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REGROW WILLOW

DIGITAL CIRCULAR CONSTRUCTION FOR EARTH–WILLOW HYBRID STRUCTURES

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The construction industry relies heavily on finite resources and follows a linear economic model of take–make–waste, causing significant environmental degradation through resource depletion and waste generation. Introducing alternative material cycles in construction could provide a solution to this impasse by enabling closed material loops, minimising waste, and diversifying material sources.

ReGrow Willow presents a willow–earth hybrid system for architectural and construction applications that enables circular material cycles through bespoke digital fabrication processes and computational tools. It incorporates lightweight, mobile, and adaptable fabrication equipment and promotes a long-term circular approach while embracing a low-impact concept that can deliver immediate reductions in energy and material consumption.

Expanding on earlier research that reinterpreted the vernacular wattle and daub material system through digital design and fabrication (Zanetti *et al.*, 2023), this research leverages willow, a rapidly renewable material that grows up to 2m annually and replenishes each year after harvesting through short rotation coppice (SRC) practices. As a bio-based material, willow can be composted at the end of its life cycle, offering a circular disposal option. *ReGrow Willow*'s objective is to demonstrate a comprehensive construction system utilising willow in combination with earth, a material that retains its recyclability indefinitely without loss of value (Morel *et al.*, 2021). The synergistic combination of these two materials, with willow serving as tension reinforcement for the earth, is advanced through tailored computational workflows. The development of customised fabrication processes hints at the scalability potential of the prefabricated building elements, while integrative digital design tools manage the interdependencies between architectural design, material systems, structural performance, and fabrication processes.

Research context

Understanding the array of construction materials available at present relies on recognising that their selection is a direct consequence of historical periods of industrialisation, leading to standardisation (Hebel and Heisel, 2017). As a result of the challenges arising from the need to achieve consistent properties for mass production or the appeal of more convenient alternatives, many vernacular materials were abandoned during earlier industrial revolutions. However, the principles of

1. Close-up of the research demonstrator. © Tobias Wootton.

customisation, aided by digital fabrication, provide an opportunity to industrialise and reintegrate sustainable, local materials, and to embrace their inherent imperfections. The ensuing diversification of construction material choices can reduce dependence on limited sources and resource depletion. This approach involves exploring processes for industrialising bio-based, renewable alternatives and substitutes for traditional aggregates.

The most notable example of revitalising renewable building materials is the recent industrialisation of timber construction, demonstrating that automation can scale up formerly manual processes, making them economically viable. This transformation can be enabled through digital workflows and robotic fabrication methods (Apolinarska *et al.*, 2016; Krieg and Lang, 2019). Industrialisation can also be pivotal in advancing innovative engineered materials like cross-laminated timber. Leveraging the flexibility of digital fabrication, timber construction can be enhanced through material programming (Wood *et al.*, 2020; Tamke *et al.*, 2021). These experiences serve as a blueprint for reintroducing naturally grown materials through digital construction technology.

Recent explorations into fast-growing renewable materials like flax, willow, and bamboo offer the potential to shift construction towards utilising cultivated resources that regenerate more rapidly than timber. These efforts involve both converting these materials into standardised industrial products, such as using willow for robotic winding filaments (Eversmann *et al.*, 2021), and exploring innovative fabrication processes and morphologies to enhance their structural stiffness (Dahy *et al.*, 2019; Eversmann *et al.*, 2021; Gil Pérez *et al.*, 2022). Another perspective involves developing methods tailored to unprocessed natural materials (Crolla, 2017). This approach promotes sustainability by avoiding additional processing stages and the associated energy consumption. It reflects principles seen in vernacular techniques like wattle and daub construction, where willow stems are used in their natural state. Leveraging digital design and fabrication's flexibility and adaptability can further enhance this approach, managing imperfections and inherent variations in the material (Devadass *et al.*, 2016; Mollica and Self, 2016; Allner *et al.*, 2020), potentially aided by artificial intelligence.

Earth is another material deeply rooted in global vernacular practices and currently experiencing a resurgence through industrialisation and digital fabrication (Schweiker *et al.*, 2021; Gomaa *et al.*, 2022). Its industrialisation has the potential to transform earth into a sustainable and circular option compared with conventional construction materials subjected to compression, like concrete or bricks. Examples include the industrial processes and machinery designed for rammed earth (Kloft *et al.*, 2019; Heringer *et al.*, 2022), as well as those developed for 3D printing (Dubor *et al.*, 2019; Fratello and Rael, 2020).

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Bespoke fabrication solutions for natural material complexity

Due to uncharacterisable variations inherent to natural materials, building with bio-based materials – such as willow – poses unique challenges that require the coevolution of the material system and the fabrication process.

Willow stems, for example, display unique characteristics such as varying length, thickness, and strength, and the presence of knots, which significantly influence their behaviour. It is crucial to develop a system capable of handling and adapting to these variations without introducing additional processing to homogenise the material. A comprehensive fabrication system is thus established that incorporates bespoke machinery, incorporating a readaptation of industrial techniques and machinery from other fields.

To address differences in length, willow stems are initially spliced into a continuous macrofibre (Fig. 2), which is then deposited following various weaving patterns within a bed of poles by a custom-built Cartesian coordinate robot (Fig. 3). The varying thickness of the willow stem is managed by a spring-loaded, custom-made extruder that regulates extrusion speed according to the pattern. Employing additive techniques, stepper motors handle the XY motion to navigate the fabrication bed while building successive vertical (Z) layers (Fig. 2), forming a component with cell-like features (Fig. 4).

2. Willow branches are spliced into a macrofibre (left), which is woven into morphologically differentiated components (centre). Earth is pneumatically extruded at high pressure into selected cells of the willow formwork (right). © Karlsruhe Institute of Technology (DDF/dos).

3. Utilising additive techniques, a custom 2-axis machine is employed to extrude and deposit continuous macrofibres made from spliced willow branches. © Karlsruhe Institute of Technology (DDF/dos).

4. Willow component. © Karlsruhe Institute of Technology (DDF/dos).

5. Detailed design highlighting the different weaving patterns used to fabricate the willow components. The joinery system is integrated in the components and guides the distribution of earth. © Karlsruhe Institute of Technology (DDF/dos).

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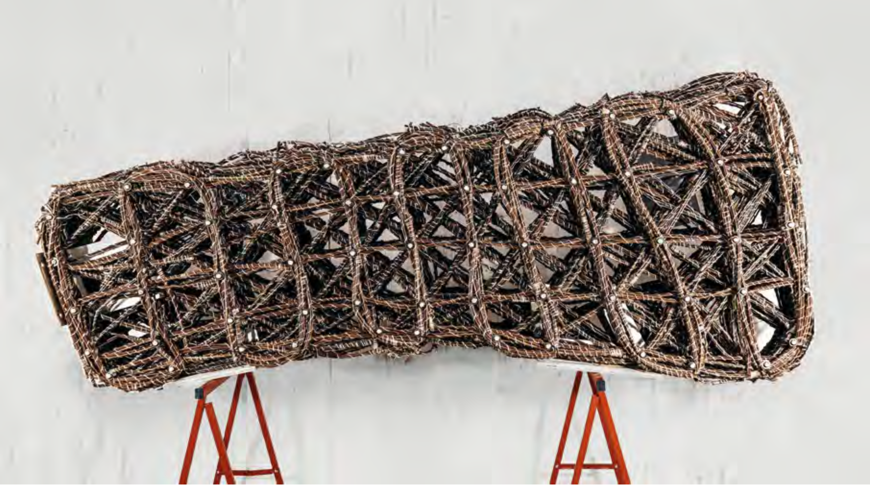

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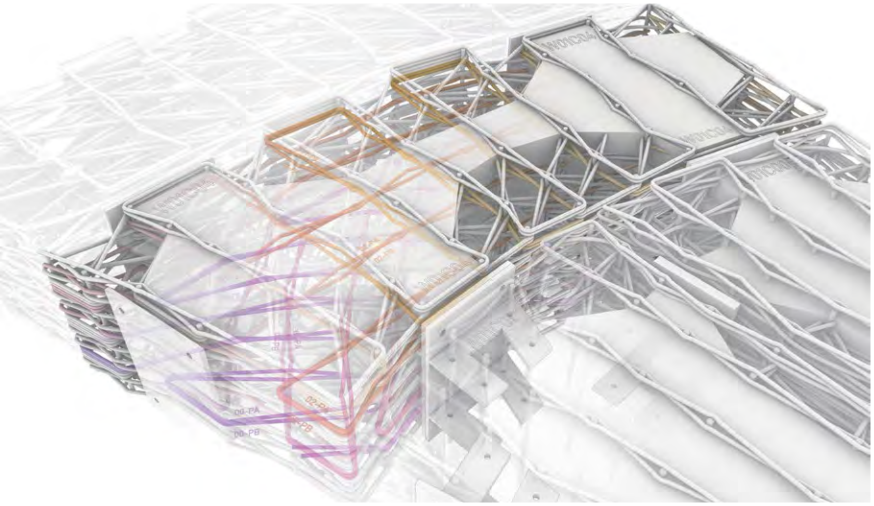

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To create the composite material, the earth is shot into selected cells within the willow formwork using an adapted plastering machine (Fig. 2). This machine employs pneumatically actuated extrusion and high-pressure spraying to compact the earth mixture and fill crevices within the willow formwork. This approach relies on geometry and the fabrication process to combine the two materials, enabling them to work together, much like reinforced concrete. In this case, the focus was on fine-tuning a range of parameters related to the earth mixture, machine specifications, and component design. The aim was to achieve compatibility between geometry and extrudability while also reducing the weight of the earth and minimising shrinkage through the incorporation of bio-based additives, like straw. Ultimately, this resulted in the formulation of an earth mixture that incorporates commercially available construction-grade materials, tailored for compatibility with the earth-filling machine.

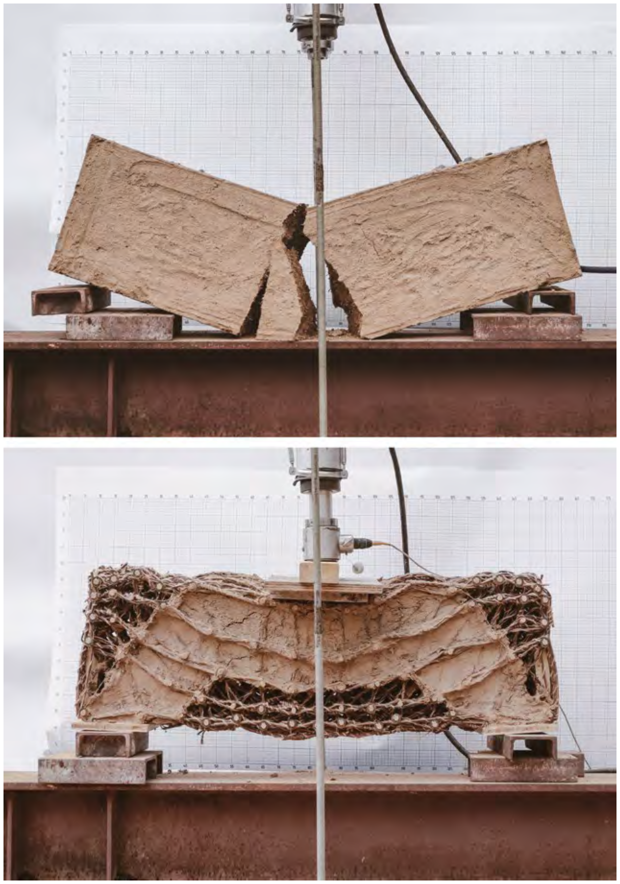
The requirement for earth to dry for at least four weeks after being cast means that prefabrication is a preferred process over on-site fabrication solutions. Prefabrication enables precise control over the drying parameters (weather protection, humidity, temperature), thus ensuring better quality.

The adaptability of the fabrication system extends beyond accommodating the unique material system. The basic principles underpinning the weaving machine's design, for example, also facilitate its scalability, thereby allowing for the scalability of the resulting building elements.

Further developments could be implemented to offer even more solutions to fabrication with the inherent variations of plant-based materials. As the willow formwork is used for its tensile strength, properly tensioning the macrofibre during weaving is crucial. However, depending on the thickness and the presence of knots, the bending behaviour of this macrofibre around the vertical elements in the fabrication bed can be unpredictable. Incorporating sensors to enable real-time adaptation and control may signify a shift towards closed-loop systems in digital fabrication to deal with inhomogeneous materials in construction applications.

Integrative design of willow–earth construction components

The development of building components is central to shaping the overall design methodology, which evolves from the intricate interactions among fabrication prerequisites, practical application, form, and overarching design considerations. The system's geometric freedom,



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6. Tests to verify the structural performance of the hybrid components (below) compared with components made solely of earth (above). © Karlsruhe Institute of Technology (DDF/dos).

resulting from the collaborative development with the fabrication process, enables morphologically differentiated elements that incorporate adaptive weaving and material placement tailored to local requirements and structural performance. Their design can vary in overall shape, cell size and arrangement, predominant weaving direction, and whether they are filled with earth. To accommodate the inherent natural variations in willow, the component design adopts a repetitive sequence of weaving patterns, embracing a redundancy-based design approach for heterogeneous materials (Fig. 5).

The resulting willow components are used for their tensile strength and simultaneously serve as formwork and reinforcement for waste-free and material-efficient earth construction. Assessing the composite behaviour of willow and earth, initial qualitative destructive testing (Fig. 6) reveals that hybrid willow and earth components demonstrate significantly increased ductility compared with earth components, enabling observable deformations before fracture and withstanding loads at least nine times greater in structural tests.

This design methodology prioritises the creation of a construction system through the development of its constituent parts. It explores an architectural language rooted in materiality and fabrication systems, leveraging the functional and intricate complexity achievable through digital design and fabrication. These digital workflows enable architects and engineers to experiment with different designs and adjust parameters to achieve specific goals while navigating the complexities of developing and implementing an innovative construction method. This approach aligns with the research goal of establishing flexible design and fabrication processes capable of accommodating diverse inputs, facilitating the integration of this construction method into conventional design and building practices. In this way, the workflows developed in this research effectively enable a digital reinterpretation of a historical material system into a modern digital construction technology.

Research demonstrator

This research is applied through the creation of a spatial structure featuring interconnected arched walls (Fig. 7), serving as a tangible representation of the design, structural, and construction possibilities. The demonstrator, located at the Federal Horticultural Show 2023 in Mannheim, Germany, showcases a series of partially enclosed spaces (Fig. 9). It also incorporates concepts of microclimatic adaptation and local energy harvesting, exemplifying a comprehensive shift towards a sustainable built environment.

The installation comprises 63 prefabricated components, with maximum dimensions of 0.80x2.20x0.4m and weights ranging from 30 to 500kg. These weight variations stem from factors like component dimensions, the earth-filling ratio, and the specific earth mixture utilised. The components incorporate a joinery system for inter-component and assembly connections (Fig. 8), enabling a relatively fast assembly process – completed in three stages, each taking two days. The structure also incorporates design-for-disassembly principles through reversible connections, signifying a shift towards an architecture that can be easily disassembled for potential reuse of its components or remanufacturing.

Computational workflows inform the material articulation and distribution in the overall structure (Casalnuovo *et al.*, 2023). This results in a material gradient, with earth primarily used at the foundations and willow prevailing at the top. This is achieved by resizing the willow cells according to the global tension-compression pattern. As a result, cells become denser in high-tension areas and

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7. View of the research demonstrator. © Christoph Engel.

8. Close-up of the research demonstrator's details. © Karlsruhe Institute of Technology (DDF/dos).

the earth-to-willow ratio is increased in areas with greater compressive stress (Fig. 1). Stress patterns determine the size and arrangement of components and guide the design and alignment of weaving patterns.

Various earth mixtures are tested in different walls, focusing on the proportion of additives like straw, significantly affecting the components' weight and structural performance. Future applications might apply a principle like gradient concrete (Herrmann and Sobek, 2017), selectively distributing different earth mixtures based on the proportion of compressive loads. This approach entails completely filling all components with earth. However, an adaptive composition of the earth mixture ensures that the increase in volume does not lead to a proportional increase in weight. Destructive tests support this configuration, demonstrating its effectiveness in reducing deformation compared to components made exclusively of willow (Casalnuovo *et al.*, 2023). Earth may also contribute to fireproofing the structure, although additional tests might be needed when using a high straw content (DIN Deutsches Institut für Normung e.V., 2018; Schäfer, 2021). Different finishing treatments are also showcased, resulting from the capabilities and constraints of the fabrication system. One side of the structure features one outer layer of willow exposed, while the other side is plastered with earth.

As weathering poses a significant challenge in earth construction, additional measures are necessary to support the construction system. In earth construction, sediment erosion can be reduced by implementing water breaks, such as protruding stone layers (Heringer *et al.*, 2022). In willow–earth structures, this can be achieved by incorporating horizontal willow patterns as the outermost layer. In future applications, weathering protection should be further improved by adopting other principles from traditional earth construction, such as using overhanging roofs to shield buildings from rain. To prevent rising ground humidity, the structure is elevated on concrete blocks. This offers further insight into incorporating circular principles within the design process, as these concrete blocks are reused elements and their dimensions become a critical predefined parameter for the structure's design.

At the end of the structure's lifecycle, the concept envisions that it can be readily disassembled, thanks to the reversible connections, and repurposed either in part or as a whole. While digital design and fabrication for bespoke components offers the potential for material-efficient construction, ultimately reducing resource depletion and transportation energy, it does not facilitate the repurposing of individual elements in different configurations. When all other options have been exhausted, the materials can be separated into earth-based and plant-based components. Earth can then be recycled for new construction, while plant-based materials can be returned to the biosphere, potentially contributing to the regeneration of new renewable resources.

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Conclusion and outlook

This research illustrates a localised approach that harnesses the customisation potential of digital design and fabrication towards the development of digital circular construction. It offers a digital reinterpretation of European vernacular architecture adaptable to diverse contexts, focusing on local solutions rooted in forgotten crafts and regional construction practices. It exemplifies collaborative development of design and fabrication strategies, alongside computational engineering, facilitating the exploration of digital construction technology rooted in historical sustainability principles and local sourcing.

The lightweight, scalable, and cost-effective machine, which can be easily moved to different locations for prefabricating components from local sources, has the potential to serve as a scalable model for extending this technique to various regions. In a wider perspective, custom digital design workflows and digital fabrication technologies may offer a model for revitalising architecture deeply tied to its environment, addressing local climate, resources, and culture. This approach can lead to a construction and architectural practice where development strategies, workflows, and open-source technologies become shared foundations, rather than a standardised global style.

This research also highlights the importance of a multi-disciplinary exploration involving collaboration with farmers, environmental organisations, and policymakers. It sets the stage for a comprehensive shift towards a local bioeconomy, as exemplified by willow cultivation on wetlands. Because of their adaptability in flood-prone areas (Roeder *et al.*, 2021), willows can be cultivated without disrupting existing agricultural zones and can function as short-term carbon sinks (Rytter *et al.*, 2015). The research has the potential to expand the possibilities and architectural language of earth construction and holds significance for the broader adoption and diversification of renewable materials in architectural applications. Future endeavours will focus on creating fully certified components that meet fireproof, soundproof, and building physics standards, and assessing their economic feasibility.

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9. View of the research demonstrator. Image: © Karlsruhe Institute of Technology (DDF/dos).

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