TerraTimber

Digital circular construction methodologies for structural hybrid building systems with reclaimed wood and earth

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The TerraTimber research demonstrator examines digital circular construction techniques that utilize reclaimed wood and earth in hybrid structural systems. Through computational design and Augmented Reality (AR)-aided assembly, a full-scale modular system comprising columns, beams, slabs, and walls is investigated, focusing on a hybrid floor component. Geometric interlocking and friction provide a shear interface between wood and earth, thereby creating structural synergy. Computational tools optimize the integration of irregular reclaimed wood elements, while wooden nails enable metal-free connections and recycling. AR technologies enable assembly, combining computational precision, material imperfections, and human craft skills. A 1:1 prototype was built, and structural tests were conducted to assess load-bearing capacity and serviceability. The system ensures structural performance, exhibiting only 4.8 mm of deformation under typical residential load conditions, while offering design opportunities, particularly in terms of ceiling appearances. This modular approach extends material lifecycles, aligns with Digital Upcycling principles, and promotes resource efficiency for sustainable construction.

Keywords: *augmented reality (AR), circular construction, computational design, design-to-build, design-by-inventory, digital upcycling, earth, hybrid structural systems, modular construction, recycling, reuse, timber, wood nails, reclaimed wood*

INTRODUCTION

As interest in more sustainable construction grows, hybrid building systems that combine bio-based and mineral materials such as wood and earth are gaining attention. These systems can reduce the environmental footprint of buildings and provide synergistic benefits in several areas, such as structural and thermal performance, acoustic insulation, and fire resistance. Recent architectural innovations, coupled with materials science investigations, have begun to explore the untapped potential of the earth in horizontal elements for structural applications, particularly in floor slab systems. An example of this principle is the HORTUS office building, which demonstrates the integration of earth in a hybrid floor system assembly (Bonwetsch, 2024). In this case, the earthen component is self-supporting, while the timber structure carries the main structural loads. This approach integrates acoustic, fire insulation, and thermal mass directly into the floor, thus

Figure 1
TerraTimber
research
demonstrator

enhancing the multifunctional performance of the construction.

Recent research investigates the possibility of employing earth as a structural component between main load-carrying elements, such as timber or steel beams (HFT-Stuttgart, 2024), which builds upon historical references of the Prussian vaulted ceiling system, proposing the possibility of the earth taking an active role in load transfer. Another method uses wooden laths encased in earth covering to create a load-bearing framework, where the earth provides fire protection to the wooden laths and enhances the floor slab's thermal performance (Trummer, 2021). Additionally, timber-earth solid ceilings have been used in commercial buildings (Trummer, 2024). These systems feature timber beams as the primary load-bearing structure, with wooden laths fixed in between, and earth used as infill. In this arrangement, the earth primarily serves as a building physics function, acting as thermal mass and providing acoustic insulation, which demonstrates that hybrid floor systems can serve multiple purposes simultaneously. Together, these factors represent a trend towards more regenerative construction methods, resource conservation, and synthesis of different approaches, thus laying the groundwork for new, performance-based applications of natural hybrid floor systems. This approach aims to integrate and activate the earth as a load-bearing element, allowing it to resist compressive forces, while the timber takes on the tensile forces. However, this interaction is only effective if there is a proper shear interface and efficient transfer of shear forces between the two materials. A circular, metal-free solution is implemented in the TerraTimber research demonstrator's hybrid floor slabs through the arrangement of waste wood pieces into an articulated geometry that enables effective force transfer between the materials through geometrical interlocking. It is here implemented with industrial wood offcuts that are digitally upcycled and turned into large-scale floor slabs. This approach aims to integrate and activate the earth as a load-bearing element. This principle has already been tested with promising results in a CLT floor slab made with wooden shear blocks placed on top to create geometrical interlocking. Compared to metal screws, the wooden blocks demonstrated a higher slip modulus (k_{ser}) and reduced deformation in the full-scale (1:1) component (Haußer, 2025).

This paper describes the development and realization of a full-scale mock-up of a modular system that incorporates timber, reclaimed wood, and a hybrid wood-earth building system (Figure 2), demonstrating the principles of circular architectural design enabled by digital techniques.

METHODOLOGY

Central to this research was the development of hybrid wood-earth floor slabs, which highlighted the structural synergy between wood and earth while adopting a design-by-inventory approach that integrated reclaimed wood elements - primarily sourced from industrial waste - into circular construction components. The design process followed a bottom-up framework, considering material properties, structural principles, construction methods, and the requirements for transport and assembly. Augmented Reality (AR) was used to bridge the gap between computational design results and craft-based assembly, facilitating the creation of hybrid wood-earth floor slabs. Using AR allowed to manually handle the complexity of positioning and connecting unique reclaimed wood elements according to computational requirements. The earthen material was manually introduced into the timber framework within a temporary

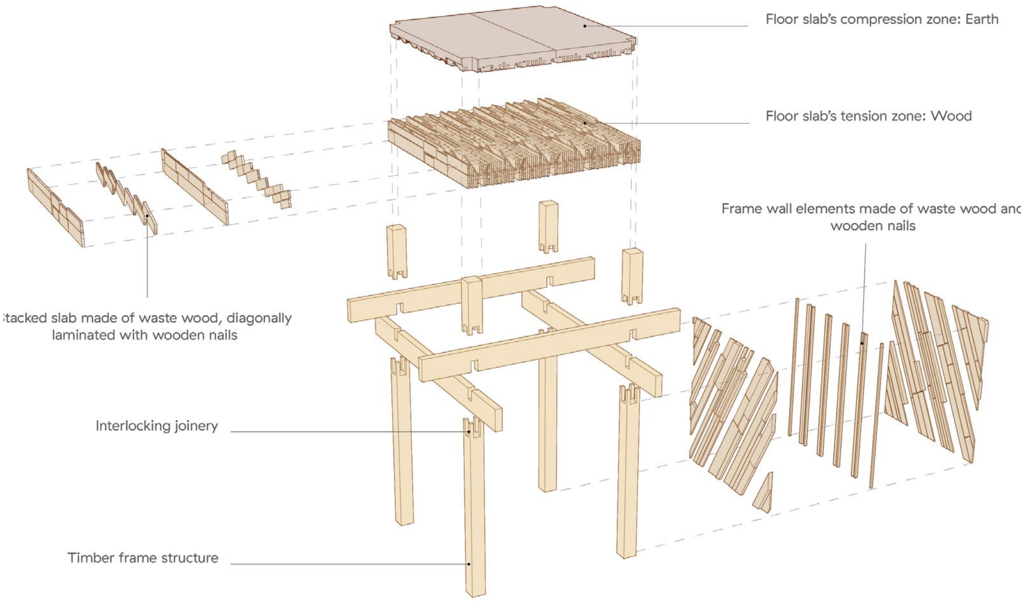


Figure 2
Exploded view of the building system

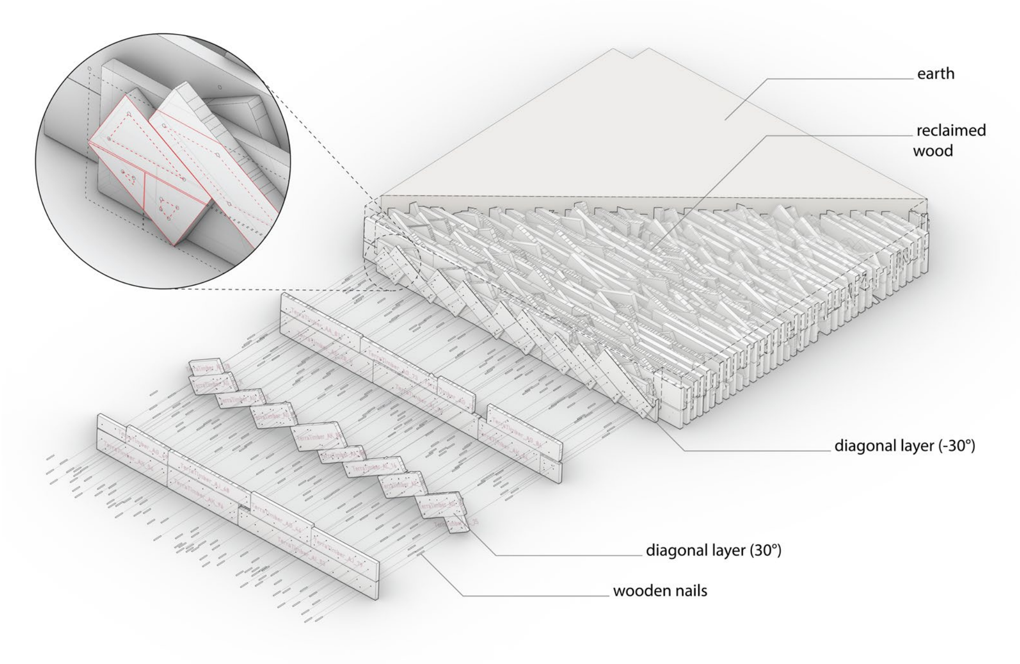


Figure 3
Computational design model (circle) geometric nailing logic

formwork, utilizing a pugmill mixer system equipped with a screw conveyor, flexible hose, and nozzle for controlled deposition. To evaluate the system's load-bearing capacity and ductility, structural tests were conducted on the 1:1 slab component, measuring both the deformation due to a representative residential load and a destructive scenario to analyze the structural behavior and inform further design optimization. By merging manual and digital craftsmanship, this research established a proof of concept for a hybrid construction system utilizing reclaimed wood and earth, showcasing the potential inherent in digital upcycling.

Computational Design

This research utilized a previously developed workflow that enabled the transition from creating digital and physical inventories of waste wood pieces to employing bin-packing techniques for aggregating them into structural components (Zanetti et al., 2025). The methodology was applied to an inventory of industrial offcuts digitized using photogrammetry to capture their geometric variability and enable computational processing. The offcuts vary in height (100-200 mm), length (280-1800 mm), and depth (21-36 mm). The computational design workflow followed a layered approach, systematically aggregating waste wood elements using a bin-packing algorithm. The layer depths were based on the range of depths found in the inventory, which were grouped into four categories due to the limited quantity of available material. The script inputs included a digitized inventory of wood pieces, a predefined volumetric boundary subdivided into layers according to the varying heights of the available

Figure 4
AR-supported assembly

inventory, and alternating aggregation angles per layer following a repetitive pattern of 0°, 30°, 0°, -30°. This pattern was inspired by diagonally laminated timber principles, enhancing structural integrity by distributing forces more effectively. The workflow included an intersection analysis between adjacent layers to identify contact zones, where elements from different layers meet. These areas served as the basis for placing wooden nails that connect the layers (Figure 3). The resulting intersection outlines were offset by a defined distance, ranging from 26 to 32 mm, varying to prevent overlap between nails on different layers. Nail placement was determined at discontinuity points along these outlines, where the angle is below 150° and where no other nail is located within a 25 mm radius. These parameters were based on the minimum edge distances required for the wooden nails; however, optimal spacing may vary depending on specific load case scenarios and Finite Element Analysis (FEA) results, which were not part of this research.

Since the overall component dimensions did not always align precisely with the combined lengths of individual inventory elements, the script was designed to cut elements to fit the required layer length rather than leaving gaps. A cutting list was generated for fabrication, including specified lengths and updated element identifiers. Any remaining offcuts were reintegrated into the inventory for use in the following layers.

Finally, the script generated a detailed 3D model that supported fabrication through AR, providing a layer-by-layer arrangement of wood elements, unique identifiers for each component, and precise nail placement locations.

The script was designed to automate the design process, managing the inherent complexity of working with irregular waste wood materials and addressing the limitations that make manual handling challenging. Despite these advances, several challenges remain and require further investigation. For example, overlapping elements between layers can result in discontinuities that compromise cohesive assembly. However, since bin-packing algorithms are order-dependent, they are difficult to optimize, often necessitating complete reconfiguration rather than incremental adjustments. In this first phase, outcomes were visually evaluated by the team, with configurations manually accepted or rejected. Additionally, the project explored a metal-free structural connection between wood and earth, taking advantage of the geometric articulation produced by the bin-packing process. This articulation emerged organically from the irregularity of the inventory and the bin-packing logic, rather than being predefined within the script. Future research should focus on developing methods to analyze and optimize this emergent geometry, enabling a more systematic integration of material irregularities into structural performance.

AR-supported Digital Fabrication

Following previous research, Augmented Reality facilitated the assembly process (Fischer et al., 2024). Using Hololens 2 glasses, visualizing design data from Rhino and Grasshopper through the Fologram plugin, a 1:1 scale digital model of the floor slab component was projected onto the ground layer-by-layer, allowing for the precise identification and placement of individual elements (Figure 4). The AR-supported assembly of diverse and irregular reclaimed wood elements enabled effective handling of unique geometries and inconsistencies. It acted as a template for placing each element in an AR-supported manual construction process. The AR overlay provided real-time spatial guidance, reducing the need for conventional drawings or measuring tools. This not only enabled the building process but also helped deal with the tolerances and imperfections of the irregular wood elements. Furthermore, the visual clarity and interactive interface of the AR system made it easier for untrained workers to participate in the assembly process. Once the position of a specific element was determined, a nail gun was used to drive 4.7 x 58 mm wooden nails (Lignoloc) according to the positions indicated by the digital template.

Figure 5
Multistorey building system

Structural Test Design

This research demonstrator aimed to develop scalable hybrid building systems suitable for multistorey applications. To support this objective, tests were defined to evaluate the hybrid floor slab's structural performance. The main aim was to assess the behavior under typical residential load conditions. The tests simulate real-life scenarios relevant to multistorey housing structures and provide critical data on strength, stiffness, deformation behavior, and failure modes. Notably, the earth mixture used in the system - free of cement additives - demonstrated a compressive strength of approximately 1.67 N/mm^2. The insights gained from this empirical analysis informed the iterative development of the building system and its potential for scalable application in residential construction.

RESULTS

The primary structural support system consisted of a timber frame. Timber columns, measuring 20 × 20 cm, supported the vertical loads, and the horizontal elements were arranged as beams with a cross-section of 10 × 40 cm. This arrangement depicts a portion of a multistorey architectural model (Figure 5) intended to explore the use of hybrid floor elements in combination with lateral bracing systems. Japanese timber connection principles inspired the primary load-bearing structure, showcasing demountable connections that require no fasteners (Moradei, 2018). For example, one wall, constructed from recycled wood elements, was installed between the columns, providing lateral stiffness. Additional cross-bracing in the direction perpendicular to the wall was achieved using metal tension cables connected to the structure. This combination of measures allowed both in-plane and structural stability while retaining the overall system's reversible and demountable nature. The size of one hybrid floor component - 1.25 meters wide, 2.5 meters long, and 40 centimeters high - was determined according to predetermined standards in timber construction, enabling future integration into standard building structures. The lower surfaces of the ceiling elements displayed a purposeful pattern of smooth and rough surfaces, designed for acoustic performance while also emphasizing aesthetic value as a design potential.

Figure 6
Hybrid wood-earth floor slab

Figure 7
(top) Test scenario with residential loads
(bottom) Test scenario until failure

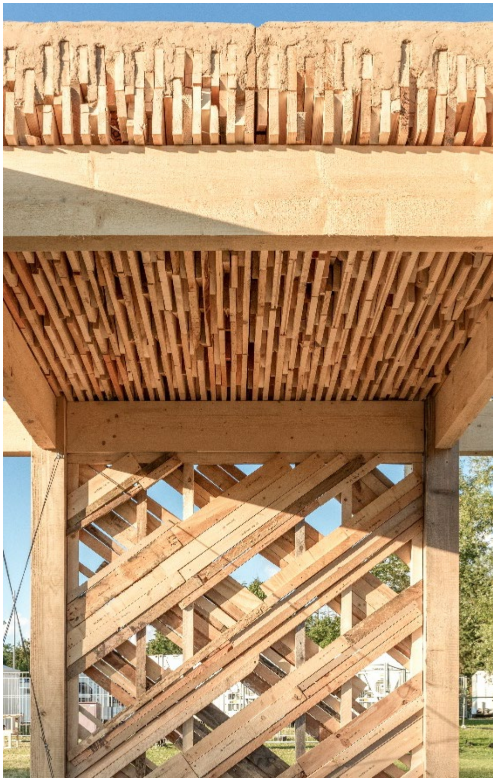
Structural Evaluation

Full-scale 1:1 tests were conducted to evaluate the load-bearing capacity and ductility of the hybrid floor slab system. Two distinct test procedures were performed. First, the floor slab element was subjected to a representative residential load to quantify its deformation, ensuring compliance with predefined serviceability limits. Second, the component was loaded to failure to systematically analyze the failure mechanism, providing critical insights for further optimization and design refinement. To replicate the actual support conditions, the tests are conducted using a test setup in which the hybrid wood-earth slab is supported by concrete blocks, with a span of 2.25m between the supports. The load is uniformly distributed across the slab's surface using steel beams, wooden plates, and wooden fiberboards.

This arrangement ensures a realistic load simulation, which is crucial for understanding the behavior of the hybrid wood-earth slab and its failure mode (Figure 7). In the first test scenario, the floor slab component was subjected to a uniform load of 3.3 kN/m², with 1.0 kN/m² attributed to the additional installation load and 2.3 kN/m² attributed to the variable loads, as per DIN EN 1991-1-1 (2010).

This standard defines the design loads for residential buildings (1.5 kN/m²), including partition loads (0.8 kN/m²). A screed is often necessary for timber floor slabs to meet sound and vibration requirements. However, due to the high mass already added by the earth, the screed can be eliminated, explaining the reduced installation loads of 1.0 kN/m². The deformation

Figure 8
Articulated ceiling and spatial interior impression



limit for timber slabs is l/300, meaning that in this case, the maximum allowable deformation due to the span length is 7.5 mm. The structural test revealed a deformation of 4.8 mm, within the acceptable limit, due to the applied load, which is only 64% of the allowable deformation. This indicates that, in further steps, the span can be increased, and the overall height of the component can be reduced.

The second scenario involved a destructive test to determine the failure mode during load application. When the nails broke, failure occurred at a load of 110 kN. Prior to failure, visible deformations were observed, indicating a ductile material behavior, which is desirable for structural elements.

CONCLUSION & DISCUSSION

The TerraTimber research demonstrator offers a viable proof of concept for a novel hybrid building system that combines reclaimed wood and earth through a design-by-inventory approach, supported by computational design methods and AR-enhanced fabrication. By integrating industrial wood waste and earth into a structurally reinforced composite, the project reveals the potential of circular construction beyond traditional, compression-based applications of earth. The layered bin-packing approach, utilizing rotation angles from diagonally laminated wood, facilitated the creation of wood elements that are structurally interlocking while addressing the geometric variation in the reclaimed stock. The design process emphasized material considerations, fabrication feasibility, and the integration of digital and physical realms, resulting in a hybrid system that fulfills structural requirements while enhancing architectural expressiveness and acoustic performance.

AR has demonstrated significant potential in integrating computational results with manual construction techniques, enabling element placement that is independent of conventional templates and tools. This approach highlights a promising direction for inclusive and accessible construction techniques that are applicable in both technologically advanced and resource-constrained environments.

Structural tests of the hybrid reclaimed wood and earth composite slab yielded promising results, demonstrating minimal deformation under service loads and a high failure load. The results provide a foundation for future enhancements, primarily by incorporating automated assessment criteria into the design process and conducting additional tests under varied conditions.

Future developments should strive to increase the relative competitiveness of these systems compared to conventional alternatives. This success stems from a development process that attentively balances functionality, structural performance, manufacturability, and design specifications. By enhancing these factors, broader adoption of hybrid wood-earth floor systems becomes feasible, while also increasing their relevance within traditional building practices.

This project proposes a circular building component. If the floor slab is not reusable at the end of its life cycle, it can be disassembled and recycled. The earth contained within the component can be directly recycled by shredding or washing. At the same time, the wooden elements can be incorporated into cascading wood systems for secondary or tertiary applications, further enhancing resource efficiency. The research illustrates that hybrid systems can optimize architectural solutions while prioritizing environmental sustainability and resource efficiency, integrating digital upcycling, and embracing material irregularities as a benefit, thus offering new prospects for circularity, adaptability, and resilience in architecture.

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