber to form hybrid structural systems. In contrast to state-of-the-art projects, where FFPC elements predominantly operated under compressive loading, the systems analyzed here employ FFPCs primarily in tension, while timber components carry compressive forces. This complementary load distribution enhances overall material efficiency and structural performance. Moreover, diversifying bio-based resources mitigates challenges associated with material scarcity, environmental impacts, and constraints of growth cycles, supporting a more resilient and sustainable construction paradigm.

## 3. Research Questions

Despite the ecological and structural potentials of coreless-filament-wound FFPC, the method is a relatively recent and lesser-known technique that has not yet achieved mainstream adoption in the construction industry. This raises the question of how novel material systems and construction methods can transition from experimental prototypes within academic contexts to permanent architectural structures. Adoption is constrained by uncertainties in mechanical performance, long-term behaviour, and lack of integration into standard construction guidelines, while the construction industry is generally slow to innovate (Zavari et al., 2016).

Innovation can emerge endogenously within the industry through incremental improvements or exogenously via knowledge transfer from research or other industries. Empirical studies highlight a lack of collaboration between academic researchers and construction practitioners (Hadiwattege & Senaratne, 2018), which limits the dissemination and practical application of new methods. Knowledge remains fragmented, and value assessment is often asymmetric. Two central questions follow: How can collaborative frameworks accelerate the transfer of experimental research into practical construction applications? And how can dissemination be deployed as an active design and research strategy to advance the adoption and further development of FFPC hybrid structural systems?

## 4. Case Studies of Flax-Timber Hybrid Structures

This study evaluates the dissemination strategies of FFPC-timber hybrids in architecture through three case studies led by the authors. The first project involved an exhibition demonstrator and a subsequent design workshop with architecture students. The second project consisted of a year-long master's program studio with 25 students collaboratively designing and constructing a research pavilion from material research to assembly. The third project represents the first permanent structure using FFPC-timber hybrid as the primary structural material, aiming to integrate academic research with local construction industries.

### 4.1. LIVING PROTOTYPES

The Living Prototypes exhibition showcased a flax-timber hybrid structure developed through a collaboration among three research teams from different Universities, exploring resource-efficient, digitally fabricated living spaces that utilise bio-based materials such as flax, earth, and bioplastics. The exhibition presented these results as an immersive living space installation composed of three interconnected elements (Figure 1a), with the flax-timber hybrid slab system exemplifying the structural potential of FFPCs.

The slab integrates principles from lightweight suspended structures, channelling forces primarily in tension through the fibre network. Off-the-shelf three-ply timber plates serve as the main load-bearing elements, while a newly developed winding pin geometry accommodates complex fibre angles, reducing kinking and stress concentrations. The pre-assembled timber frame serves as a stay-in-place winding frame, eliminating the need for custom steel forms and allowing for flexible geometry and anchor placement. By combining material insights, interface design, and fabrication strategies, the project advances a point-supported hybrid slab workflow. Integrated with earthen vertical supports, it demonstrates new potential for structural expression and regenerative construction, extending beyond conventional architectural typologies.

Following the exhibition, a workshop was conducted to evaluate and refine the digital tool for designing hybrid timber-flax slab systems. 20 architecture students participated (Figure 1b), most with experience in parametric design and 3D-printed earthen construction, but limited familiarity with fibre-reinforced hybrid assemblies. Using a Grasshopper-based design tool (McNeel Associates, 2023), participants implemented fibre pattern generation within predefined slab boundaries and support points (Figure 1c). An optimisation module allowed users to specify permissible support ranges and provided immediate structural feedback, identifying support locations that maximise geometric stiffness under a distributed vertical load of 2 kN/m², thereby informing integration with 3D-printed earthen wall systems.

The workshop showcased the tool's capability in designing an FFPC-timber hybrid slab, demonstrating that with minimal instruction, participants could engage with materially informed, structurally responsive design processes. While the tool does not generate new system logics, the experiment highlights its role as a mediator between computational logic, material behaviour, and architectural application, underscoring the value of interactive digital tools in disseminating knowledge and enabling broader engagement with hybrid natural-fibre construction techniques.


*Figure 1. (a) Living Prototypes Exhibition, 2022, © Erik-Jan Ouwerkerk; (b) Hybrid material system design workshop; (c) Hybrid slab design outcome of digital tool, adapted from design workshop, 2022, © IAAC*

## 4.2. ITECH RESEARCH PAVILION 2024

The ITECH Research Pavilion 2024 emerged through a collaborative, bottom-up design process involving researchers and students with diverse disciplinary backgrounds. While focused on FFPC-timber hybrids, the studio deliberately avoided prescriptive methods; instead, design, fabrication, and analysis approaches were co-developed through iterative experimentation and prototyping. Initial exercises built material intuition by exploring the dynamics of combining flax fibres and timber into hybrid systems. Parallel upskilling seminars and workshops introduced computational frameworks for material-informed design, digital fabrication, and form-finding, providing the basis for integrative experimentation. Students rotated through specialised technical groups, allowing knowledge circulation in computational design, fabrication, and material testing across the cohort. Through systematic parameter collection and testing, the team collectively defined a computational and material design space, from which the final hybrid system evolved.

The materialisation of the pavilion served as a critical demonstration and verification testbed, evaluating design logic, fabrication method, and system performance under real-world conditions. The pavilion was realised through a combination of robotic milling, cutting, and CFW. Fabrication was primarily executed by the team, with external support for CNC milling of timber plates and crane-assisted on-site assembly (Figure 2a). The joint fabrication process served not only as production but as an extension of the design research process. The team collectively addressed unforeseen challenges related to robot reach, fibre slippage, and tolerance management, iteratively fine-tuning design details and protocols. This problem-solving generated a deeper understanding of the material system behaviour and further refined the design system. Installed in a public university park (Figure 2b), the pavilion served as a publicly accessible research demonstrator, making the research tangible to broader audiences. Situated in a central campus location, the project embedded academic research within an active public environment, inviting spontaneous feedback on materiality, sustainability, and the aesthetic language of fibrous architecture while serving as a pedagogical model for public research demonstration.

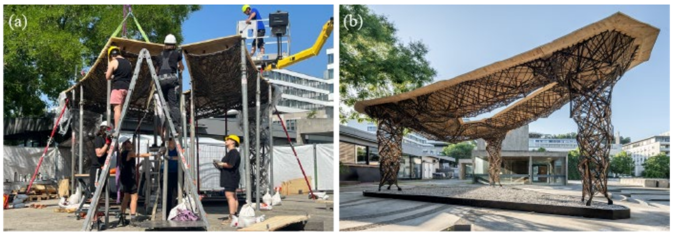



*Figure 2. (a) Construction process of the research pavilion; (b) Finalised pavilion in the public university park. © ICD/ITKE 2024*

## 4.3. HYBRID FLAX PAVILION

The Hybrid Flax Pavilion is the first permanent structure incorporating FFPC-timber hybrid components as primary structural roof elements (Figure 3a). The 380 m$^2$ pavilion features an undulating roof composed of 44 components, including 20 FFPC-timber hybrid beams with spans of approximately 8.3 m (Figure 3b). Realisation was enabled through digital prefabrication workflows and collaboration between regional timber and composite manufacturers located within 200 km of the final building site. The development of the FFPC component was achieved in three phases: research prototyping, technological integration, and industrial production. Initial prototyping was conducted in-house using a robotic filament winding fabrication platform (Figure 3c), while the subsequent phases were executed at an industrial composites manufacturer using a traditional filament winding machine (Figure 3d).

Collaboration with the industry partner marks the first production of FFPC components at this scale and complexity on a traditional lathe-type filament winding machine. This achievement required developing a bespoke computational workflow that adapts RCFW methodologies for lathe-type machines. The workflow translates geometric design and robotic fabrication data into industrial machine-compatible tool paths, packages data in an agreed-upon exchange format, and executes motion commands directly on the industrial controller using multi-file control program architecture. This novel programming and control strategy extended the existing machine capabilities to unlock previously unattainable component morphologies, utilising existing industrial infrastructure with minimal hardware modifications.

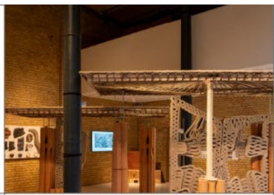
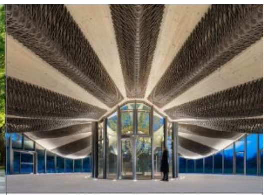

*Figure 3. Hybrid Fiber Pavilion (a) Exterior view showing the undulating roof; (b) Interior view showing fibre bodies of the hybrid roof elements; (c) Robotic prototyping of component in research context; (d) Production winding of component in industrial context using conventional filament winding machine © IntCDC University of Stuttgart*

## 5. Discussion

### 5.1. MATERIAL MORPHOLOGY AND STAKEHOLDER INTEGRATION

Material morphology views materialisation as an active driver of form rather than a result of predefined geometry. Across three projects, FFPC structures expanded this *morphospace* (Ahlquist, 2016) by exploring parameters emerging at the interfaces of design, fabrication, and assembly (Table 1). The stakeholders' engagement with the projects introduces a set of influential parameters whose impact on the design morphology varies according to the stage at which they are integrated into the process. The Living Prototypes component employed a top-down approach with predetermined material allocation, utilising timber to form compression plates and ridges and FFPC to form tensile suspension elements. A design workshop evaluated the robustness of the geometry-generation tool, involving participants with no prior knowledge of the material or structural system. The workshop outcomes introduced layout variations and optimised support locations. Yet despite these variations, the underlying system logic and overall morphological framework remained unchanged.

Table 1: Comparative overview of project characteristics across three FFPC-timber hybrid implementations © Erik-Jan Ouwerkerk and IntCDC University of Stuttgart

| |  |  |  |
|---|---|---|---|
| Name | Living Prototypes | ITECH Research Pavilion | Hybrid Flax Pavilion |
| Year | 2022 | 2024 | 2024 |
| Use | Exhibition | Research Pavilion | Building Demonstrator |
| Lifespan | Temporary | Temporary | Permanent |
| Materials | Clay / Fibre+Timber | Fibre + Timber | Steel + Fibre + Timber |
| Collaboration Type | Workshop + Exhibition | Master Studio + Research | Industry + Research |
| Collaborators | Master Students + Researchers | Master Students + Researchers | Industrial Manufacturing Specialists + Researchers |

The ITECH Research Pavilion design engaged students and researchers through fundamental knowledge transfer in materials, structure, and fabrication. This participatory framework enabled students to contribute to the design of the development tool itself, fostering bottom-up processes where neither system geometry nor logic was predetermined. The structural system emerged from an exploration of parameters and interrelationships across multiple stakeholder interfaces. Consequently, the design manifests as a materially informed structural system where timber and flax fibre allocation and orientation are liberated from conventional building typologies, governed instead by structural tendencies and digital fabrication *morphospace* parameters.

On the other hand, the Hybrid Flax Pavilion combined a high degree of early design freedom in the hybrid system logic development with progressively reduced flexibility to meet building regulations, construction detailing, and budget constraints. Once defined, the system underwent a rationalisation process to streamline fabrication and reduce costs. The academia-industry gap was bridged through the direct integration of research developments into industrial infrastructure. Project complexity, combined with industrial expertise, defined the achievable *morphospace* of the hybrid component.

## 5.2. PROJECT SCALE AND RESEARCH INTEGRATION

While student workshops and temporary installations provide valuable platforms for testing experimental concepts and novel materials, the Hybrid Flax Pavilion extends this research to a permanent building, demonstrating the feasibility of using advanced FRPCs at an architectural scale. Ensuring practical viability required strategic design decisions. Despite the roof's geometric complexity, all fibre components shared an identical geometry, streamlining fabrication and structural verification. Given the unconventional use of biomaterials in load-bearing applications, three full-scale hybrid components were tested for instantaneous, long-term, and cyclic loading to validate system integrity. Beyond the primary structure, the permanent building integrates essential architectural systems, including façades, insulation, waterproofing, electrical, and HVAC installations. Extended lifespan requirements and collaboration with industry partners and contractors demonstrate the practical reliability and integrability of the system. An embedded long-term monitoring system enables continuous collection of performance data, providing empirical insight into material behaviour and validating the applicability of FRPC in load-bearing architecture.

## 5.3. BEYOND PROTOTYPING

### *5.3.1. From academia to industry*

Academic research operates within an exploratory and iterative framework characterised by a comparatively high tolerance for uncertainty and error, driven by knowledge generation rather than profit. In contrast, industrial practice prioritises reliability, reproducibility, and financial viability. Although the overall rate of innovation within the construction industry remains relatively low (Zavari et al., 2016), the Hybrid Flax Pavilion highlights an emerging exception. Following demonstrations of sufficient technological readiness, large-scale FPC manufacturers have shown a willingness to engage with architectural applications as a means to diversify their product portfolios while maintaining acceptable levels of risk.

For fibre producers, novel applications establish new product lines, diversifying offerings across industries and geographic markets. For composite manufacturers, new component typologies and technical methodologies enable entry into previously underrepresented sectors, particularly construction. Increased project implementation, as demonstrated here, provides opportunities to influence regulatory frameworks, including building system certifications, potentially accelerating the adoption of sustainable construction practices.

### *5.3.2. Dissemination as a 2-way process*

While knowledge transfer can take many forms, studies show that compared to isolated mechanisms, integrated strategies combining multiple dissemination modes proved to be more effective (Hadiwattege & Senaratne, 2018). The present paper exemplifies active dissemination wherein researchers adopted end-user perspectives, tailoring content and delivery to specific audiences: established professionals, workshop students, and master's students. This contrasts with passive dissemination through exhibitions or academic publications alone. All three projects contribute to education and skill transfer, preparing practitioners to adapt these techniques beyond academic contexts. Critically, dissemination operates bidirectionally: external interaction prompts researchers to revisit assumptions and methods. In the Living Prototypes project, the interface between research institutes focusing on different material systems increased the design flexibility in flax-clay joints and system layouts. In the ITECH Research Pavilion, students from diverse disciplines directly contributed multidomain knowledge to the research framework.

The Hybrid Flax Pavilion exemplifies integration between industry and academia through bi-directional knowledge exchange. Collaboration yielded a novel computational and machine-control workflow enabling previously unproducible component geometry. For research, an industry partnership provided fabrication-informed design feedback reflecting established manufacturer constraints. For the industry, collaboration unlocked new morphological capabilities without substantial infrastructure modification. The resulting computational workflow serves as an integrated tool for design, path planning, simulation, and motion control applicable to future research and industrial production.

### *5.3.3. Lightweight modularity*

Comparison across the three flax-timber typologies indicates that modularity strategies are critical determinants of system scalability, adaptability, and practical implementation. From an industrial perspective, segmentation enables standardisation, transportability, and reduced fabrication risk, critical factors for broader adoption. For architects, segmentation extends beyond practicality; it becomes a design language that governs the rhythm, articulation, and expressive capacity of the system. The challenge lies in achieving modularity that increases versatility without reducing the system to prefabricated kits. Situated along a continuum between material expressiveness and industrial modularity, discretisation defines both structural logic and architectural agency. Future development should explore adaptive segmentation strategies that maintain design flexibility while establishing sufficient standardization for practical implementation, enabling these hybrid systems to transition from research prototypes to viable architectural building systems across diverse applications.

## 6. Conclusion

This paper examined the development of FFPC-timber hybrid systems across three projects of increasing scale and impact. These case studies demonstrate how material morphology, project scale, and stakeholder integration collectively expand the design morphospace of bio-based composite construction. Each project introduced distinct parameters at different stakeholder interfaces, enabling translation of CFW methodologies from research platforms to conventional industrial machinery. While these projects employ divergent approaches, from component prototyping to temporary pavilions to permanent structures, each strategy offers distinct value in disseminating bio-based composite construction. Temporary installations demonstrate system integration and public engagement; participatory design studios unlock generative design possibilities, yielding unprecedented experimental morphologies; permanent structures validate long-term performance and regulatory compliance. Collectively, these complementary pathways contribute essential knowledge, technical capabilities, and demonstrated precedents that shape the trajectory of bio-based materials in construction, moving FFPC-timber hybrids from experimental research toward established architectural practice.

## Acknowledgements

This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618.

The authors express their gratitude to fellow investigators Gregor Neubauer, Renan

Prandini, Christoph Schlopschnat, as well as Monika Göbel, Marta Gil Pérez, Valentin Wagner for their technical and intellectual support. Additionally, we extend our appreciation to Dnyaneshwari Mete, Nestor Beguin, and Huanyu Li for their passion and engagement in the workshop.

## References

Ahlquist, S. (2016). Sensory material architectures: Concepts and methodologies for spatial tectonics and tactile responsivity in knitted textile hybrid structures. *International Journal of Architectural Computing*, *14*(1), 63–82. https://doi.org/10.1177/1478077115625525

Akhil, U. V., Radhika, N., Saleh, B., Aravind Krishna, S., Noble, N., & Rajeshkumar, L. (2023). A comprehensive review on plant-based natural fiber reinforced polymer composites: Fabrication, properties, and applications. *Polymer Composites*, *44*(5), 2598–2633. https://doi.org/10.1002/pc.27274

Baley, C., Bourmaud, A., & Davies, P. (2021). Eighty years of composites reinforced by flax fibres: A historical review. *Composites Part A: Applied Science and Manufacturing*, *144*, 106333. https://doi.org/10.1016/j.compositesa.2021.106333

Barbhuiya, S., Das, B. B., Kapoor, K., Das, A., & Katare, V. (2025). Mechanical performance of bio-based materials in structural applications: A comprehensive review. *Structures*, *75*, 108726. https://doi.org/10.1016/j.istruc.2025.108726

Dambrosio, N., Zechmeister, C., Estrada, R. D., Kannenberg, F., Gil Pérez, M., Schlopschnat, C., Rinderspacher, K., Knippers, J., & Menges, A. (2021). Maison Fibre: 2021 Association for Computer Aided Design in Architecture Annual Conference, ACADIA 2021. *ACADIA 2021: Realignments*, 270–279. https://doi.org/10.52842/conf.acadia.2021.270

Gil Pérez, M., Guo, Y., & Knippers, J. (2022). Integrative material and structural design methods for natural fibres filament-wound composite structures: The LivMatS pavilion. *Materials & Design*, *217*, 110624. https://doi.org/10.1016/j.matdes.2022.110624

Hadiwattege, C., & Senaratne, S. (2018). *Dissemination of academic research knowledge to construction industry: Insights from knowledge management literature*.

Kampp, A. H. (1939). Geography of the Fiber-Flax Industry. *Economic Geography*. https://www.tandfonline.com/doi/abs/10.2307/141425

Keller, K. W. (1990). From the Rhineland to the Virginia Frontier: Flax Production as a Commercial Enterprise. *The Virginia Magazine of History and Biography*, *98*(3), 487–511.

Xu, X., Peng, G., Zhang, B., Shi, F., Gao, L., & Gao, J. (2025). Material performance, manufacturing methods, and engineering applications in aviation of carbon fiber reinforced polymers: A comprehensive review. *Thin-Walled Structures*, *209*, 112899. https://doi.org/10.1016/j.tws.2024.112899

Yan, L., Chouw, N., & Jayaraman, K. (2014). Flax fibre and its composites – A review. *Composites Part B: Engineering*, *56*, 296–317. https://doi.org/10.1016/j.compositesb.2013.08.014

Zavari, M., Mortaheb, M. M., & Kashani, H. (2016). Barriers to New Technology Dissemination in the Construction Industry. *Proceedings of International Structural Engineering and Construction*, *3*(1). https://doi.org/10.14455/ISEC.res.2016.23

Zechmeister, C., Bodea, S., Dambrosio, N., & Menges, A. (2020). *Design for Long-Span Core-Less Wound, Structural Composite Building Elements* (pp. 401–415). https://doi.org/10.1007/978-3-030-29829-6_32