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Horizontal Earth: A Novel Perspective on the Shear-Bond between Timber and Earth in Bending-Stressed Components

T Haußer[1] and R La Magna[1]

[1]dos - Design of Structures, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

E-mail: tamara.hausser@kit.edu

Abstract. The development of innovative and sustainable building materials is becoming crucial in the construction industry, which is increasingly focusing on environmentally friendly and circular solutions to reduce its ecological footprint. The use of locally available and renewable resources, along with the reinterpretation of traditional building systems, can contribute to further establish the use of ecological and circular materials in construction.

Horizontally spanning structures offer significant opportunities for resource conservation, as they typically require large amounts of material for their realisation. Earth, a widely available yet often overlooked building material, possesses acceptable compressive properties and is traditionally used for walls, such as wattle and daub. Combining earth with timber, which resists tensile forces effectively, broadens its applications to include elements subject to bending stress as slabs. This strategic material pairing also lowers the need for wood - a crucial aspect given its limited availability.

The application of the hybrid material system in bending-stressed components poses several technical challenges, the most significant being the need for efficient shear force transfer between timber and earth to guarantee a reliable material bond. To analyse the shear transfer capacity of the timber-earth-composite, several push-out tests were conducted - a proven method for timber-concrete-composites. Various types of fasteners, such as screws and wooden shear connectors, were implemented to ensure efficient force transfer between the materials. The resulting bond characteristics were evaluated for scalability in two full-scale components.

Various modelling approaches, including the γ-method and the truss model method, have been investigated, with particular emphasis on the truss model to capture the non-linear behaviour of earth materials and the bond conditions identified through component testing. The objective is to establish a viable calculation method that facilitates the scaling up of timber-earth slab spans, allowing for the identification of optimal configurations of material arrangement and thickness, and thereby enhancing their potential for real-world applications.

Timber-earth-components represent a sustainable composite material that not only meets structural requirements but also offers advantages in sound and fire protection, as well as thermal mass, therefore providing a promising alternative for the construction industry.

1 Introduction

Construction and demolition waste constitutes a substantial proportion of waste streams in numerous industrialized countries, accounting for approximately 30 mass-% of total waste generation [1], and reaching up to 54 mass-% in Germany [2]. Consequently, the implementation of sustainable and resource-efficient building materials is increasingly imperative for mitigating environmental impacts.

The concept of combining different materials to harness their respective advantages has been extensively studied in the context of timber-concrete composites. Various methods can be employed to connect the materials, such as screws [3], metal plates [4], or notches [5]. These techniques facilitate the transfer of shear forces between timber and concrete, ensuring effective bonding and structural interaction between the materials.

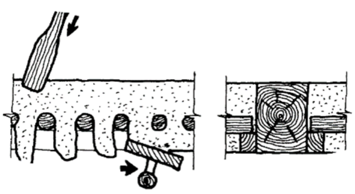
The Global Warming Potential (GWP), which quantifies the potential contribution to the greenhouse gas effect (e.g., through sourcing and production), is assessed at 251 kg CO_2-equivalent per unit volume for in-situ concrete of grade C25/30. In contrast, rammed earth construction exhibits a GWP of only 9.7 kg CO_2-equivalent per unit volume, representing approximately 4% of that associated with concrete [6]. Although rammed earth materials possess lower compressive strength, necessitating the use of greater volumes of earth to achieve comparable structural performance, the overall reduction in CO_2 emissions still remains.

Another key advantage of earth is its ease of reuse. Since it only dries and undergoes no chemical reaction - unlike concrete - earthen materials can be readily recycled without generating waste or loss of value [7].

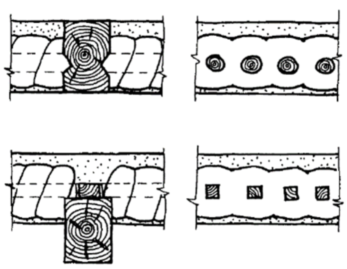
2 Timber-Earth as a Building Material for Horizontal Elements

2.1 History

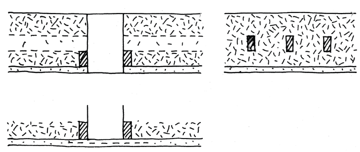
Timber-earth composite construction has a long-established history. Archaeological evidence from the 6th to 5th centuries BCE indicates the use of wooden skeletal frameworks with wattle infill, subsequently coated with earth [8]. In Germany, earth has traditionally been employed for vertically loaded systems through wattle and daub techniques. Several methods also exist for integrating timber and earth in horizontally spanning structural elements. One such technique is the spalier-slab system, in which wooden battens are arranged at intervals of 3-6 cm between supporting beams. Moist earth is then pressed down through the battens and leveled from below to create a continuous slab (Figure 1a). Another traditional ceiling system employs straw-earth rolls, formed by soaking bundles of straw in a moist earth mixture and spirally winding them around a central wooden pole (Figure 1b)[9]. A third approach uses rammed earth ceilings (Figure 1c), wherein the earth is placed onto a movable formwork and compacted laterally using stakes - similar to rammed earth wall construction - to produce a smooth, plasterable surface [8].



(a) Spalier-slab (from [9])



(b) Straw-earth rolls (from [9])



(c) Rammed earth ceiling (from [8])

Figure 1: Various historical ceiling types incorporating earthen materials

The advent of industrialization in the mid-19th century led to a significant decline in earth-based construction techniques, resulting in their considerable obsolescence within mainstream building practices [8]. Nevertheless, recent years have witnessed a resurgence in the utilization of earth as a construction material, predominantly motivated by its sustainable characteristics.

2.2 State of the Art

The use of earth in construction is steadily gaining importance. Initially employed predominantly for wall elements, recent research is increasingly exploring its application in horizontally spanning structures. In

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particular, vaulted ceilings have gained attention, as their shape ensures the presence of only compressive forces, while horizontal forces are transmitted through the primary supporting framework.

The House of Research, Technology, Utopia and Sustainability (HORTUS) office building has successfully demonstrated the use of earth in form of vaulted ceilings. In this configuration, the earth component autonomously supports itself, while the wooden framework bears the primary structural loads. This construction methodology integrates beneficial properties, such as acoustic and fire insulation, into the ceiling structure [10].

Ongoing research is investigating whether earth placed between primary structural elements can independently carry structural loads, rather than being implemented solely as self-supporting elements [11]. Another approach involves using vaulted earthen ceilings reinforced with willow to reduce horizontal forces, thereby minimising the size of the timber beams required in the main supporting structure [12]. In order to increase the load-bearing capacity of the vaulted ceilings, different earth mixtures are currently being tested [13]. One variation contains 2% of a mineral binder, which increases strength and reduces water demand, while the more conventional mixture contains 4% cement, significantly complicating the material's reuse.

Another concept involves wooden laths covered with earth to form a load-bearing structure [14]. In this system, the earth stabilizes the wooden laths while enhancing the structure's thermal properties. A further development of this concept is the "Timber-earth Solid Ceilings" [15], already implemented in an office building. Timber beams form the primary structural framework, with wooden laths spanning between them and the intervening spaces filled with earth. Here, the earth primarily provides building-physical functions - such as thermal mass - rather than serving as the main load-bearing component.

In contrast, this research investigates the use of earth in bending-stressed components in combination with timber, with the aim of optimising the force distribution between the two materials. In this system, earth resists compressive forces, while timber resists tensile forces. To facilitate this interaction, a strong shear bond between the materials is crucial, which will be examined in more detail in the following sections.

3 Characterisation of Earth Material

Earth, a mixture of clay, silt, sand, and aggregates of various sizes, does not undergo any chemical transformations during the hardening process, unlike concrete. It simply dries, which allows for straightforward reuse. By regulating the amount of water added and incorporating additives such as aggregates of different sizes or straw, the usage of earth can be adjusted. This versatility unlocks a wide range of potential applications across different sectors. Notably, when earth is used in its plastic state, the addition of straw effectively mitigates the formation of shrinkage cracks due to the higher amount of water added.

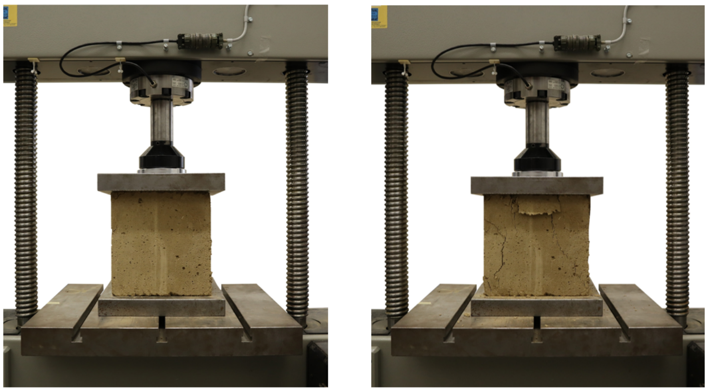

Figure 2: Earth cube test; Left: Before load application; Right: After load application

As an initial step, a plastic earth mixture consisting of building clay, sand, and straw was examined to facilitate hydraulic extrusion processing, followed by compaction using a vibrating plate. To determine the material's compressive strength, eight cubic specimens with 20 cm edges were produced and tested under compression until failure (Figure 2). The results showed an average cube compressive strength of 1.67 N/mm².

To achieve higher compressive strength and, in particular, to reduce shrinkage, a significantly drier earthen mixture with an increased proportion of larger aggregates (0–22 mm) was employed for further investigations. According to the datasheet for this mixture, its compressive strength increases to at least 3.0 N/mm² after hydraulic compaction, which is required to attain its final strength [16].

4 Testing Methodology

To ensure effective force transfer between timber and earth, appropriate shear connectors are required. To this end, various types of shear connectors were investigated, and small-scale shear tests were conducted. In these experiments, two different screw arrangements were employed: one oriented perpendicular to the timber panel and one at a 45° angle, as typically applied in timber-concrete composites. Additionally, two variants of wood connectors were tested: wooden dowels with a diameter of 20 mm and rectangular wooden blocks. For each configuration, at least three identical test specimens were fabricated and evaluated. To determine the maximum load capacity, maximum deformation, and, hence, the slip modulus k_{ser} of both the entire specimen and the individual connectors, the small-scale shear tests were carried out in accordance with DIN EN 26891 [17]. The slip modulus represents the ratio of the applied load to the resulting deformation under a specific loading condition and is a fundamental parameter for calculating the composite behaviour between timber and earth, which is crucial for both the structural design and numerical modelling of the composite system.

Figure 3: Small-scale shear tests: The two images on the left show the applied shear connectors, while the two images on the right display the specimens filled with earth - before load application and after loading until failure

Particularly promising results were achieved with the wooden blocks (Figure 3), which attained an average k_{ser} of 2929 N/mm per connector, whereas the wooden dowels exhibited only an average value of 1619 N/mm. Consequently, wooden blocks were selected for one of the initial full-scale prototype. The screw connections generally demonstrated lower performance; for instance, horizontally oriented screws yielded an average k_{ser} of 1102 N/mm per connector (Figure 3). Although the diagonally oriented screws provided approximately 16% higher slip modulus values, the horizontal arrangement was preferred due to difficulties encountered when using screws at a 45° angle during fabrication involving hydraulic compaction of the earth [18].

To extend the insights obtained from the small-scale shear tests, the performance of the shear connectors was subsequently evaluated using full-scale specimens (3.0 m x 1.0 m), as depicted in Figure 4. The connectors were installed on a 6 cm-thick cross-laminated timber (CLT) panel, composed of three layers and conforming to strength class C24. Subsequently, the earth was applied in two successive 5 cm layers, which were compacted to achieve an overall component thickness of 16 cm.

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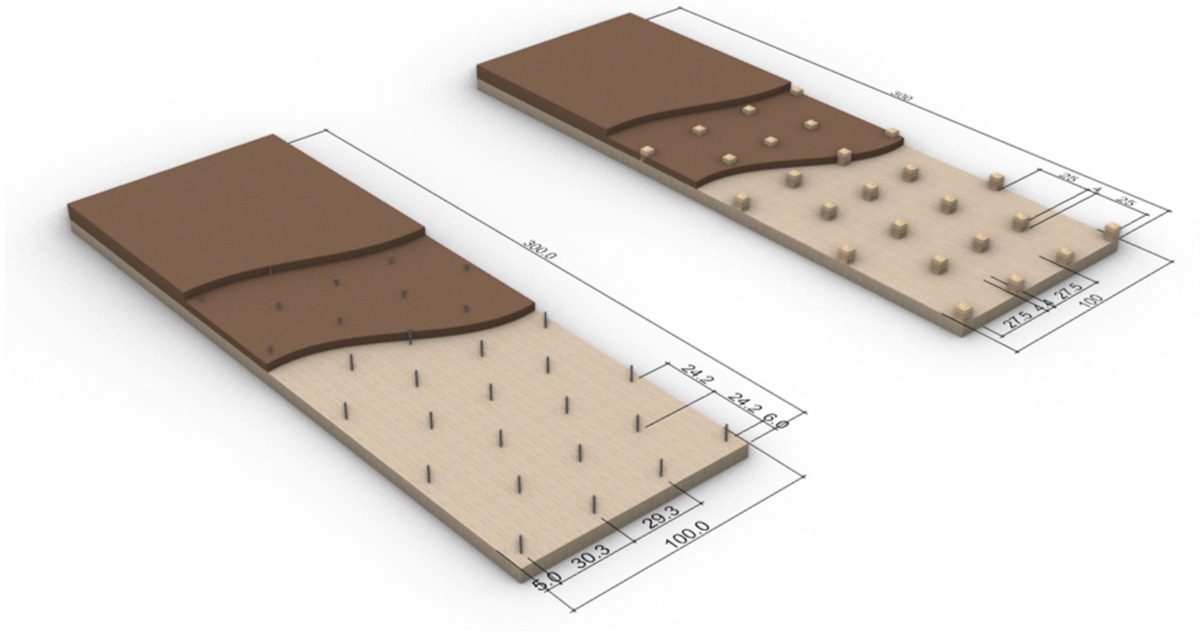

Figure 4: 1:1 Component illustrating two types of shear connectors: Screws oriented perpendicular to the timber panel, and wooden blocks

To characterise the composite behaviour, the specimens were subjected to a uniformly distributed load of 11.9 kN/m², while deformations were continuously recorded. The slab with incorporated wooden shear blocks exhibited a mid-span deformation of 19 mm, whereas the slab with screw connectors resulted in a deformation of 29 mm. In contrast, a simple timber panel loaded solely with earth would have deformed by 63 mm. Thus, the implemented shear connectors not only facilitated a measurable composite action between timber and earth, but also revealed distinct slip moduli, as indicated by the greater deformation observed with the screw connectors.

Since the applied loads on the components exceed the standard service loads for office or residential buildings, the resulting deformations are also larger than the typically allowable l/300 in timber construction. Therefore, for subsequent investigations and calculations, the loads and consequently the deformations are recalculated based on an additional dead-load of 1.0 kN/m² for the floor structure and a service load of 2.7 kN/m², which, according to DIN EN 1991-1-1 [19], represents the design load for residential buildings (1.5 kN/m²) including partition loads (1.2 kN/m²).

5 Modelling Approaches

For the analysis of the hybrid material system comprising timber and earth, preliminary investigations were conducted employing the γ-method. This method is typically utilized for the analysis of up to three wooden cross-sections that are flexibly connected or alternatively, for timber-concrete composite cross-sections to determine internal forces and stress distributions. This approach is also incorporated in DIN EN 1995-1-1, Appendix B [20]. In particular, the method is applicable to statically determinate simply supported beams subjected to uniformly distributed loads, wherein local stress concentrations induced by shear connectors are not separately considered.

In contrast, the truss model method explicitly accounts for local stress concentrations arising from the presence of shear connectors. In this approach, a two-dimensional model is employed in which one member represents the timber and a separate member represents the earth. In the regions corresponding to the shear connectors, these members are interconnected via cantilever arms that are hinged at their ends. Truss rods connect the two chords between the shear connectors, ensuring that both the timber and the earth deform identically (Figure 5).

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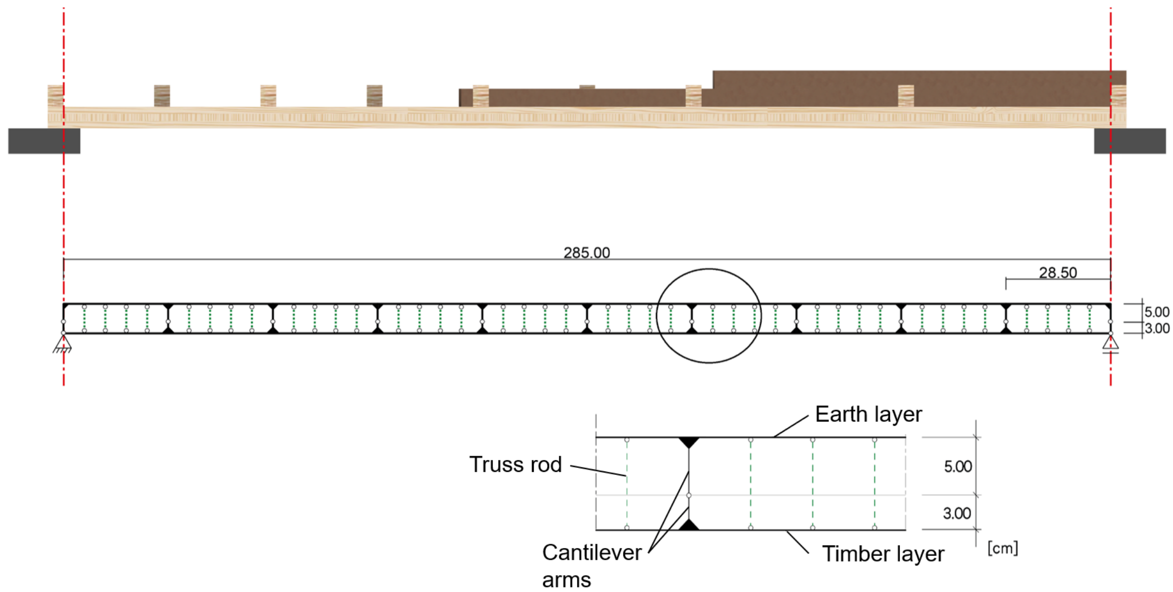


Figure 5: Truss model method – Representation of the structural system illustrated by the full-scale prototype with wooden shear blocks

Both modelling approaches were examined in [18], where a comparative analysis was performed on the internal forces and deformations under linear-elastic assumptions. However, because nonlinear material behaviour was not yet incorporated, this paper focuses on its detailed analysis and integration to enable a more realistic representation of the stress distribution in the materials. For the subsequent nonlinear analyses, which concentrate exclusively on the combination with wooden shear blocks, a maximum characteristic compressive strength of 3.0 N/mm^2 and a Young's modulus of 3500 N/mm^2 were adopted for the earthen material ([18]).

When comparing linear-elastic and nonlinear analyses, the different stress distributions result in a deformation range of 22.5 mm versus 18.5 mm for the wooden shear blocks under a distributed load of 11.9 kN/m^2. This represents an approximate 22% increase in deformation relative to the full-scale (1:1) prototype measurements. In the absence of further investigations into the material's compressive strength and Young's modulus, the current material parameters have been conservatively maintained. Although a comprehensive evaluation of the material properties is essential for future studies, the available data permit preliminary estimates that underscore the potential of the material combination.

To date, the slip modulus k_{ser} has been treated as a characteristic value. However, for a comprehensive design approach, it is essential to include safety factors. In accordance with DIN EN 14358 [21], k_{ser} is therefore determined based on its 5%-quantile, resulting in the values for the wooden blocks presented in Table 1.

Table 1: Slip modulus k_{ser} for wooden blocks [21]

Test specimen	k_{ser} [N/mm] per fastener
WB01	3898
WB02	2359
WB03	2532
Number of specimens	3
Average value	2929
5% Quantile	**1213**

The 5% quantile values are considerably lower, due to the limited number of test specimens evaluated so far. To obtain a more representative estimate with reduced discrepancies, additional prototypes for the small-component shear tests are necessary.

6 Results and Discussion

Using the two-dimensional truss model that accounts for the inherent nonlinear mechanical response of the earth, a comprehensive parametric investigation was conducted to quantify the achievable span lengths as functions of the thicknesses of both the earth and timber layers. The analysis systematically varied three critical design parameters: (1) the wooden shear block configuration - specifically, the number and spacing; (2) the thicknesses of the timber and earth layers; and (3) the overall slab length. Three different design configurations were examined, as shown in Figure 6, with the aim of providing insight into the theoretical spans achievable under the initial calculation approach.

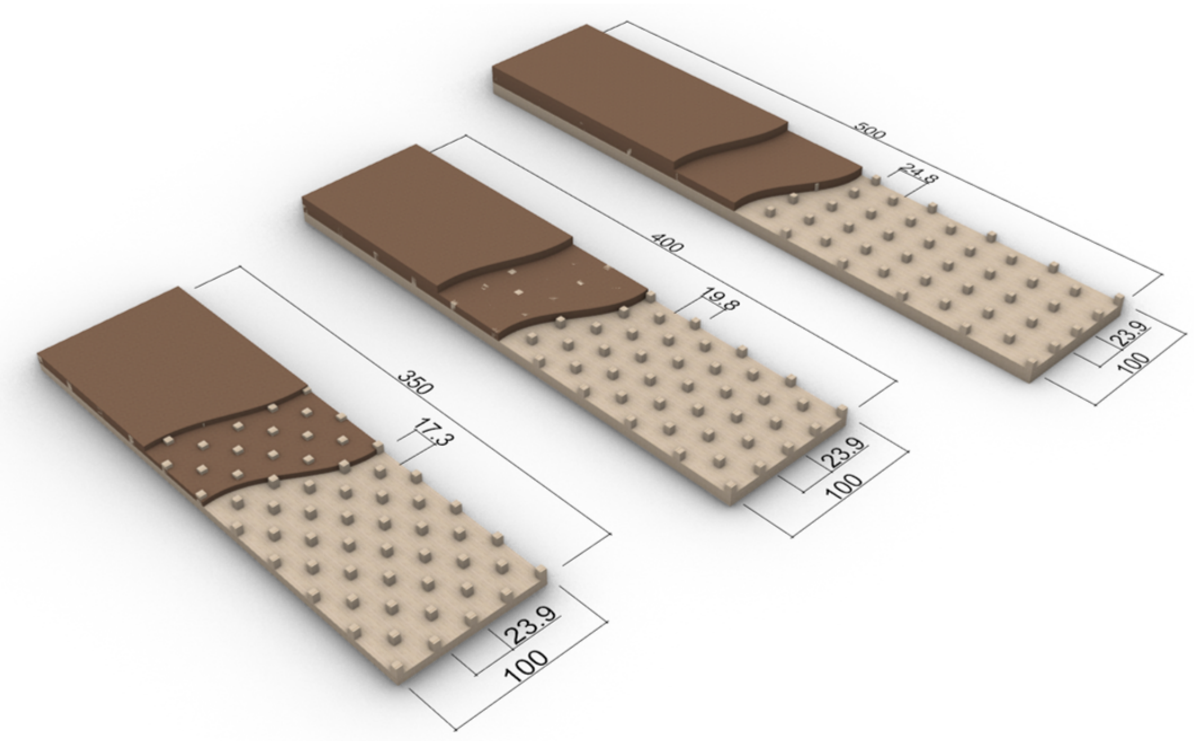
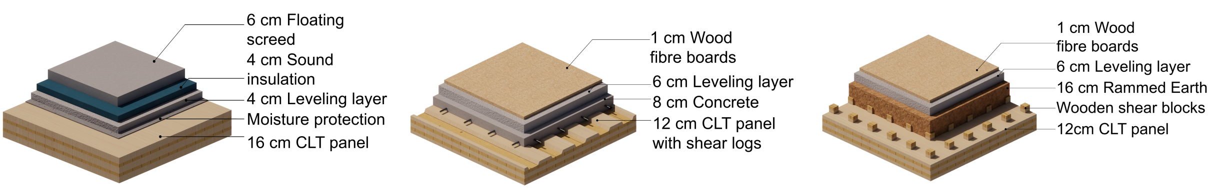


Figure 6: Overview of potential timber-earth slab configurations, illustrating variations in material thickness, shear block arrangement, and span length

In order to facilitate a valid comparison with purely timber slabs, as well as with timber-concrete composite slabs, the floor assembly details play a critical role. Due to the mass contributed by the concrete or earth in combination with the CLT panel, it is possible to omit the screed, which is typically indispensable in purely timber floors. Figure 7 illustrates potential floor assemblies for a 5.0 m span, including purely timber floors [22], timber-concrete composite floors [23], and timber-earth composite floors.



a) CLT panel b) Timber-concrete composite c) Timber-earth composite

Figure 7: Possible typical floor constructions for a pure timber ceiling, a timber-concrete composite ceiling, and a timber-earth ceiling

For purely timber slabs, a permanent load of 2.0 kN/m² is assumed to account for the necessary screed application. In contrast, the timber-earth slab only requires an additional permanent load of 1.0 kN/m², which is added to the slab's self-weight.

Table 2 summarizes the various spans of the ceiling elements along with their corresponding required thicknesses. Additionally, it presents the stress distributions in both the earth and the timber. Mid-span deflections were evaluated under three distinct conditions: The deflection predicted by the numerical model, the maximum permissible deflection (defined as l/300), and the deflection arising solely from the cross-laminated timber (CLT) panel in combination with the floor assembly shown in Figure 7(a). Furthermore, the analysis incorporates both the 5% quantile and the mean values of the slip modulus k_{ser}.

Table 2: Parametric variations of the hybrid material system: Influence of shear connector quantity, k_{ser} value, material thickness, and component length

			Span [m]					
			3.5	3.5	4	4	5	5
Timber-earth composite								
Thickness of earth		[cm]	12	10	12	12	16	14
Thickness of timber panel		[cm]	8	8	10	8	12	12
Number of shear connectors			95	95	95	95	95	95
Slip modulus k_{ser}		[N/mm]	1213	2929	1213	2929	1213	2929
Loads	$g_{k,1}$	[kN/m²]	2.90	2.48	2.99	2.90	3.93	3.50
	$g_{k,2}$	[kN/m²]	1	1	1	1	1	1
	q_k	[kN/m²]	2.7	2.7	2.7	2.7	2.7	2.7
Stress distribution (Earth)	top	[N/mm²]	-1.79	-1.88	-1.79	-2.00	-1.87	-1.94
	bottom	[N/mm²]	0.05	0.05	0.05	0.05	0.05	0.05
Stress distribution (Timber)	top	[N/mm²]	-4.86	-3.58	-5.34	-3.70	-5.08	-3.62
	bottom	[N/mm²]	5.28	5.38	6.50	6.20	6.73	5.68
Midspan deformation	Actual deformation	[mm]	11.7	9.4	13.0	13.0	16.8	13.3
	$l/300$	[mm]	11.7	11.7	13.3	13.3	16.7	16.7
	Percentage	[%]	100	81	98	98	101	80
Only timber plate								
Thickness of timber panel		[cm]	8	8	10	8	12	12
Loads	$g_{k,1}$	[kN/m²]	0.34	0.34	0.42	0.34	0.50	0.50
	$g_{k,2}$	[kN/m²]	2	2	2	2	2	2
	q_k	[kN/m²]	2.7	2.7	2.7	2.7	2.7	2.7
Midspan deformation	Actual deformation	[mm]	21.3	21.3	19.0	36.2	27.2	27.2
	$l/300$	[mm]	11.7	11.7	13.3	13.3	16.7	16.7
	Percentage	[%]	183	183	143	272	163	163
Minimum timber panel thickness to meet all requirements								
Thickness of timber panel		[cm]	10	10	12	12	16	16

Within the framework of this study, it was demonstrated that load transfer between the two materials can be achieved using both a 5% quantile value of k_{ser} = 1213 N/mm and a mean value of k_{ser} = 2929 N/mm, resulting in a substantial reduction in deflection compared with purely timber floors. Reporting both the 5% quantile and the mean values for stresses and deformations provides an estimate of possible lower and upper performance bounds, particularly given the limited number of experiments conducted to date.

All applied loads were assigned corresponding partial safety factors and incorporated into the stress calculations. On the earthen side, a partial safety factor of 1.5 was adopted in accordance with DIN 18940 [24], thereby limiting the maximum compressive stress in the earthen layer to 2.0 N/mm². Moreover, numerical analyses indicate that spans of up to 5.0 m are feasible, though these findings should be validated by further full-scale prototype testing.

Table 2 illustrates that incorporating timber and earthen materials in combination with effective shear transfer can reduce the amount of timber required for floor systems. For instance, standard design provisions dictate the use of a 16 cm thick CLT panel for a 5.0 m span. However, by applying a nonlinear analytical approach and accounting for the compressive contribution of the earthen layer, this study demonstrates that a 12 cm thick CLT panel with a 16 cm earthen layer on top is sufficient. In comparison, [23] indicates that a notched timber–concrete composite floor slab spanning 5.0 m requires a 12 cm thick CLT panel together with an 8 cm thick concrete topping. Although the volume of earthen material used here is notably more than that of a concrete overlay, its substantially lower Global Warming Potential (GWP) makes it a promising alternative to both purely timber floors and timber–concrete composite floors.

7 Conclusion

The use of timber and earth as horizontally spanning structural elements, interconnected via shear connectors to ensure effective load transfer and stress distribution, demonstrated significant potential. This was evidenced by the slip modulus values obtained from small-scale shear tests, which confirmed the ability to transfer forces between materials through shear connectors. The most promising results were achieved with wooden shear blocks in the small-scale shear tests, as also proven by the reduced deformation of the 1:1 component - only 30% compared to scenarios with no interaction between the materials.

Building on the findings, numerical analyses were conducted to explore potential slab spans using a hybrid structural system of timber and earth. The results demonstrated the possibility of extending slab spans, making the system more viable for real-world applications. For a slab span of 5.0 meters, the implementation of timber-earth composite assemblies demonstrated a theoretical 33% reduction in the required CLT volume compared to a timber-only panel system. In comparison to timber-concrete composite systems, the timber-earth hybrid slab alternative requires twice as much earth as concrete, while the thickness of the CLT panel remains unchanged to ensure equivalent structural capacity. Given the significantly lower Global Warming Potential (GWP) of earth - only 4% compared to concrete - the timber-earth composite presents a promising and environmentally sustainable alternative. These numerically derived findings will be further validated through comprehensive full-scale experimental testing to confirm their accuracy and applicability.

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