InterTwig—Willow and Earth Composites for Digital Circular Construction

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Abstract

The construction sector has high resource demands and generates a significant amount of waste, a consequence of its linear approach. A shift towards renewable and local material sources and the implementation of closed material cycles represent a significant opportunity for the construction industry to curtail the depletion of raw materials. To address these challenges, this paper presents a strategy for a novel circular construction method that combines willow, a rapidly renewable material, with earth and is enabled by digital fabrication, which can sustain their industrialisation through tailored processes. Emerging from a materiality perspective, the research revisited vernacular building techniques that used plant- and earth-based composites, exemplified by the vernacular wattle and daub, to understand how these can be enhanced through digital design and digital fabrication. Willow (Salix) is a woody plant native to Europe whose stems can be harvested yearly, thanks to specific forestry practices, namely short rotation coppice, that allow the plant to regenerate in rapid cycles. To use willow for construction, geometry and textile techniques were implemented to create stable structures. In combination with earth, a finite but abundant and infinitely recyclable material, it creates a sustainable and circular composite that exploits the structural characteristics of each constituent material. Digital design methods enabled the exploration of different geometrical variations and ensured an increased degree of control over their complexity at different scales. The research results were tested in a full-scale prototype, demonstrating the principles of the envisioned construction systems.

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1 Introduction

The construction sector has high resource demands and generates a significant amount of waste, a consequence of its linear model, in which resources are extracted, used and lastly disposed of as waste (Çetin et al. 2021). It is responsible for more than a third of global resource consumption (Klep 2015) and accounts for about 50% of all extracted material (European Commission 2020). In the EU, it accounts for over 35% of all waste generated (Eurostat 2022). A shift towards alternative, local means of sourcing and use of materials, as well as implementing concepts for assembly and disassembly, opens new possibilities for the construction industry to reduce the depletion of raw materials and implement circular material cycles.

Material flows in a circular economy can be divided into biological and technical cycles (Ellen MacArthur Foundation 2022). Technical cycles focus on extending the life of secondary raw materials through reuse or recycling. Biological cycles rely on renewable resources or biodegradable materials that are used, regenerated and finally returned to the biosphere. Considering the European context, wood is regaining importance and remains the only significant renewable building material in the industry for structural applications. However, within the repertoire of historic building techniques, other construction methods that use renewable materials can be found. One such construction method is exemplified by the European vernacular wattle and daub, in which renewable materials are combined with earth-based materials into a sustainable composite. Such vernacular techniques and materials, based on old craftsmanship and know-how, are of limited applicability for mass production and have been sidelined by the industrial revolution over the years.

To create novel circular material cycles, the material shift should therefore be supported by devising new fabrication concepts, tools and technologies. Digital fabrication, in particular, can enable custom solutions for novel material processes, providing in this way a plausible industrialised serial construction. With the help of digital fabrication, renewable materials other than wood (such as bamboo, willow, reed and flax) are being revised through new processing techniques. The approaches are disparate, ranging from post-processing the raw materials for use in additive manufacturing (Dawod et al. 2019) or filament winding (Gil Pérez et al. 2022), to using the material with minimal processing thanks to demountable joints (Bouza and Asut 2020; ETH Zurich 2022).

Combinations of renewable materials with other materials allow for the creation of composites that exploit the specific properties of each material. Such investigations combine, for example, willow and mycelium (Özdemir et al. 2022), wood and concrete (Dias et al. 2018), bamboo and earth (MAS Dfab ETH 2022) or wood and earth (Trummer et al. 2022).

This paper aims to investigate a novel circular construction method that combines willow, a rapidly renewable material, and earth. In particular, it aims to understand how this building composite, already present in the vernacular language, can be enabled and enhanced through digital design and digital fabrication. Starting from a materiality perspective, the research revisited plant- and earth-based composites by exploring novel building techniques through hand-made prototypes at increasing scales accompanied by the development of their respective digital fabrication concepts and custom machinery. This ultimately led to the fabrication of a full-scale demonstrator made of the combination of willow and earth.

2 Materials and Methods

To explore novel circular material systems, the research started by examining the properties of the materials. The objective was to assess their suitability for construction applications by reviewing relevant literature. This exploration aimed to gain insights into the materials' potential for circularity, their current applications, and their availability. Concurrently, the research iteratively developed initial concepts for utilising these materials, primarily focusing on architectural applications, structural characteristics, circularity, and digital fabrication prospects.

One selected concept was further developed as a construction system. Its fabrication system and details were prototyped and tested in different configurations, using both hand-made and digital techniques. Eventually, a full-scale demonstrator served to test the correlations between the different parts of the design, fabrication and assembly process.

This progression involved incrementally scaling up the research prototypes and employing a design-through-making methodology. Additionally, specialised subtopics such as material characterisation and the advancement of the digital fabrication system were explored, incorporating feedback loops with the primary line of investigation.

2.1 Material Selection

2.1.1 Willow

Plant-based materials have a high potential for introducing sustainable and circular principles into construction and for rethinking building materials as non-dependent on finite resources. In particular renewable materials, defined as "materials that are continually replenished at a rate equal to or greater than the rate of depletion" (Ellen MacArthur Foundation 2019), and rapidly renewable materials, defined by USGBS as "made from agricultural products that are typically harvested within a 10-year or shorter cycle" (USGB 2022), offer the potential to introduce circular systems that are based on biological cycles, returning the materials to the biosphere at the end of their lifecycle.

Specific forestry practices for rapidly renewable materials, namely short rotation forestry (SRF) and short rotation coppice (SRC), are currently used for energy production and can enable large-scale harvesting. Notably, SRC involves shorter cycles in which the plant is cut back to the stump and regenerates year after year (Verwijst et al. 2013). Although SRC is still marginal in Germany and most European countries compared to land used for cropland and forests (Faasch and Patenaude 2012), the area has been increasing in recent years and could replace marginal agricultural land with minimal effects on overall food and feed production (Aust et al. 2013).

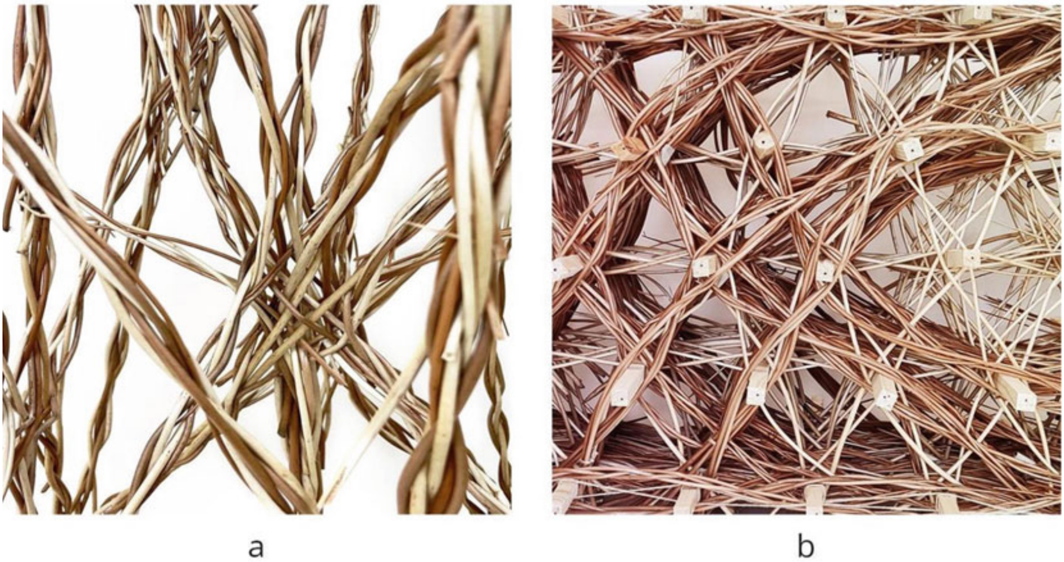
Willow (Salix), in particular, can be coppiced every year and the plant remains productive for several decades (Fig. 1). Although willow species are present worldwide, their main natural distribution is in the northern hemisphere (Verwijst et al. 2013). When they are not used as energy crops, willow is sold in bundles after being left to dry for a year (Fig. 2).

Thanks to the combination of fast growth cycles, regional availability and the existence of forestry practices for its commercial availability, willow could become a local alternative to bamboo in Europe, albeit showing vastly different structural properties. For willow to be considered a building material, structural and consistent stiffness was introduced by exploiting geometrical and textile principles, such as weaving and braiding (Fig. 3).

These techniques utilise the bendability of the willow stems to form three-dimensional woven or

Fig. 1 Willow (*Salix*) plants during harvesting

Fig. 2 Bundles of willow stems after a 1-year growth cycle and a 1-year drying period



a

b

Fig. 3 Exploratory prototyping implementing braiding (**a**) and weaving (**b**) techniques

braided structures that have a higher structural stiffness than the single stems, while still retaining tensile capacity. This study tested different types of commercially available willow to determine the best balance between flexibility, thickness, area of cultivation and growth cycle (Table 1).

Among the initial concepts (Fig. 4), additive willow weaving (Fig. 4b) was chosen as the

Table 1 Different commercially available willow types were tested and evaluated according to their flexibility, area of cultivation and length after a 1-year cycle

Plant	Length of stems (1-year growth cycle) (cm)	Average diameter of stems (mm)	Closest area of cultivation (commercially available)	Availability in large quantities	Flexibility after 14 days of soaking
Salix alba	250	9	Spain	+++	+
Salix purpurea uralensis	240	8	Germany (Rheinland-Pfalz, RP)	+++	++
Salix fragilis	220	9	Germany (RP)	+	+++
Salix purpurea	260	8	Germany (RP)	++	+++

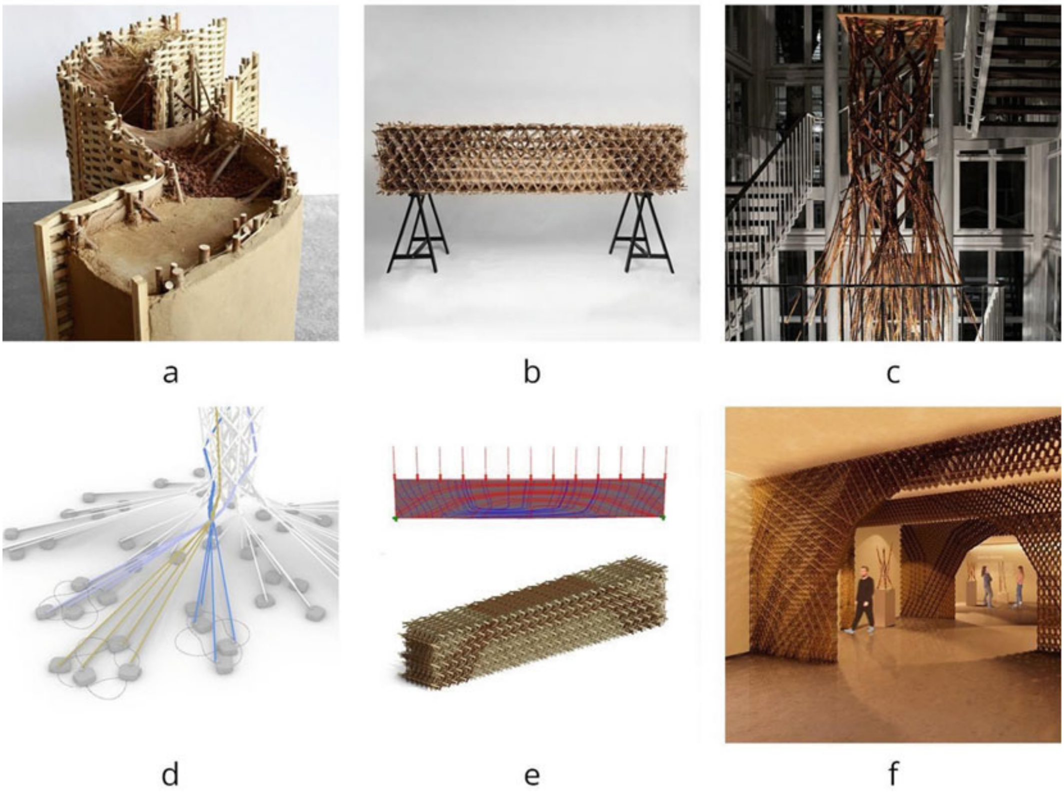


Fig. 4 **a**–**c** Initial 1:1 prototypes used to assess the initial concepts for **d** digital fabrication, **e** structural optimisation potential and **f** envisioned architectural application

Table 2 Earth techniques for construction

Technique	Processing state[1]	Processing intensity	Load-bearing
Mortar and bricks	Plastic	Low	Yes
Cob	Plastic	Low	Yes
Rammed earth	Optimum	High	Yes
Earth bag	Plastic	Low	Yes
Compressed earth blocks (CEB)	Optimum	Medium	Yes
Adobe	Plastic	Low	Yes
Wattle and daub	Plastic	Low	No
Light earth	Liquid	Low	No
Plaster	Plastic	Low	No
Deep-soil mixing	Plastic	Medium	Yes
Casting in willow formwork (InterTwig)	Plastic	Low	Yes

method with the most potential for further research thanks to its simple fabrication process, geometrical freedom for different construction applications and potential for localised earth infill.

2.1.2 Earth

Earth-based materials have been used in vernacular architecture both as individual construction elements (e.g. monolithic walls) and in combination with other materials (e.g. wattle and daub). Previous research into their benefits in terms of climate control, and their effect on humidity and energy efficiency (Fabbri et al. 2022) has renewed efforts for earth-based materials to be re-introduced into contemporary architecture. Offering an alternative to currently predominant aggregate materials, they require far less embodied energy during manufacturing than traditional building materials (Bruno et al. 2020). Earth-based materials have also been found to have a significantly lower global warming potential than traditional concrete (Hegger et al. 2007). Depending on the application and the preprocessing, earth-based materials can be crushed and mixed again for new applications or returned as soil without loss of value or generating waste (Hegger et al. 2007). In particular, if earth-based materials are used without stabilisers (such as cement)—which improve their properties but make the final material system irreversible (Zami and Lee 2010)—the clay binding allows a complete and low-energy recycling of earth (Linden et al. 2019) with no loss of mechanical strength. In this way, earth-based materials can be considered infinitely recyclable.

A selection of different earth construction methods is shown in Table 2, highlighting their differences in terms of the amount of processing required, whether the final structure is load-bearing and their state during construction.

2.1.3 Earth and Willow Composite

Willow as a fast-renewable and locally abundant material has been used in vernacular practices for several centuries. Examples range from basket weaving, where willow is used in a three-dimensional arrangement, to wattle and daub, where a two-dimensional woven lattice is used as infill within a timber frame structure. However, these techniques are generally small-scale and do not create load-bearing components.

Using woven willow as tension reinforcement for the compression-bearing earth components can create three-dimensional building elements for a self-contained construction system. Additionally, implementing the woven willow structures shown in Sect. 2.1.1 as an integrated permanent formwork for earth means that the

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[1] Optimum refers to the optimum water content state where the soil reaches maximum dry density. Plastic state indicates an excess of water above this level. Liquid state is from the point when the earth begins to crumble when rolled into a specific cylindrical shape.

Table 3 Additives for earth (based on Vyncke et al. 2018; Cruz 2013 and own research)

Additive	Function	Relative cost	Circularity
Straw	Tension reinforcement, lighter weight	€	Yes, biodegradable
Sawdust	Shrinking improvement, lighter weight	€	Yes, biodegradable
Seagrass	Tension reinforcement, lighter weight	€€	Yes, biodegradable
Sand	Increased compression strength	€€	Yes, reusable after separation
Stones	Increased compression strength	€€	Yes, reusable after separation
Pozzolans	Increased compression strength	€€	No, irreversible chemical stabilising process
Biopolymer	Increased durability	€€€	Yes, recyclable
Cement	Increased durability	€€	No, irreversible chemical stabilising process
Lime	Increased durability	€	No, irreversible chemical stabilising process
Soda	Increased durability	€	No, irreversible chemical stabilising process
Sodium hydroxide	Increased durability	€€€	No, irreversible chemical stabilising process

placement of earth could be optimised thus saving material and energy, contributing to the overall sustainability of the composite.

Different techniques and material mixtures were explored to find those that could bond and be poured into the woven willow to provide structural stability, through a series of experiments informed by prior research.

Initial findings showed that clay was an essential part of the mixture as it introduced cohesion by acting as a binding agent between the willow formwork and the earth mixture. However, too much clay causes cracks to appear when drying as it increases the amount of shrinkage. Since the mechanical behaviour of earth depends not just on cohesion but also on friction due to the granular additives (Morel et al. 2021), sand or other aggregates were essential. While the addition of sand improved the shrinking behaviour, it decreased the plasticity of the mixture (Fabbri et al. 2022) thus making it more difficult to fill in the cavities. When choosing the additives, it was important to evaluate their circularity—avoiding using cement and similar additives—with a preference for locally sourced and minimally processed materials. Table 3 lists additives, in terms of their function, relative cost and circularity.

The final mixture was created by using commercial earth products, with known standards. These were tested in small prototypes in combination with different additives (Fig. 5). The two products, known as “plaster underlay” (Conluto 2022) and “building loam” (Claytec 2022), were mixed in a 10:1 ratio. The former contains a large part of sand and aggregates—for strength and to avoid shrinking—while the latter contains significant amounts of clay, which contributes to plasticity and cohesion. This mixture was then combined with straw fibres of 1–2 cm to further avoid shrinking (Fabbri et al. 2022).

The result was a mixture used in a cob-like technique in which the additive content and water content could be varied to achieve the

Fig. 5 Small prototypes combining commercially available earth products with different additives

optimum mixture properties. This technique is compared to other earth techniques used in construction in Table 2.

2.2 Fabrication and Geometrical Strategy

2.2.1 Additive Willow Fabrication

Material Preparation Before the willow can be used for weaving, it must be temporarily softened to enhance its flexibility by soaking in water or by steaming. The latter method is faster, taking six hours to reach the required flexibility for the foreseen application, instead of two weeks. Soaking offers, however, the potential for a less energy-intensive process, whose timing could be matched with the schedule of a fabrication line.

Setup for Fabrication The setup for fabrication comprised a bed of wood poles in which willow is arranged in an additive process to create a three-dimensional structure (Fig. 6). In this first exploration, a base grid of equilateral triangles was chosen in order to make use of their resistance to deformation. The distance between the vertical elements followed the need to minimise free-spanning willow stems, which act as unreinforced elements, while maximising the spacing for reachability during the weaving process.

Weaving Patterns The weaving process followed a sequence of patterns, which transformed the otherwise thin and bendable material into load-bearing configurations. Different approaches were explored, aided by creating various weaving sequences with digital techniques, which were then tested in prototypes (Fig. 7). Two main approaches emerged and were categorised into linear and closed patterns (Fig. 6). The final configuration consisted of a combination of the two, exploiting their individual strengths: linear patterns distribute the stress throughout the component, while closed patterns, which follow the triangular base grid, stabilise the component locally. Different patterns were alternated to create sequences that created cell-like configurations.

Several parameters were observed to influence the resulting strength of the prototypes (Fig. 8). The tightness of the weaving around the vertical elements was important as this increased the friction and the pattern would be closer to the shortest path, thus creating components more resistant to deformation. The prototypes also tended to delaminate under shear stress as no chemical binders were used between the layers, in order to maintain the circular potential of the final product. This was counteracted by adding strings and self-locking washers (Fig. 9).

2.2.2 Earth Casting

Earth Distribution The willow formwork consisted of distinct cells, bounded by layers of

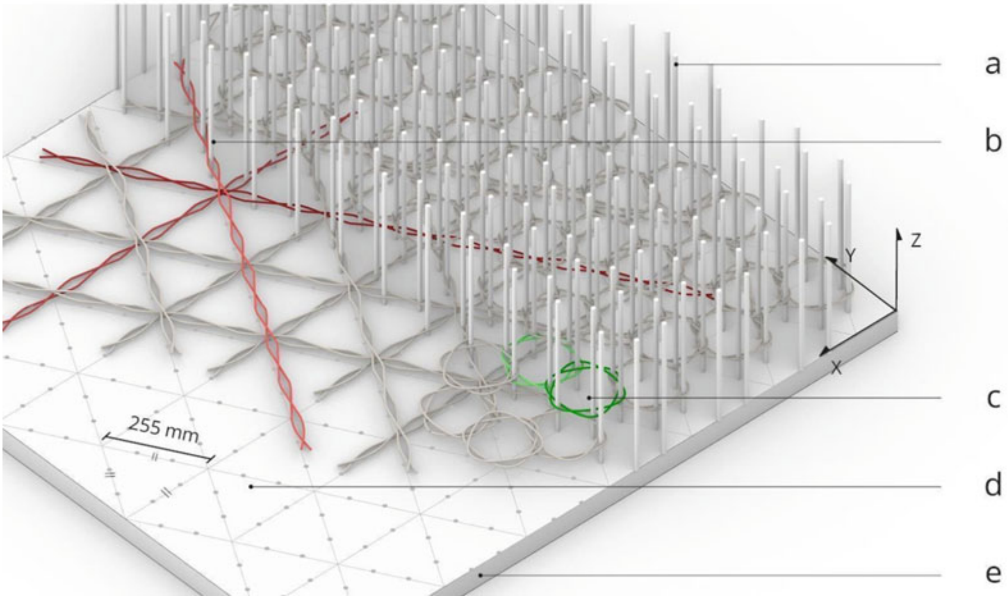

Fig. 6 Fabrication setup showing weaving patterns on poles (**a**), with linear (**b**) and closed (**c**) types, which create the cell-like structures (**d**)

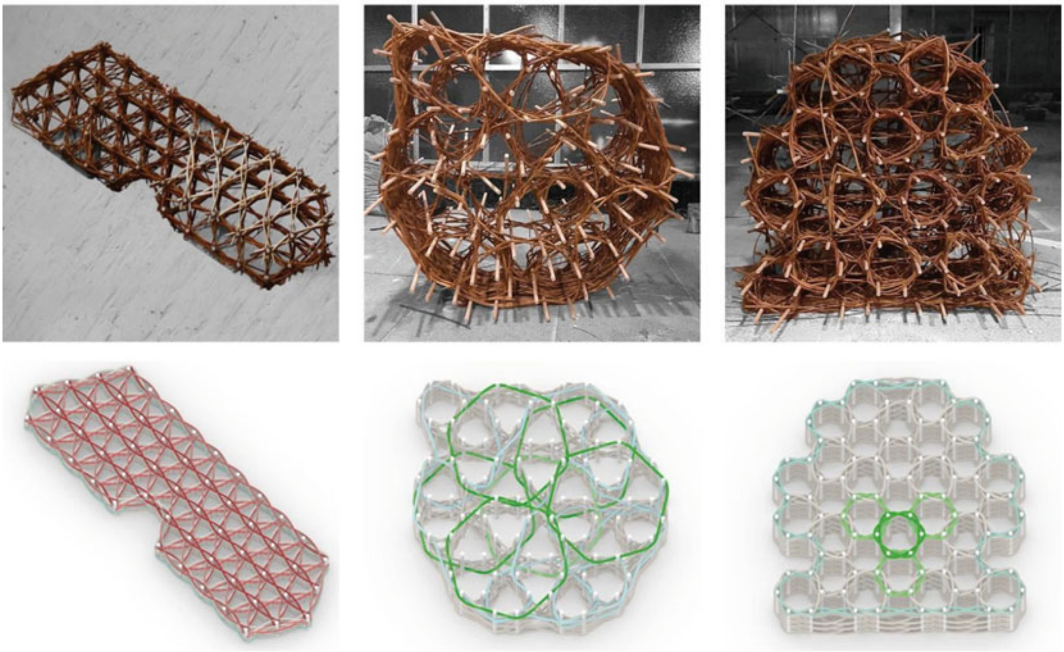

Fig. 7 Different types of weaving pattern configurations, developed digitally and tested with hand-made prototypes

Fig. 8 Prototypes to test the influence of different parameters

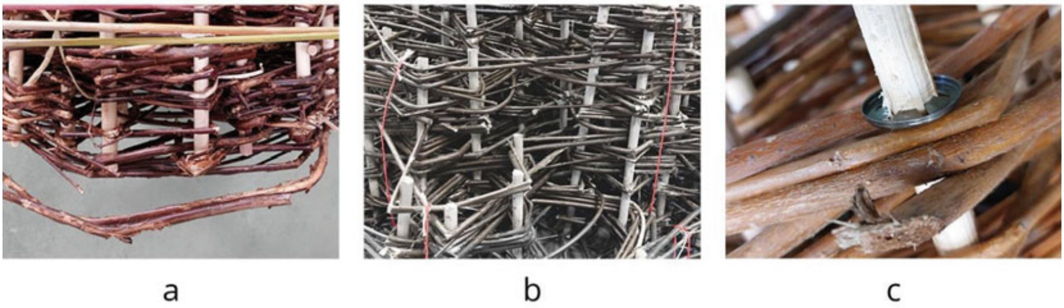

Fig. 9 Delamination (**a**), strings (**b**) and self-locking washers (**c**)

willow on each side, which enabled the use of plastic-state earth as a filling material.

Two parameters were considered when choosing which cells to fill. As earth was the main contributor to self-weight, minimising the earth infill meant easier handling and transportation. Secondly, the surface area exposed to air had to be maximised, in order to aid evaporation and reduce drying time (Fig. 10).

Setup for Fabrication There are a number of readily available tools and machines to aid the filling process; however, using them adds constraints on the composition of the earth mixture as the additive sizes and viscosity need to conform to the machine dimensions and the extrusion mechanism.

Long straw fibres reduce the amount of shrinking but will block the pipes used with

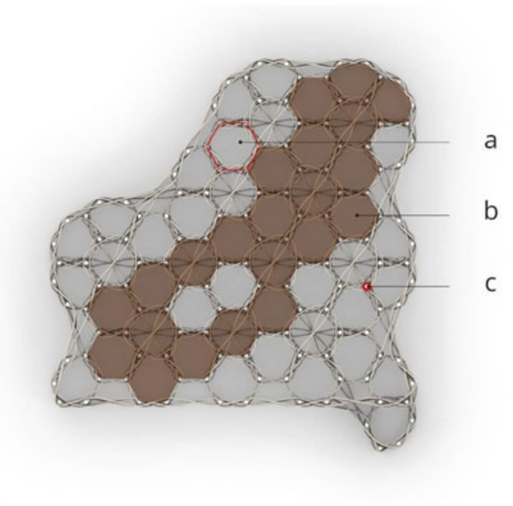

Fig. 10 Top view of a component showing willow cells (**a**) and earth-filled areas (**b**) defined by poles (**c**)

conventional mortar pumps and are also more likely to separate from the earth mixture during compaction. However, choosing a mixture using such tools can streamline the process and make the construction system more viable.

Process of Fabrication Compaction was done locally in each cell by a concrete vibrator. This was to ensure that the mixture reaches all the crevices in the components and that air bubbles are removed (Fig. 11). Thus, the entire process emerged, starting with pre-mixing the dry ingredients, adding the water in a concrete mixer to create a uniform material; filling was then done by hand in batches and followed by the compaction with a concrete vibrator.

2.2.3 Digital Fabrication Development

In order to prove the feasibility of the automated digital weaving process, a customised digital fabrication system was developed. This consisted of a two-axis, stepper motor-driven system, controlled by an FPGA-based controller running G-codes, which pulls willow stems within the bed of poles (Fig. 12).

The unpredictable behaviour of unprocessed materials gave rise to several challenges during the development of the digital fabrication system.

Firstly, analysing the process of hand-weaving versus machine-weaving highlighted some key differences. During hand-weaving, the willow is supported in two points and the bending location is controlled by the distance of these two support positions, whereas the machine pulls the willow stems through the bed of poles. This results in less control over the point where the willow bends and higher friction with the poles, with a consequent higher chance of stems breaking in case of patterns with small bending radii. While this aspect can be minimised, a specific repertoire of machine paths that avoided tight radii had to be developed.

Due to the changing diameter of the willow stems, the orientation for machine-weaving was crucial. The thinner sections were able to take on more bending but were also less resistant to the large stresses caused by pulling at the end effector

Fig. 11 Willow and earth combination in a component, top (**a**) and side (**b**) views

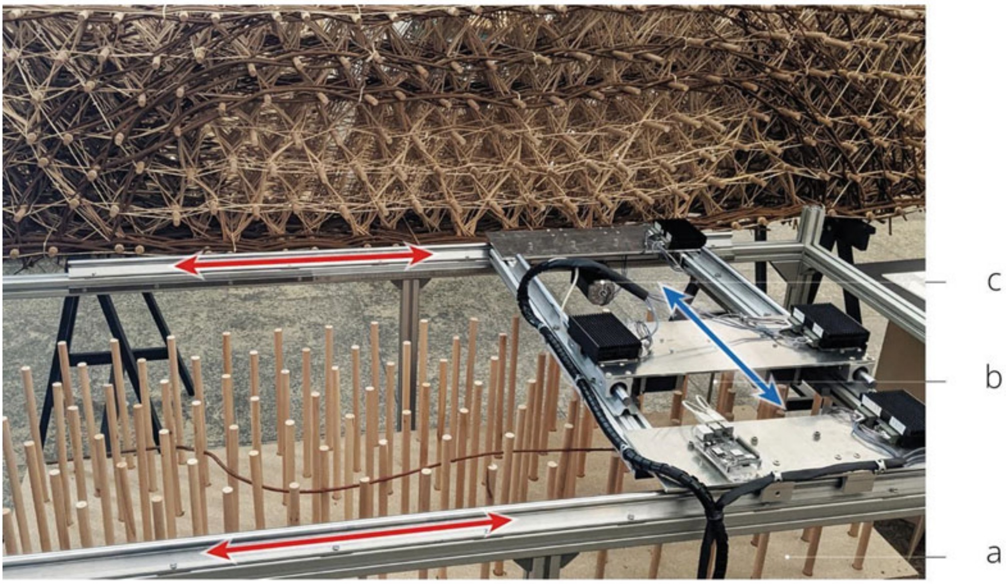

Fig. 12 View of the two-axis machine showing the bed of poles (**a**), the end effector (**b**) and the stepper motors (**c**)

which resulted in the willow breaking. Thicker parts of the willow were more resistant to tearing but also stiffer to bend which in turn meant that the forces were transferred to the wooden poles effectively bending them about their vertical axes. Finally, the varying lengths of the willow stems were also considered during the machine fabrication by designing the machine paths with overlaps between consecutive branches.

2.3 Component Design

The design language emerged from the possibilities of geometrical freedom that the fabrication process affords, enabling non-standardised elements that can be tailored to specific conditions. In the XY fabrication plane (see Fig. 6), a large range of shapes is possible, while the freedom is restricted to a variation of heights in the Z direction, up to a maximum of 50 cm to avoid bending the vertical elements excessively.

Seven final weaving patterns were repeated in different sequences until the desired height was reached to create a component (Fig. 13). In this way, redundancy was introduced in the system to counterbalance the inconsistencies created by the non-processed willow stems. A digital design process was developed that automated the workflow from overall volumetric geometry to the creation of the fabrication setup and patterns, which were finally exported either as instructions for a person weaving or as a coded path for the machine.

Two different component types were explored in this study.

Components Made of Willow and Earth These were planned to be used in a horizontal orientation with respect to the fabrication setup. Their maximum size was restricted by the weight of the final components, to ensure transportability. The geometrical freedom in the XY plane was exploited to create interlocking components (Fig. 14) and the sequence of weaving patterns was tuned to allow for bigger gaps so that the earth could flow between the cells.

Components Made of Willow These could be arranged more freely, horizontally or vertically with respect to the fabrication setup. In this case, a pattern sequence that created denser components was implemented to achieve more stable configurations.

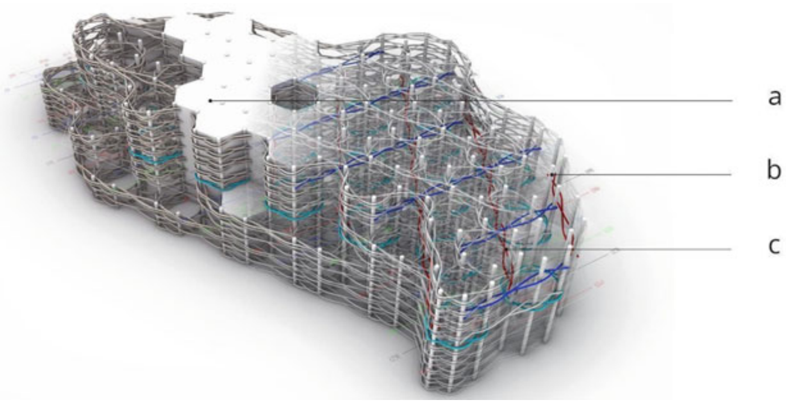

Fig. 13 Example of a willow and earth component, which shows earth (**a**), poles (**b**) and different weaving patterns (**c**)

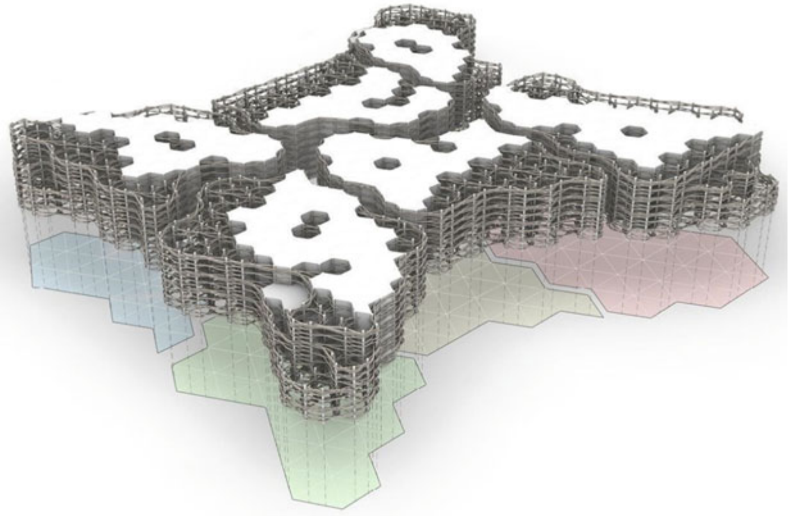

Fig. 14 Interlocking component system

The component design included the integration of additional elements for joinery, transportation and assembly.

2.4 Material Characterisation

As this is a new material combination for which no standard exists, a wide variety of structural test scenarios were necessary to understand both the respective properties of the individual materials and the behaviour of their combination.

For the classification of willow, the focus was placed on different tensile test scenarios. Willow is a natural material that has a large variation in tensile strength due to material imperfections, so five identical samples were tested. The tensile test of individual willow stems (Fig. 15a) aimed to obtain an average value of the maximum tensile stress. Stems of different thicknesses were tested and the tensile force was converted to stress with respect to the available cross-sectional area. Three willow stems laid parallel to each other (Fig. 15c) provided a reference value to braided willow (Fig. 15b) to be able to record the influence of the braiding on tensile strength.

For the earth tests, cube samples were made with a side length of 20 cm (Volhard and Röhlen 2009) to test the compressive strength of the self-developed earth mixture (see Sect. 2.2.2) once the equilibrium moisture was reached (about six weeks) (Volhard and Röhlen 2009).

Fig. 15 Single willow stem (**a**), three willow stems braided (**b**), three parallel willow stems (**c**), braided willow in the testing machine (**d**)

To test the interaction between willow and earth as a composite material, rectangular test specimens with dimensions 10 cm × 10 cm 75 cm were made, which underwent bending tensile strength tests using a four-point bending setup.

Finally, two willow reinforcement types were examined. First, the willow was placed in the formwork in three layers (Fig. 16), where the reinforcement acted as a tie rod. The second type was a three-dimensional willow structure (Fig. 17). Due to the spatial reinforcement structure, a three-dimensional force transmission was expected (cf. truss).

The test scenarios described above were carried out qualitatively and still require further development steps to obtain quantitative results from them.

The preliminary tensile tests of the single willow stems showed that they can absorb an average tensile stress of about 70–90 N/mm^2, depending on the minimum and maximum cross-sectional area of the tested willow stems. The earth cubes absorbed an average compressive stress of 1.8 N/mm^2.

In the case of the braided willow stems, lower absorbed tensile force was observed in comparison to the willow stems that were laid parallel to each other. Although the braided willow had a reduced tensile force, the better bonding effect between willow and earth was a great advantage.

Furthermore, a tensile stress capacity was observed in the earth-willow test specimens, which withstood a load of up to 2.2 kN in the four-point bending setup before the beams failed or the deformation became too large, compared to specimens made of only earth with the same dimensions, which broke directly under their self-weight.

3 Results

A full-scale demonstrator named “InterTwig” was developed and built by an interdisciplinary team of students and researchers at the Karlsruhe Institute of Technology (KIT). It was presented in Karlsruhe in July 2022 (Figs. 18 and 19).

The demonstrator served as a proof of concept to test the whole process from design to fabrication to assembly, widening the scope of the research from components to a whole structure representative of a construction system. Specifically, it aimed to test component logics (interlocking components vs. joints) and different application potentials (load-bearing willow and earth components vs. lightweight willow

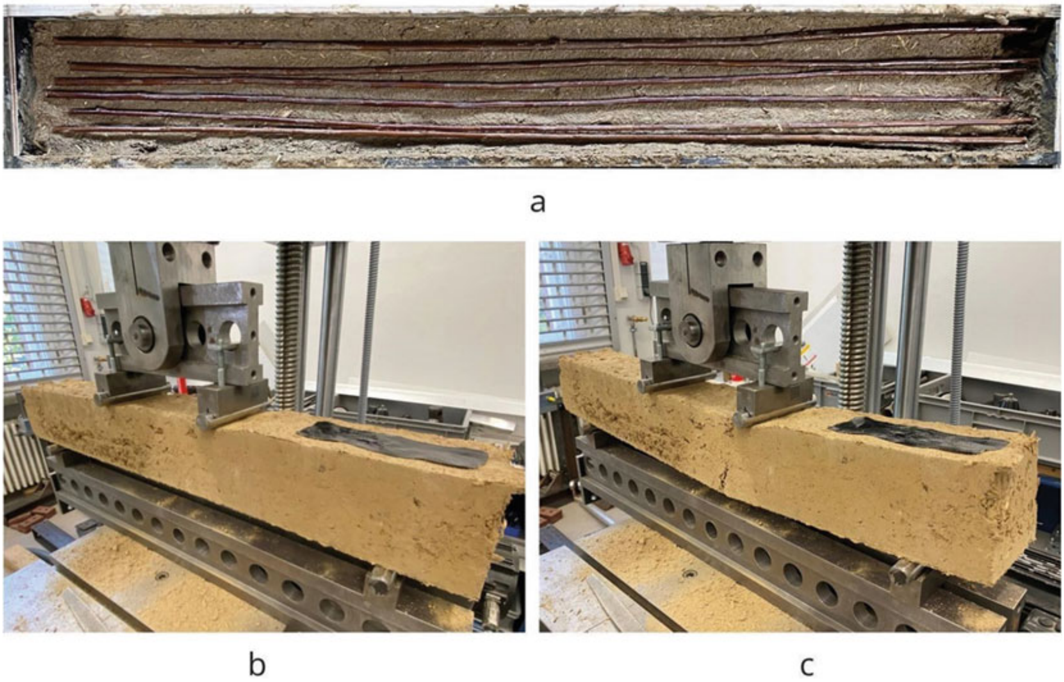

Fig. 16 Test specimen with willow laid in layers parallel to each other (**a**), specimen before loading (**b**), specimen at failure load (**c**)

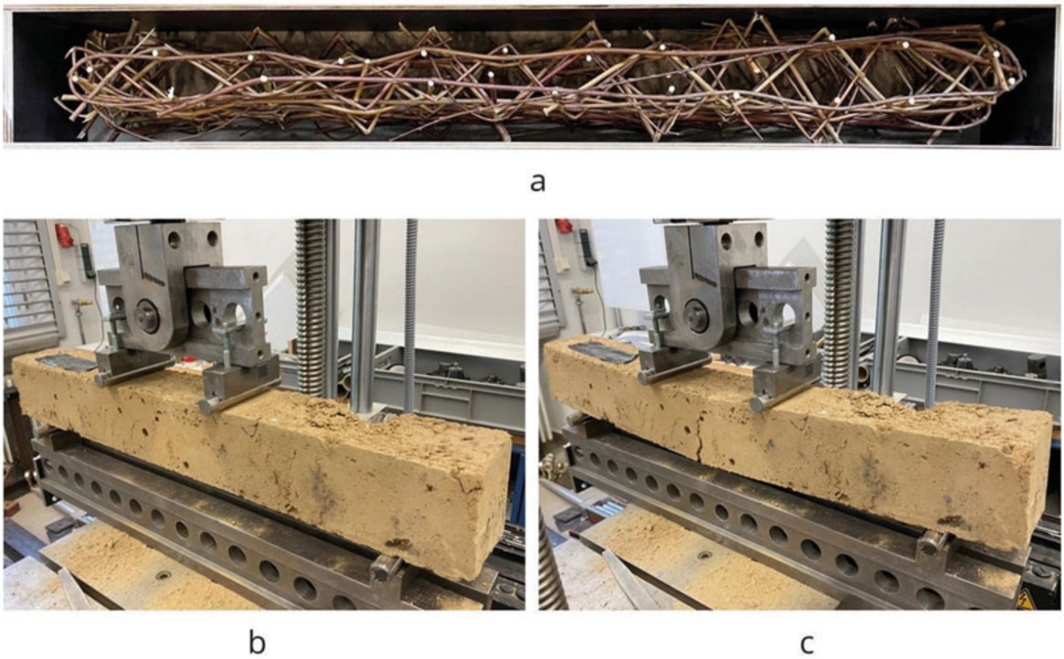

Fig. 17 Test specimen with spatially braided willow (**a**), specimen before loading (**b**), specimen at failure load (**c**)

Fig. 18 View of InterTwig

Fig. 19 Top view of InterTwig

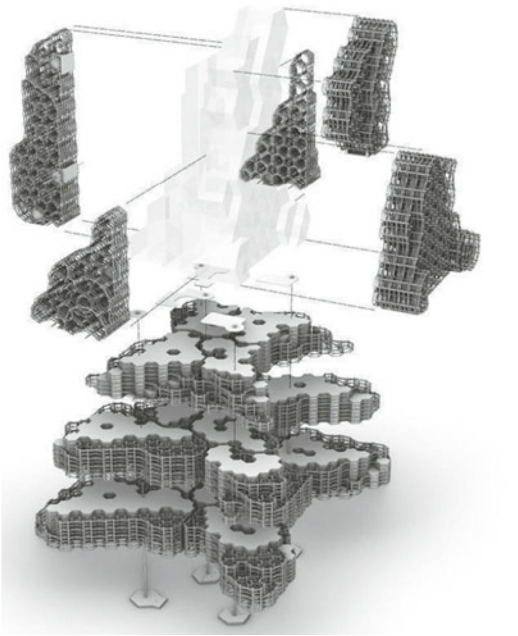

Fig. 20 Exploded view of InterTwig

components), integrate a structural scenario for earth distribution and test the assembly process.

Designed as a freestanding structure, the demonstrator forms a tapered shape that rises to a height of about 4 m. Its core is articulated into four legs at the base with a ground plane area of 7.5 m^2.

It consists of 21 components that have been prefabricated, thus enabling a production that is independent of weather conditions and a construction system that optimises ease of assembly and disassembly (Fig. 20). The 16 components at the base of the structure, composed of willow and earth, are geometrically interlocked and stacked on site. Here, the willow acts as a permanent formwork and as a tension reinforcement in the composite material. The top five components, which are made primarily of willow and mechanically connected to the bottom, are arranged in different layer orientations to create a vertical segment that relies on component-integrated joints and showcases the intricate filigree of the material system (Fig. 21). The structure’s materials are therefore functionally graded, with earth being predominant at the bottom to carry the loads from the top and distribute them over a larger area. To determine the proportion of earth to willow, each component was first analysed globally with reference to its local position, thus determining the approximate direction of the component's internal forces. This informed the overall earth distribution, which, thanks to the versatility of the willow formwork, can be placed only where needed, facilitating the implementation of material efficiency principles to create structural earth components that are lighter than usual applications like rammed earth. This resulted in earth and willow components with a total weight ranging between 150 and 430 kg and an average of 315 kg (Fig. 22).

By designing a construction and material system that does not use chemical binders, the components can be separated into renewable (willow, wood and straw) and non-renewable (earth) materials and circulated back through different cycles. By maintaining the earth in its raw form with no stabilising agents, it can be removed from the willow framework by saturating it with water and recycled without any significant loss of value. Once the earth is removed from the components, willow and wood can be returned to the biosphere through composting or anaerobic digestion.

The temporary purpose of the structure represented an opportunity to implement and test a construction system that was designed to work with reversible, easily accessible joinery systems and lifting anchors (Fig. 23). These connections are integrated into the components with wooden plates that are kept in place by the woven willow layers, while the lifting anchors for the components made of willow and earth additionally employ a threaded rod. A truck with a mounted crane was used to transport and instal the structure, which was assembled in 5 h and disassembled in 3 h (Fig. 24).

Digital design techniques were fundamental to handle and control the intricacy of different weaving patterns and their modification and optimisation according to the principles

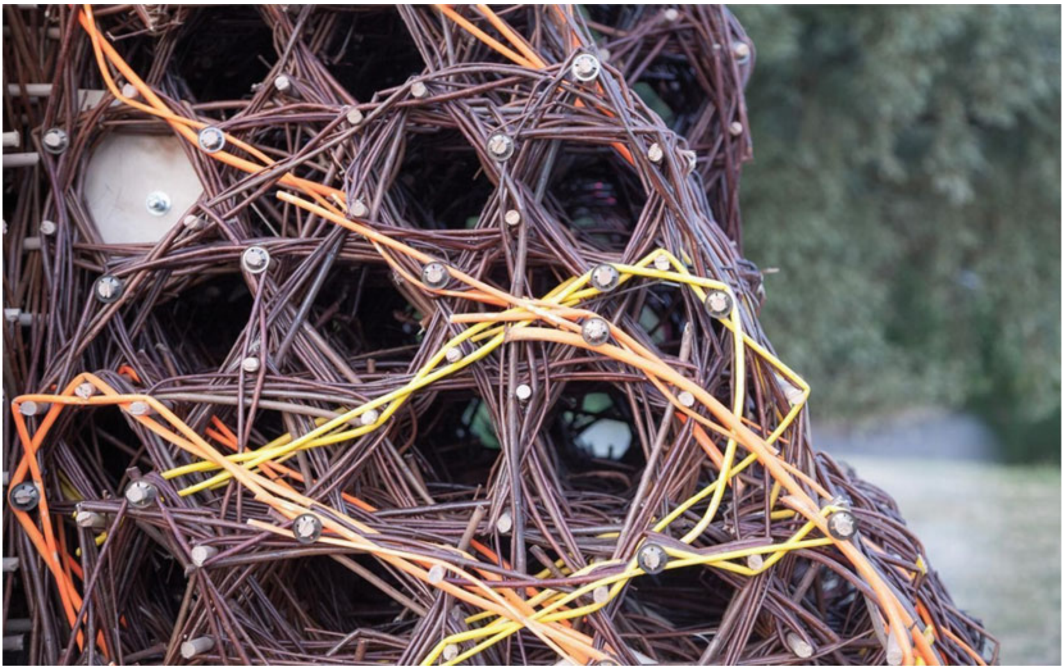

Fig. 21 Detail of a willow component, showcasing two pattern types (orange and yellow) and an integrated joinery

Fig. 22 Earth and willow components before assembly

Fig. 23 Exploded view of a portion of InterTwig showing the joinery system

discovered in the iterations of exploratory prototypes. While the application of digital techniques in this study focused on automation aspects, this is the first step for a process that could inform the geometries, both global and detailed, according to structural principles, thus adapting them to specific design conditions.

A process that mutually informed handcrafting, digital design and digital fabrication was developed, exploring the innovation potential provided by their combination. Digital design and digital fabrication allowed the development of customised principles that deal with the imperfections and variations that are intrinsic in plant-based materials, by-passing the standardisation necessary to conform to existing fabrication processes. While the current prototypes were mostly hand-crafted, a digital fabrication system was developed using the principles discovered in the study that could enable automated and affordable applications.

4 Discussion and Conclusions

The presented work showcases a proof of concept for the development of willow and earth composites for circular construction and their potential for digital fabrication, as well as

Fig. 24 Assembly of InterTwig

providing relevant research questions for future investigations.

Further research needs to be conducted on collecting data for quantifying and validating the structural performance and mechanical behaviour of the composite material. Although the results of this work are to be considered ahead of application scenarios in industry, increased automation, especially regarding earth casting, can contribute to enhanced efficiency and facilitate their implementation in construction both in terms of technology and economics. A higher degree of geometrical freedom will enable refinements and optimisations according to structural and material efficiency principles, as well as novel architectural parameters to further expand a language that is driven by the materiality and the possibilities of resolution and articulation afforded by the material system.

This study demonstrates a model for broadening the current construction material boundaries by revisiting vernacular materials and techniques and redefining their contemporary potential. In particular, it contributes to extending the expressive, morphological and construction potentialities of renewable materials and earth composites towards the field of architectural exploration. By implementing a design-through-making methodology, in which strategies are developed with hands-on physical prototypes across different scales and result in a 1:1 experimental proof of concept, it showcases the potential for a unified understanding of conceptual, material and production aspects.

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