Hybrid Weaving Processes

Reinterpreting traditional weaving techniques through digital fabrication for architectural willow-jute hybrid building elements

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This research explores the integration of traditional weaving techniques with digital design and robotic fabrication to produce architectural willow-jute hybrid elements. By addressing the heterogeneous nature of rapidly renewable materials, the study establishes an iterative digital-physical workflow, where fabrication constraints influence computational models. To balance craft-based intuition with algorithmic control, custom design automation tools, fabrication simulations, and a robotic end-effector are developed to enhance scalability and feasibility. The system was tested through the fabrication of full-scale modules, incorporating different weaving strategies to evaluate how fiber placement and geometry affect stability performance. A simplified load test was conducted to compare the dimensional stability and stiffness of the components, providing early insights into their potential as reinforcement in hybrid construction systems. This approach demonstrates how hybrid construction methodologies can transform material limitations into design opportunities, advancing sustainable and scalable solutions utilizing rapidly renewable natural construction materials.

Keywords: *Hybrid Weaving Processes, Natural Fibers, Robotic Fabrication, Traditional Weaving Techniques, Material-Driven Design, Sustainable Architecture, Craftmanship, Automation, Digital Craft*

INTRODUCTION

The construction industry is increasingly exploring sustainable fabrication methods that reduce environmental impact and enhance material efficiency (Çetin, De Wolf and Bocken, 2021). Building using natural materials offers significant advantages due to their renewability and low-carbon footprint, but their integration into construction processes presents multiple challenges (Heisel, Hebel and Webster 2022). Recent advancements in sustainable construction using digital fabrication have been led by different institutions and research groups exploring novel ways to integrate natural materials with computational design and fabrication. The Institute for Computational Design and Construction at the University of Stuttgart has developed computational design strategies that bridge hybrid natural material components with digital fabrication, demonstrating innovative applications of bio-based materials in robotic manufacturing processes (Dambrosio et al., 2024). Similarly, the department of Experimental and Digital Design and Construction at the University of

Kassel has focused on experimental and digital construction methods, exploring new paradigms for integrating material properties, structural calculations, and fabrication technology within computational design processes (Eversmann and Rossi, 2024; Lienhard and Eversmann 2020). The Karlsruhe Insitute of Technology has further expanded the field by developing computational and robotic workflows that accommodate the inherent variability of natural materials, emphasizing the scalability of bio-based construction techniques (Olah, Zareian and Dörstelmann, 2025).

This research explores the intersection of traditional weaving techniques, digital design, and robotic fabrication to develop a hybrid willow-jute weaving methodology. By leveraging computational workflows, the developed method reinterprets the manual interlacing of natural fibers into a digitally controlled process, allowing for automated fabrication and scalable implementation. An adaptive and iterative approach is implemented to translate material constraints into design drivers, enabling component fabrication feasibility and repeatability despite the inherent heterogeneity of willow & jute fibers.

A key aspect of this study is the integration of hybrid weaving within robotic fabrication workflows to fabricate willow-jute hybrid modules with controlled geometric properties. This process is supported by the development of custom digital tools, parametric algorithms, and a robotic end-effector, which facilitate the placement and assembly of fiber structures.

By engaging with the challenges of material variability, digital fabrication, and automation, this research aims to offer an initial contribution towards the development of hybrid fabrication systems using willow-jute fiber reinforcements. The findings suggest potential applications in architectural design, large-scale digital construction, and the broader integration of sustainable materials within contemporary construction practices.

MATERIALITY

The integration of willow and jute into robotic weaving processes demands a careful evaluation of their mechanical behavior, geometric variability, and process compatibility within digital fabrication workflows. This research employs willow as the primary reinforcement element due to its high tensile strength, structural stability, and rapid renewability, making it a viable alternative to non-natural reinforcements in sustainable construction. However, its inherent stiffness and limited pliability pose significant challenges in an automated weaving process, particularly when subjected to a small bending radius.

To mitigate these limitations, jute was incorporated as a complementary material due to its higher flexibility, ability to accommodate complex curvatures, and capacity to function as an interlocking agent within the woven assembly. The high tensile strength and adaptability of jute allows it to effectively reinforce the perimeter of woven modules, providing dimensional stability and reducing stress concentrations that would otherwise lead to fiber rupture in high-curvature zones. The synergy between willow's rigidity and jute's pliability results in a hybridized material strategy that improves fabrication feasibility and component consistency.

A bending test was conducted to evaluate the maximum horizontal deflection of willow samples prior to rupture. Each specimen was clamped at one end, and the free end was gradually displaced laterally until breakage occurred. To simulate the conditions experienced by the willow during robotic weaving two sections were tested: the basal segment (0–70 cm), corresponding to the thicker and more rigid portion of the branch, and the mid-to-distal segment (70–140 cm), which is slightly thinner. These areas were selected as they typically present the greatest challenges in the weaving process due to friction and limited pliability. To quantify curvature, a perpendicular photograph was taken during each bending test, and a 250 mm

segment from the most curved region of the arc was analyzed to extract the radius of curvature. Although the procedure does not follow a standardized curvature analysis protocol, the results served to compare pliability across different willow specimens and types informing the design of curvature constraints within the robotic weaving process (See Table 1).

Table 1
Willow bending test

Plant Specimen	Full Branch Length (cm)	Average diameter (mm)	Break point distance from fixed point (cm)	Bending Radius (mm)	Curvature (mm^{-1})
Salix fragilis "Belgian Red" Specimen 1 [70 - 140 cm]	215	4,2	29	93	0,0108
Salix fragilis "Belgian Red" Specimen 1 [0 - 70 cm]	215	6,8	41	121	0,0083
Salix fragilis "Belgian Red" Specimen 2 [70 - 140 cm]	220	5,0	40	114	0,0088
Salix fragilis "Belgian Red" Specimen 2 [0 - 70 cm]	220	6,7	42	110	0,0091
Salix alba Specimen 1 [70 - 140 cm]	220	4,2	38	98	0,0102
Salix alba Specimen 1 [0 - 70 cm]	220	5,7	46	110	0,0091
Salix alba Specimen 2 [70 - 140 cm]	216	4,2	36	105	0,0095
Salix alba Specimen 2 [0 - 70 cm]	216	6,2	49	119	0,0084
Salix purpurea Specimen 1 [70 - 140 cm]	225	4,2	33	94	0,0106
Salix purpurea Specimen 1 [0 - 70 cm]	225	6,6	39	101	0,0099
Salix purpurea Specimen 2 [70 - 140 cm]	222	4,7	28	95	0,0105
Salix purpurea Specimen 2 [0 - 70 cm]	222	6,5	43	115	0,0087

Additionally, softening techniques such as water soaking and steam bending were considered to enhance willow's pliability. However, while prolonged water immersion facilitates increased flexibility, it introduces significant time constraints incompatible with an unplanned iterative testing process. Conversely, steam bending enables accelerated willow softening within a controlled high-humidity thermal chamber, achieving optimal malleability in approximately one day. Despite its effectiveness, this approach was ultimately deemed unsuitable due to its high energy consumption and consequent carbon footprint, contradicting the project's sustainability objectives.

Given these constraints, the design of each component prioritizes smooth and continuous geometries, avoiding sharp angles or abrupt changes in curvature throughout the structure. Rather than addressing these material limitations via complex technical interventions, the approach focused on developing a geometry-informed design process. By systematically analyzing willow's inherent bending behavior, the component geometry was adapted to align closely with the willow's natural flexibility, significantly reducing stress concentrations. Through iterative computational modeling and physical prototyping, the design was refined to accommodate the willow's mechanical constraints organically, allowing the fibers to follow continuous curves that prevent breakage and deformation during robotic deposition.

Furthermore, a unidirectional robotic weaving strategy was developed to minimize stress-induced fiber rupture while preserving the structural integrity of the willow elements. This method enables a more reliable and continuous willow deposition process, minimizing interruptions and enhancing overall consistency.

FABRICATION PROCESS

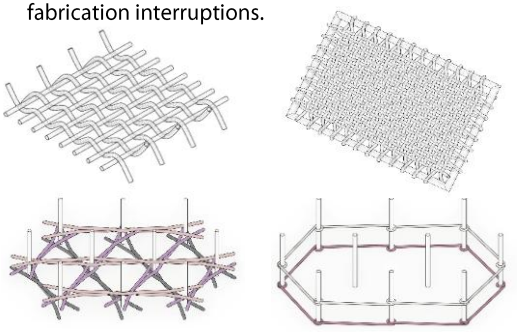
The selection of an appropriate weaving technique for robotic fabrication required a systematic analysis and abstraction of existing interlacing methods to develop a strategy that aligns with digital construction constraints, material properties, and automation feasibility. This research explores the geometric logic of traditional weaving processes, adapting them into a format suitable for computational workflows and robotic execution based on a fixed framework made of vertically arranged wood poles, which serve as the weaving

frame and establish fixed points for interlacing the woven structure.

Through this process, the chosen weaving strategy draws from both warp-and-weft weaving and wicker weaving techniques, each informing a different aspect of the hybrid fabrication process. Warp-and-weft weaving served as the basis for the placement of the willow, in which the fixed framework of vertically arranged wooden poles functions as the warp, or the static support, while willow branches act as the weft, the active interlacing elements. The willow fibers are deposited in a layer-by-layer sequence, interlacing around the wood poles to create the woven structure.

Wicker weaving, on the other hand, inspired the integration of jute into the system. In this case, jute yarn, a more flexible and finer material, is woven around the same wooden framework in a manner similar to traditional wickerwork, where a pliable material wraps around a rigid frame to form a structured surface or boundary. The jute encircles the vertical poles, reinforcing the perimeter of the modules and enhancing their dimensional stability. This complementary weaving approach enables the creation of a hybrid structure in which willow provides the primary tensile resistance, while jute enhances edge cohesion and mitigates deformation across the assembly. A key objective of this strategy is to anticipate material behavior in order to establish a continuous weaving process reducing fabrication interruptions.

Figure 2
Wicker & warp-and-weft weaving techniques



a) Warp-and-weft weaving (Willow weaving technique)

b) Wicker weaving (Jute weaving technique)

The fabrication strategy adopts a modular approach in which the inherent imprecisions and deviations associated with natural fibers are accommodated through an iterative design–fabrication–testing process. To reduce the reliance on auxiliary fabrication elements, the computational workflow introduces a geometric standardization method that reconfigures each input geometry into a parametric grid of equilateral triangles. The edge length of these triangles is variable and can be adjusted based on the desired resolution of the woven structure.

This resolution is informed by incremental material testing, particularly focused on frictional behavior between the willow branches and the wooden poles, as well as the operational constraints identified through iterative testing of the robotic end-effector during the weaving process. The custom dual-function end-effector designed specifically for handling both willow branches and jute yarn within the same robotic workflow was designed to navigate between closely spaced vertical wooden poles of the weaving bed. Its physical dimensions and the spatial clearances required for its maneuvering directly influence the minimum feasible spacing between the vertical wooden poles. As tighter grids increase friction, risk of material damage and robotic tool collisions, the triangular resolution can be calibrated accordingly to balance material performance, structural density, and robotic accessibility.

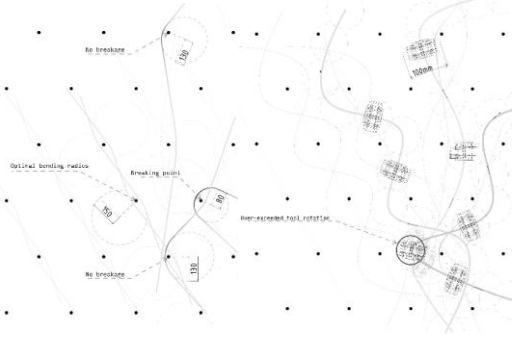
An alternative exploration to address these challenges could involve replacing the pulling method where willow branches are robotically pulled through the weaving bed, with an extrusion-based process potentially reducing material stress and improving process continuity (Olah, Zareian and Dörstelmann, 2025).

Figure 3
Willow-jute hybrid fabrication detail

The adaptation of interlacing techniques into a computational workflow requires translating manual weaving logic into parametric control strategies creating a material-informed path planning. This computational approach facilitates development of multiple fiber structures, including adjustments of fiber trajectories based on material constraints and fabrication conditions. The system accounts for bending limitations, modifying the rotation of the end-effector and its offset distance to the wood poles to minimize friction during the weaving process.

Additionally, to accommodate irregularities in willow length and variations in stiffness along its span, the woven paths can be retraced to enable a more consistent execution of weaving patterns while maintaining weaving friction.

Figure 4
Willow bending diagram and robotic toolpath



a) Willow bending diagram b) Robotic toolpath

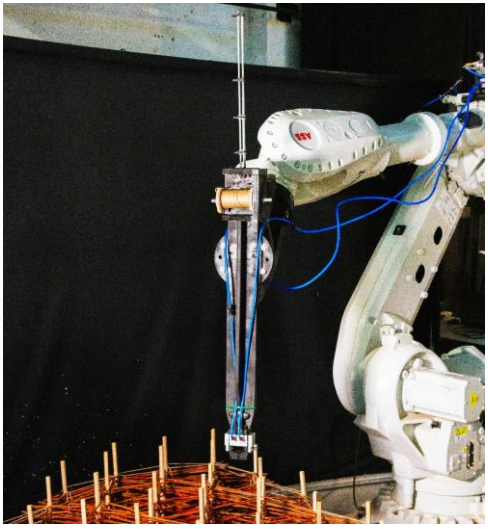
Figure 5
Fabrication setup

Instead of fabricating predetermined shapes, the geometry of the components emerged through a compromise between the willow's physical limitations and digital control parameters. The minimum achievable radius of curvature without causing material failure was identified through the bending test (See Table 1) and used as a constraint in the generation of robot toolpaths. These curvature thresholds were embedded into the parametric logic, ensuring that every trajectory remained within the elastic range of the material. As a result, the robot's movement and the component's formal outcome were both directly shaped by the willow's resistance to bending.

The dimensional parameters of the components are designed to correspond with the effective woven span; however, when a given trajectory surpasses the feasible willow length, an automated overlapping algorithm is triggered. This algorithm places an additional willow branch along the same path, introducing a controlled overlap distance to increase willow's friction and reinforce the overall cohesion of the woven structure.

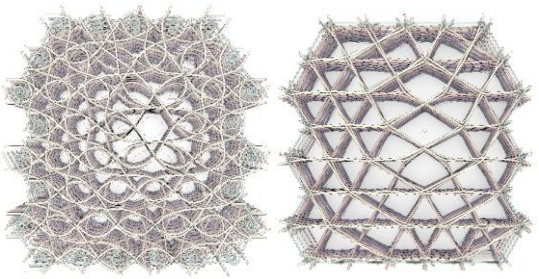
Further refinements are made to address willow inconsistencies, particularly in diameter fluctuations along the length of each branch. The gripper's closing distance is adjusted to improve handling and contact with willow fibers, based on data gathered from multiple categorized specimens. The layering strategy is also tested to compensate for the non-uniform thickness of willow fibers. By positioning each woven layer as close as possible to the previous one, friction forces between willow and wood poles are leveraged to enhance the weaving process.

The integration of two distinct natural rapidly renewable materials requires the development of two independent fabrication strategies within the same construction system.



Willow is supplied in individual branches and serves as the primary woven fiber, providing tensile strength and geometric rigidity. Jute, on the other hand, comes in yarn form, allowing it to be woven into more complex trajectories, particularly interesting for perimeter reinforcement. Jute plays a critical role in stabilizing the modular components, addressing the inconsistencies that arise when attempting to construct a perimeter with only unidirectional willow weaving patterns.

To support this material-informed fabrication approach, a digital simulation of the willow's behavior under bending was developed, allowing the expected shape of the woven elements to be approximated before fabrication. This simulation served as a predictive tool to visualize the deviations between the ideal robotic toolpath and the actual willow response, offering insights into how the material might deform once interlaced into the framework. By comparing the simulated behavior of the fibers with the programmed trajectories, potential inconsistencies or unrealistic curvatures could be identified early in the design process. Additionally, the simulation of the robotic toolpath enabled a early detection for possible collisions between the end-effector and the weaving bed.



a) Robotic toolpath b) Digital simulation

Figure 6
Robotic toolpath and digital simulation of woven component

During fabrication, alternative jute weaving strategies were tested to assess their structural impact. The introduction of continuous multidirectional jute layers demonstrated an increase in component resistance, leading to a fabrication strategy in which a jute layer is added every three layers of willow. This hybrid interlacing system enhances component resistance performance while maintaining fabrication feasibility and automation compatibility.

TOOLS DEVELOPMENT

In addition to the fabrication strategies, the developed algorithms and computational workflows follow the same principles of material adaptation applied in the physical process. The computational workflow begins by generating a parametric grid of equilateral triangles, where each vertex defines the placement of a vertical wooden pole. The system also identifies the perimeter locations in order to apply appropriate boundary constraints. Once the framework is established, the system categorizes the weaving patterns into two types: unidirectional paths and custom trajectories.

Unidirectional Trajectories:

These trajectories follow a predefined logic aligned with the four primary weaving directions: horizontal, ascending right diagonal (Diagonal Direction 1), ascending left diagonal (Diagonal Direction 2), and perimeter reinforcement. Within this weaving mode, perimeter weaving is exclusively assigned to jute fibers, while willow follows a zig-zag interlacing pattern alternating between the horizontal and diagonal directions. Although this approach is based on a structured directional logic, it also incorporates flexibility in material placement. Users can manipulate fiber densities and define local variations by introducing material gradients or selectively adjusting the number of weaving passes across specific regions. This allows for greater responsiveness to reinforcement, geometric, or aesthetic requirements, making the system adaptable rather than strictly automated.

Custom Trajectories:

In addition to the unidirectional system, the workflow allows for custom paths integration by the

user. This weaving system enables customized layer definition, allowing the introduction of specific curves into the weaving sequence. The script analyzes the custom input, assigns a material selection (either willow or jute), and automatically creates the toolpath enabling fabrication feasibility.

While the system is constrained by a layer-by-layer fabrication logic, each individual layer offers full freedom to generate any weaving pattern, as long as it complies with the bending limitations of the selected material. This constraint-aware flexibility allows for the generation of more expressive and responsive weaving patterns, while ensuring that the fabricated fibers align with the closest weaving poles and maintain a coherent interlacing logic.

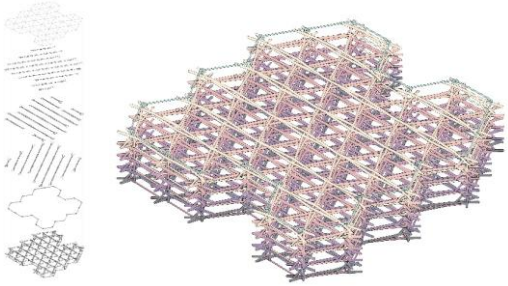
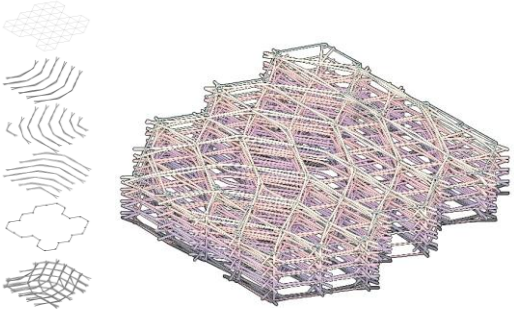


Figure 7
Unidirectional & custom trajectories

a) Unidirectional trajectories



b) Custom trajectories

Finally, the script enables customizable stacking of weaving layers, allowing for both automatic and user-defined sequencing. In the automatic mode, layers follow a predefined stacking logic: Horizontal, Diagonal Direction 1, Diagonal Direction 2, and Perimeter. Alternatively, the manual mode allows the user to override this sequence, defining the stacking order based on specific design or material requirements.

This computational framework aims to explore different fiber placement processes while maintaining a degree of design flexibility. It enables a dynamic interaction between parametric control and material-driven adaptation, seeking to balance automated fabrication with the possibility to add custom trajectories.

The integration of two distinct fiber materials—each with specific mechanical properties and fabrication requirements—required adaptation of fabrication methodologies to accommodate two independent weaving strategies within a single robotic setup.

To address these challenges, a custom-designed robotic end-effector was developed, capable of handling both rigid willow branches and flexible jute yarn within a single fabrication cycle. The end-effector was developed as a dual-function tool, integrating two independent weaving mechanisms within the same setup. On one side, a pneumatic gripper system was designed to securely grasp and manipulate willow fibers, facilitating controlled deposition within the woven structure. On the opposite side, the tool was equipped with a jute yarn feeding system, allowing for the execution of intricate woven patterns using a continuous thread.

Figure 8
Robotic dual end-effector

Transitioning between these two fabrication methods required a 180-degree rotation of the robotic arm's six-axis configuration, enabling seamless alternation between willow and jute weaving without requiring a tool change.

To enhance the fabrication process while accommodating the material differences, the robotic workflow was structured to synchronize the switching between the two weaving techniques. The fabrication sequence was designed so that each material was deposited within the same automated workflow, eliminating unnecessary interruptions. The dual end-effector enabled the robotic system to dynamically alternate between willow and jute, integrating both materials with minimal downtime.

This novel approach to hybrid robotic weaving demonstrates how custom end-effector development can extend the capabilities of digital fabrication, allowing for the controlled integration of multi-material woven structures. The implementation of adaptive toolpath generation and material-specific deposition strategies ensures that both rigid and flexible fiber reinforcements can be seamlessly incorporated into digital construction methodologies, paving the way for scalable, hybrid material systems in architectural applications.

CASE STUDY & EXPERIMENTAL VALIDATION

To assess the performance of the proposed hybrid fabrication system, a series of full-scale modules were produced as part of an initial experimental validation. These components were designed following the standardized triangular grid system and fabricated using the developed robotic weaving methodology, combining both willow and jute fibers (See Figure 10).

Each module served as a platform to test specific aspects of the system, including fiber handling, the controlled deposition of materials, the coordination of weaving sequences, and the influence of varying pattern strategies on the mechanical behavior of the components. Variations were introduced intentionally in both the willow and jute interlacing strategies: some modules prioritized dense unidirectional willow layers, others incorporated partial openings within the woven surfaces while additional configurations explored the effects of enhanced jute reinforcement along the perimeter or across selected zones. This allowed for comparative observations regarding how different combinations of material placement and woven structure logics influence dimensional stability and component stiffness.

To assess fabricability and observe deformation behaviour, a quantitative approach was initially followed to categorize the materials used and document the associated fabrication process. Basic physical parameters, such as willow dimensions and curvature thresholds, were collected during module production to allow comparison across different configurations. In parallel, qualitative feedback was gathered by observing the structural response and handling performance of each component, particularly during robotic deposition and post-fabrication handling. While the analysis was exploratory, it helped identify key behavioral differences between material strategies and offered insights into their implications on dimensional stability.

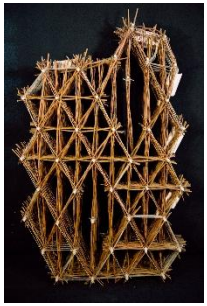
A simplified load test was also performed to obtain preliminary values of the mechanical resistance of the modules. Calibrated weights were applied on top of a planar surface positioned along the longitudinal edge of each component to simulate a distributed compressive load. Vertical deformation was monitored using a reference scale aligned with the rear of the modules and documented through a fixed perpendicular camera. The test provided early insight into the load-bearing potential and dimensional stability of the components in relation to the weaving pattern.

Table 9
Loading test results

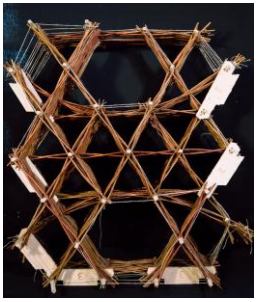
Module	Applied Load (Kn)	Deformation (mm)
Module 01	0,196	210
Module 02	0,196	60
Module 03	0,196	49
Module 04	0,196	8

Figure 10
Hybrid willow-jute fabricated modules

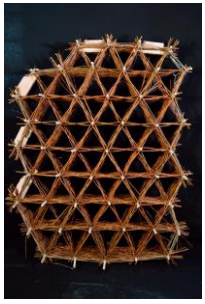
a) Module 01



b) Module 02



c) Module 03



d) Module 04

Throughout the fabrication process, insights were gained into the practical challenges of working with natural fibers in a robotic context, particularly in relation to willow variability, friction and trajectory control. The case study confirmed the feasibility of integrating computational workflows with a dual-material weaving system, while also identifying areas for improvement in terms of fabrication precision, tolerance control, and module standardization.

While the study does not aim to present a finalized architectural application, the development and fabrication of these prototypes demonstrate the potential of hybrid robotic weaving systems as a scalable approach to sustainable construction. The outcomes offer a foundation for further refinement of both design logic and robotic implementation in future research phases.

FUTURE RESEARCH AND CONCLUSIONS

Building on the outcomes of this initial exploration, future research will focus on expanding the material scope and spatial complexity of the weaving system. In particular, the use of alternative natural fibers with different mechanical and geometric properties will be investigated to assess their compatibility with robotic weaving processes. Additionally, efforts will be directed toward transitioning from a layer-by-layer deposition strategy to the generation of spatial weaving patterns. This shift aims to produce a three-dimensional reinforcement unlocking new possibilities for structural and expressive potential within hybrid construction.

Another avenue of exploration will involve the incorporation of complementary materials capable of absorbing forces beyond the tensile capacity of natural fibers. Specifically, the integration of earth-based materials will be considered to provide compressive strength, enabling the development of composite elements that respond to a wider range of structural requirements.

From the current experimental phase, several conclusions can be drawn. The proposed hybrid weaving system has demonstrated the capacity to produce components with adequate dimensional stability, suggesting its viability as a reinforcement method within broader hybrid construction strategies. The combination of willow and jute proved effective in balancing rigidity and flexibility during fabrication: while willow provided structural stiffness, the addition of jute improved edge reinforcement and helped mitigate fiber breakage during bending, reducing the likelihood of

fabrication errors and process interruptions. Nevertheless, during the fabrication process, it became evident that excessively long weaving trajectories with sharp directional changes—even when they did not cause immediate rupture of the willow—often led to excessive friction between the willow and the wooden poles. In some instances, this required either manual intervention or the repetition of the robotic path to complete the weaving sequence, undermining the efficiency and continuity of the process. These challenges highlighted the sensitivity of willow to accumulated stress, particularly when subjected to tight turning angles or prolonged contact with the supporting grid. As a result, the final components exhibited a coherent balance between geometric control and consistency.

Although further optimization is necessary, the outcomes of this research establish a foundational approach for integrating craft-based logics with digital fabrication in the context of renewable material systems. The findings offer a starting point for the continued development of hybrid construction technologies that combine robotic fabrication with material adaptability, moving toward scalable and sustainable architectural applications.

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