# Digital Design and Fabrication Strategy of a Hybrid Timber-Earth Floor Slab

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**Abstract**. The production of floor slabs with their high requirements for fire protection, thermal mass, and sound insulation is a central challenge in multi-storey timber construction. The research presented in this paper explores the possibilities of a timber-earth slab (T.E.S.) that can meet such high demands while being fully recyclable. T.E.S. comprises a hybrid structure, which aims to combine the strong tensile properties of wood with the beneficial properties of earth in terms of thermal mass, thermal activation capabilities, fire resistance, and sound insulation. It integrates a novel material technology capable of casting earth with low water content and combines it with robotic technology that enables the bespoke fabrication of a filigree wooden structure tailored to mechanically interlock with the earth infill. The proposed method makes it possible to place the earth infill in the lower part of the floor slab and thus expose it to the interior space, whereby its storage mass and component activation can be fully utilized. This paper presents the concept and design principles, initial findings on the system's loadbearing behaviour, as well as the experimental validation of the novel fabrication process in 1:4 and 1:1-scale demonstrators, in which the general feasibility of the system in assessed. The paper finally discusses the proposed methods and results of the experiments and outlines further steps for transferring the system into building practice.

**Keywords:** floor slabs; digital fabrication; timber; earth; net-zero

## 1. Introduction

The Architecture, Engineering and Construction (AEC) industry is responsible for almost 40% of global energy and process-related $CO_2$ emissions, 38% of global greenhouse gas emissions, 12% of global drinking water consumption and 40% of waste generation in developed countries [1]. Therefore, reducing greenhouse gas emissions and waste in the AEC sector has increasingly moved into our social and political focus. Digital planning and fabrication offers opportunities to address these challenges and to reduce resource consumption and increase productivity [2]. Bespoke fabrication methods allow for the use of optimized geometry, where material can be individually placed only where it is structurally or building-physically needed, thus substantially reducing the overall material consumption.

The World Green Building Council has defined three impact areas for meeting the UN Sustainable Development Goals [3] in the construction sector: Climate Action, decarbonisation of the built environment; Health & Wellbeing; and Resources & Circularity, moving the AEC sector towards a circular economy [4]. While timber is generally regarded as a sustainable, carbon-negative building material [5], its flammability [6] and low thermal inertia pose major challenges for multi-storey timber construction [7]. The resulting lack of passive cooling, which is particularly relevant for floor slabs, leads to an increased susceptibility to overheating [8], which is likely to lead to a loss of comfort and increased energy consumption, especially in increasingly hot climates [9]. The goal of the Timber Earth Slab (T.E.S.) research project [10] is to combine the strong tensile properties of timber with the positive properties of earth in terms of thermal mass, the possibilities of thermal activation, and fire and noise protection to achieve sustainability, performance and economy in one recyclable building system. The system features a minimalist approach that includes a fine-grained, load-bearing timber grid that also provides the necessary support for mechanically interlocking with an earth infill. In this grid, the wooden boards are arranged crosswise in individual layouts according to the load-bearing requirements, for which a robot-assisted assembly process is proposed. For the earth infill, the novel material technology allows the earth to be cast without ramming. As an alternative to timber-concrete slabs, where the concrete is typically cast onto the wood structure, in T.E.S., the mineral layer in the form of earth is cast into the wood structure. This results in the mineral layer being located on the bottom of the slab and thus being directly exposed towards the interior space on the ceiling (see **Figure 1**). This approach promises increased fire resistance as well as a pleasant room climate through its exposed storage mass and options for component activation.

To evaluate and validate the T.E.S. system, a robotic assembly study was conducted on the scale of 1:4. The structural behaviour of the timber structure itself was evaluated in 1:1 scale through 4-point bending tests on segments with 0.5m width and 3.12m length. Finally, the feasibility of the earth casting, the surface quality, and the rigidity of the timber-earth compound was tested by building a series of 1:1 scale prototypes and exposing them to bending and vibration.

The context and state of the art for this research is detailed in Section 2 of this paper. In Section 3, the concept and method are outlined. Preliminary results are presented in Section 4 on behalf of experimental studies to illustrate the practical relevance and implementation of the proposed method. Finally, results and conclusions of the experiments and further steps for transferring the system into building practice are discussed in Section 5.

**Figure 1.** Side view of a 1:1 scale Timber Earth Slab prototype, showing how the layer of earth is located on the bottom of the slab and thus exposed towards the interior space.

## State of the art

### *1.1. Timber-hybrid construction*

**Figure 2.** Timber-concrete-composite slab, Zurich, 2019; source: zhaw, 2019.

***Timber-concrete composite slabs.*** Timber-concrete composites are engineered wood products that are commonly used for structural components that are mainly subject to bending load; that is, from floor systems to long-span bridges. In this way, the tensile strength of wood and the compressive strength of concrete can be exploited, and the concrete layer can further be used for sound insulation and fire protection [10]; variations of this system include X-Floor [12] and Swiss Wood Concrete Deck [13]. While the proportion of concrete and reinforcement is reduced in timber-concrete slabs compared to reinforced concrete slabs, their recyclability is limited [14] and their thermal mass can usually not be utilized as the mineral layer is located at the top (see **Figure 2**).

***Timber-earth hybrid slabs.*** Historically, timber-earth hybrid construction methods are among the oldest construction methods in Germany [14]. While earth is usually applied in walls, there are also solutions for timber-earth floor slabs; most notably the latia-earth (see **Figure** 3) and the viga-earth floor slab: In both solutions, which only distinguish in the construction process, a light earth mixture encapsulates boards that span between timber beams. While developed for improving fire protection and sound insulation, the systems do not satisfy today's building standards and imply a labour-intensive construction process [16]. Alternatively, earth brick vaults were historically used to bridge the gaps between timber beams in order to provide thermal mass and fire protection [16]. In a recent example, a prefabricated floor slab showed the possibilities of combining rammed earth vaults with timber beams complying with today's building codes (see Figure 4) [18].

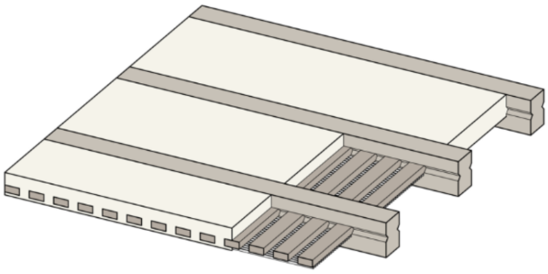

**Figure 3.** Latia-earth floor slab; source: Dachverband Lehm Germany

**Figure 4.** Model of the timber earth floor slab system; source: ZPF engineers and Herzog and de Meuron Architects.

### *1.2. Robotic timber assembly*

Integrating robotic systems in the fabrication and assembly of timber frame structures expands the digital chain throughout the whole spectrum of design to construction and enables the introduction of bespoke automated production processes [19]. Therefore, this research capitalizes on the ability of robotic arms to spatially assemble timber members into bespoke timber constructions such as previously shown in [20] [21] or [22].

A field that has not been addressed in this context yet is the development of bespoke hybrid components: This leads to a drastic increase of dependencies and iterations as the different members and their respective fabrication steps have to be designed in parallel and in dependence of each other (see Figure 5).

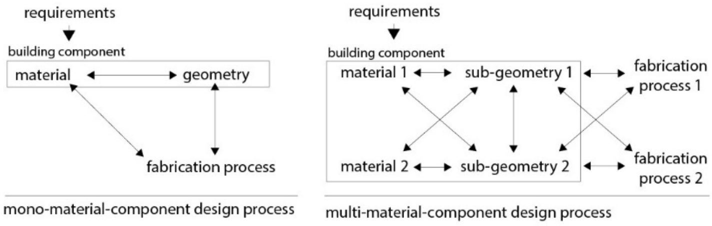


**Figure 5.** Design process

For example, to develop the geometry of the timber members, the designer not only has to address material properties and fabrication constraints but equally consider the interplay with members made from a different material and the fabrication processes connected to them. Conversely, in the development of the fabrication process for the timber members, one has to evaluate whether the process and the resulting (geometric) constraints are even compatible with the requirements of the second material and its potential fabrication steps and adapt the process if required.

## 2. Method and design principles

The design principle of T.E.S. is to combine a load-bearing timber structure with an earth infill, which provides thermal mass, fire protection, and sound insulation while conserving the timber members [15]. Based on Cross Laminated Timber (CLT), a structural system is developed in which wooden boards are not cross-laminated as a full volume but in a structurally optimized arranged grid, as previously proposed by [23], that can later mechanically interlock with a self-supporting earth infill (see **Figure** 6). In this process, it is envisaged that the bespoke timber layouts are assembled by robotic arms cutting, placing, and joining the wooden boards based on a digital model. Utilizing poured earth technology allows the earth infill to be cast into the timber structure without ramming. A custom coffering layer of non-structural beams is additionally included at the bottom of the slab to prevent potential tension cracks as well as for aesthetic reasons (see Figure 7). On top of the slab, any screed solution adapted to the individual situation can be applied, which is not the primary focus of this research.

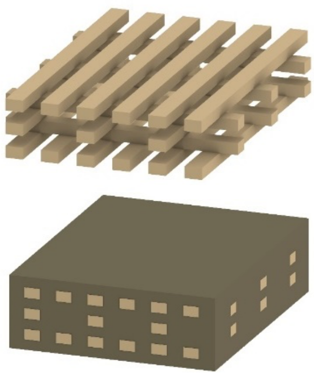

**Figure 6.** Load-bearing timber grid (top), encapsulated in an earth infill (bottom).

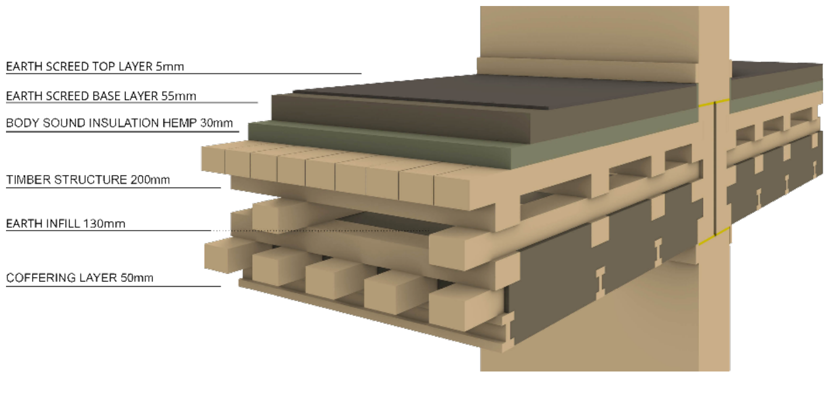


**Figure 7.** Exemplary T.E.S. system section with cover screed and body sound insulation.

**Earth infill.** To utilize the mineral layer for both fire protection and thermal mass, it is important for the earth infill to be exposed and therefore self-supported, mechanically interlocking with and encapsulating the load-bearing timber structure.

Since the dense geometry of the timber structure makes ramming the infill impossible, a poured mixture with limited aggregate size and sufficient flowability is required to fill all the gaps while not developing major cracks. These properties, usually associated with concrete technology, can be transferred to earth material by using admixtures. The rheology of earth can be controlled by mineral admixtures that act on the clay particles as plasticizers and accelerators, making the material fluid in a first step and gradually stiff in a second step, leaving enough time between the two to cast the material in a formwork. This technology is referred to as DeCo process; the admixtures allow to work with earth in a liquid state while keeping the water content to a minimum. This allows the infill to be cast without compromising the final strength of the material and without the use of cement. Further details can be found under [24].

While the proposed approach allows for the earth infill to be cast in situ into a prefabricated timber structure, the investigations in this paper also consider full-prefabrication scenarios, evaluating both the use of a vibrating needle and a vibrating table for compacting the earth within the structure.

**Timber structure.** The underlying design objective of the cross-laminated timber structure is to minimize the overall timber consumption while ensuring structural integrity to the system as well as enough density for providing mechanical interlock to the earth infill. This research thus followed both an analytical approach on behalf of a numerical parameter study, where the structure was estimated and optimized based on the analysis of an FE simulation, as well as an experimental approach, in which the results of the FE simulation were verified in 4-point bending tests of three 1:1-scale prototypes (see Section 0). While the structural system is capable of two way spanning, this phase of the research focuses on a one way scenario with a limited span of 3 meters. Structural considerations and optimization strategies thus involve densifying the start and end members in the span direction and varying the spacing of members perpendicular to the span direction as required by the shear forces. Furthermore, the effects of various board cross-sections for the load-bearing behaviour and the integrity of the earth infill are to be considered.

## 3. Experimental studies and preliminary results

### *3.1. Computational design and robotic assembly*

A parametric design model, developed in this project, allows for the generation of geometries with different lightweight cross-laminated timber panel sizes and element densities, from which machine instructions to control the assembly process can be derived automatically. The robotic assembly process of such a panel was experimentally validated through 1:4-scale studies using two collaborative UR10e robotic arms. The first robot picked and placed the timber members, while the second robot applied wood glue with a custom dispenser (see **Figure** 8).

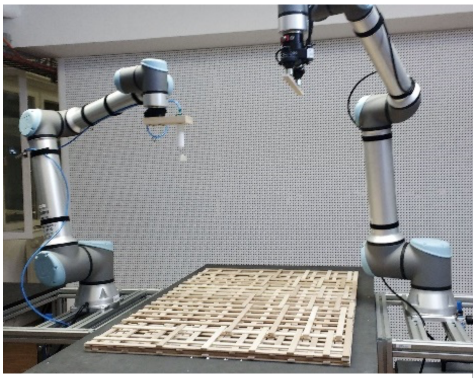

**Figure 8.** Robotic assembly study of a lightweight CLT panel with two collaborative robots in 1:4 scale.

### *3.2. Integrity of the timber-earth compound [10]*

The assessment of the general integrity of the timber-earth compound was done based on a set of 1:1-scale prototypes with various board cross sections. They were built with untreated, planed fir wood boards without finger-jointing and an earth infill with a density of approximately 2200kg/m$^3$. The earth mixture consisted of filter sludge (a left-over product from sand and gravel production consisting of clay and silt; Figure 9), 0-4mm sand, 4-8mm gravel, flax fibres, water, and stabilising admixtures and was condensed using a vibrating needle. The formwork consisted of coated plywood or oiled timber boards and was removed after approximately four days. To facilitate an even drying process, the prototypes were covered by plastic sheets and the exposed surfaces artificially humidified in the first two weeks after casting. To understand the drying behaviour of the timber-earth compound, separate prototypes were built from which material was extracted for kiln-drying

**Figure 9.** Collecting filter sludge in a gravel plant near Wasserburg am Inn.

tests. Based on their outer dimensions, prototypes were sorted in two categories: S (80x50cm) and M (312x50cm) (see Figure 12).

*3.2.1. Integrity of the earth infill without bending forces (S-series).* Based on three sets of two prototypes with 50x80cm dimensions (see Figure 11 and 12), the general integrity of the earth infill and the influence of various board cross sections (from 50x30mm to 100x40mm) and earth mixtures with various sludge and aggregate ratios was evaluated. The main evaluation criteria were the amount and size of cracks surfacing in the earth infill.

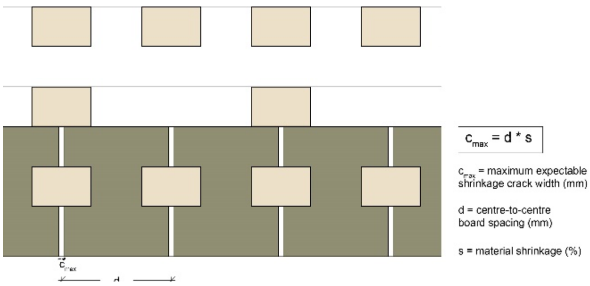


**Figure 10.** Assumptions on the evolution of shrinkage cracks parallel to the span direction: Cracks most frequently occur directly on top/underneath of boards where the earth infill reaches its minimum thickness. The larger the center-to-center spacing of the boards that are surrounded by infill, the likelier the occurance of major cracks. For example, 100mm spacing (60mm board width + 40mm gap) and 2% of shrinkage can according to these assumptions lead to cracks of up to 2mm. As for the horizontal gap between boards, a minimum width of 45mm was kept to ensure a vibrating needle can be inserted in the gaps.

**Figure 11.** Casting studies of four geometrically identical S-prototypes to evaluate different earth mixtures with various water contents and sludge/aggregate ratios.

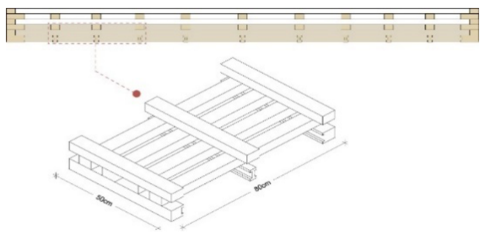

**Figure 12.** Structure of the 1:1-scale M-series prototypes, and derivation of the S-series fragments. While the 50mm bottom coffering layer remained unchanged, various spacings and board formats ranging from 50x30mm to 100x40mm were tested in the other two layers.

Already in the first preliminary results, a solid bond between the timber members and the earth infill was noticeable. If cracks surfaced, then directly on top or underneath of boards that are encapsulated by the infill with uneven shrinkage being the expected cause (Figure 10). While various earth mixtures delivered only marginally different results (see Figure 13 and Figure 14), it was

| Material | Dry Weight (kg/m$^3$) |
|---|---|
| Sludge | 500,6 |
| 0-4mm sand | 935,2 |
| 4-8mm gravel | 626,6 |
| Fibres | 3,9 |
| Admixture (Oxara) | 7,5 |

**Table 1.** Mixture design used; the ratios are highly dependent on the sludge used and therefore not transferable.

**Figure 13.** Top surface of the reference prototype: 60x40mm board format and a 24/76 sludge/aggregate ratio. Only very few and fine cracks are visible.

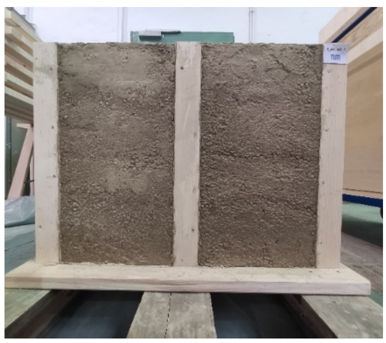

**Figure 14.** Top surface of a prototype geometrically identical to the one in Figure 13 but with a 32/68 sludge/aggregate ratio: only marginally more cracks recognizable

observed that the geometry of the timber structure plays an important role: If the minimum infill layer thickness undercut 40mm, an excessive number of cracks was the result (Figure 15), while increasing it to 50mm had only little effect. Increasing the centre-to-centre board spacing generally led to an increased occurrence of cracks (Figure 16); narrow board cross-sections therefore showed to be advantageous in this respect. Based on these insights, it was decided to conduct further experiments with 60x40mm cross-section boards, and a 24 to 76 sludge to aggregate ratio as shown in Table 1.

**Figure 15.** Top surface of a prototype with a 50x30mm board format: significantly more cracks. With the bottom layer not showing an increased occurrence of cracks, this is expected to be a result of an insufficient layer thickness of 30mm.

**Figure** 16. Top surface of a prototype with a 100x40mm board format: significantly more cracks. With the bottom surface showing a very similar behaviour, this is expected to be a result of a too large centre-to-centre distance of the boards.

*3.2.2. Integrity of the earth infill under bending (M-series).* With the earth infill being located in the tension zone of the slab, the possibility of tension forces leading to damages in the earth material had to be investigated. For this purpose, 1:1-scale prototypes with a realistic span had to be built and exposed to bending and vibrations. While the amount of extension of the bottom surface under bending is very small in theory (3.33mm at l/300 and 3m span), many concerns were raised with respect to shocks and vibrations potentially leading to damages in the infill. Three M-series prototypes with a 3 meter span and 0.5m in width (except for coffering layers geometrically identical with the prototypes for load-testing, see Section 3.3) were built with the board lamination being realized with Jowapur 686.20 glue [25] and a spindle press (see Figure 18). The coffering layer was omitted in one of the three prototypes to test its influence. To allow for bending already during the casting process, the prototypes were rested only at the supports on the sides with the formwork being attached to the timber structure (see Figure 17).

**Figure 17.** Casting Process of an M prototype. Bottom and side formwork are directly connected to the timber structure using screws and clamps, and the arrangement is not supported in the centre, to allow for bending already during the casting process.

**Figure 18.** Lamination process of the timber structure of an M-series prototype using a spindle press and IPE100 beams.

While the prototypes surfaced minor shrinkage cracks parallel to the span direction, cracks perpendicular to the span direction, an indicator for the occurrence of tension cracks, were not to be found, even when the coffering layer was omitted (see Figure 20). Transporting the slabs in a car or jumping on them after 28 days of drying did not lead to any damages. The bending of the slabs under their own weight, measured with a laser distance measuring device, amounted on average 5mm at the

**Figure 19.** The finalized set of three M-series prototypes with earth infill.

**Figure 20.** Surface excerpt from a prototype with coffering (left), showing a few shrinkage cracks in span direction but no tension cracks perpendicular to it, and without coffering (right), showing no tension cracks but an increased amount of shrinkage cracks parallel to the span direction.

point of formwork removal and 10mm after 28 days of drying. This constant increase in bending can be explained by the continuous increase of humidity in the timber boards (see 4.4.2).

### *3.2.3. Load-bearing behaviour of the timber structure (M-series) [26]*

The structural behaviour was analysed based on a slab fragment with 0.5m width and 3m one-directional span. As a first step, a numerical parameter study of various configurations was undertaken based on an FE simulation that was conducted with the software Ansys. The structure was designed towards a maximum deflection of l/300 under a design load of 8.515kN/m$^2$, derived from 3.75kN/m$^2$ permanent load and 2.3kN/m$^2$ live load. The structure was materialized with C24 fir wood without finger jointing and glued connections analogous to the M-series prototypes (see section 3.2.2).

The 60x40mm board format that was chosen based on the infill tests (see section 4.2.1.) served as the basis of a 5-layer geometry. The top and bottom layer must resist the compression, respectively tension forces from the bending moment while the FE analysis showed that the centre layer can be reduced to 10% before leading to major deformation. The boards perpendicular to the span direction must transfer shear and, towards the supports, rolling shear forces. For this reason, the spacing of the boards was densified towards the supports. Rolling shear resistance could be further improved by using an alternative timber species, particularly poplar or beach, and using boards with an annual ring angle that is as close to 45° as possible. Increasing the width to height ratio of the boards from 1.5 to 2.0 only led to a 5% increase of rolling shear resistance and was therefore not implemented.

These findings led to the design of the slab geometry of the M-series (see Figures 21 and 23) with a timber consumption of 0.0685m$^3$/m$^2$ and 10.2kN design load. Three physical prototypes were built to undertake 4-point bending tests in accordance with DIN EN 408 with the applied force and deflection measured and compared to the predictions from the FE analysis. In the experiments, the prototypes showed an increased stiffness of 5-9% compared to the FE analysis. L/300 deflection was reached at 10.10-11.03kN, failure occurred two times because of rolling shear at 13.4-13.9kN, one time because of transverse stress at 17.4kN (see **Figure** 22).

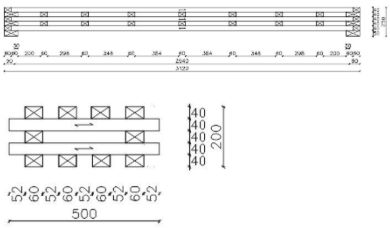

**Figure 21.** M-series prototype geometry

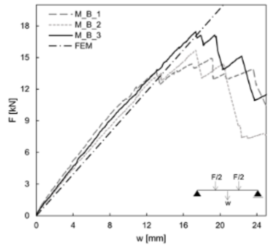


**Figure 22.** Measured bending deformation (w) of the three prototypes under applied load (F)

**Figure 23.** Four-point bending test.

### *3.3. Overall workflow*

*3.3.1 Earth filling*. Casting prototypes using a vibrating needle took two people approximately 45 minutes per square meter and resulted in a rough finish including major air pockets. In comparison, casting an 80x50cm$^2$ sample with a vibrating table resulted in a much satisfying result. The process took approximately 10 minutes, though most of that time was spent waiting for the infill to spread evenly. In further experiments, condensing the earth infill with external vibrators will be tested and evaluated.

*3.3.2 Drying behaviour of timber and earth members*. [26] The drying behaviour of the different materials at different locations was assessed by extracting material from S-series prototypes and assessing the humidity for 28 days using the kiln-drying method. In the case of the earth infill, the material would be extracted at three different locations (top surface, centre, bottom surface) to assess the drying speed in different parts of the slab. Like with the other prototypes, the objects were covered with foil and the surfaces humidified and stored in an interior space with the humidity and temperature of the air being recorded. While the humidity of the earth infill decreased from 8% to 4% at a similar speed at all locations, the humidity of the timber members, absorbing water from the surrounding earth infill, continuously increased from 8.1% of 27.7% throughout the measurement period.

## 4. Conclusion and Future Outlook

This research has presented a novel floor slab system made of timber and earth and demonstrated its general feasibility. While the robotic assembly strategy was only tested and evaluated on a 1:4 scale, both the load-bearing capacity of such a lightweight CLT and the integrity of the hybrid timber earth construction was validated on 1:1 scale. The experimental studies showed that the timber members can form a solid bond with an unreinforced, uncompressed earth infill that keeps its integrity under bending and vibration. Nevertheless, there are many open questions, including but not limited to fire resistance and sound insulation, up to which degree the structural system can be improved for longer spans, and whether an efficient and industrialized production process can be developed despite the extensive drying time of the earth infill. While the humidity of the timber members continuously increased up to 27.7% in the measurement period, it is unclear how long it takes to decrease to less than 12% again, and strategies will have to be developed for either preventing

**Figure 24.** Interior study

the absorption of water or adapting the process to the temporarily increased humidity of the timber members. The long-term goal of the project is to not only introduce the system to widespread building practice, but to expand to other components and support the expansion of timber construction beyond temperate climate zones (see Figure 24 for an interior study and Figure 25 for a future vision).

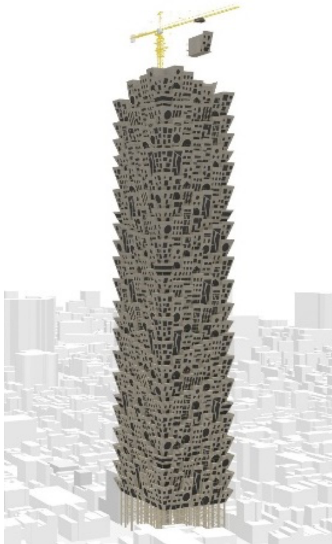

**Figure 25.** Future vision: Individualized urban construction with hybrid timber and earth construction.

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