

Bond behaviour of wood reinforcement in a clay matrix

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ABSTRACT: This research focuses on developing sustainable building solutions by replacing conventional steel and concrete systems with hybrid composite materials from clay, natural fi-bres, and wood. The aim is to create resource-efficient, load-bearing components while reducing carbon emissions through biological materials with fast regrowth and long sequestration. The study explores clay as a binder for horizontal structural components, integrating natural fibre reinforcements and profiled wooden rods to optimise material use, minimise wood consumption, and enhance the performance of the composites. Through prototyping and testing, the project seeks to demonstrate the feasibility of these earth and bio-fiber-based composites in construction, highlighting their potential for efficient, low-carbon, and cost-effective solutions.

1 INTRODUCTION

To save primary resources and embodied energy, new solutions must be developed for using previously non-industrialized materials for buildings with high structural requirements (Röck et al. 2020). This can be achieved by replacing conventional steel and concrete systems with hybrid component solutions based on a combination of resource-efficient materials and simultaneously complying with European standards (Heringer et al. 2022) (Decker 2024). Clay as a binder for vertical, load-bearing components is already established and standardised by the new DIN standard for clay block masonry (DIN 18940 2022) (Rematter 2023) (Zukunft Bau 2023). Biological materials with a fast carbon cycle promise a positive CO₂-impact as they can store carbon while renewing. The aim is to replace horizontal structural components under a bending load made of concrete with clay-bonded mixtures. Rematter AG already offers rammed earth prefabricated components in barrel vaults that span between solid timber beams (Trummer et al. 2022) The ZUKUNFT BAU project ‘HLD Element system’ by TU Darmstadt is developing a wood-clay composite system, and the Timber Earth Slab project by TU Munich and Leipfinger Bader is improving the timber-frame ceiling with clay as a non-load-bearing filler material (Vincent 2012) (Volhard 2016).

These systems show the potential of earth and wood in combination for horizontal components, whereby the load transfer is still mainly via wood cross-sections. The presented project will combine pre-stressed natural fibre reinforcements, perforated or toothed wooden rods, and liquid clay to form a hybrid composite element. The aim is to activate the clay as a cross-

section subject to compressive stress and use the fibre materials' tensile strength to minimise the wood cross-section and limit crack widths (Hebel et al. 2017). Techniques for joining and manufacturing the materials are being investigated and optimised to reduce wood consumption and make the composite material even more resource-efficient.

The research goal is the development of earth and fibre-based composites that are easily and quickly applicable during design and permitting processes. Prototyping is the primary study methodology used to represent and communicate proof of the idea's feasibility.

2 MATERIALS AND METHODS

The aim is to prove a bond between the two material groups to show the potential of earth and woodbeams working as a composite. The construction and component build-up principles of pre-fabricated steel reinforced concrete were the basis of the theory, as Andrea Deplazes states in "Constructing Architecture – materials, processes, structures": "Reinforced concrete is a composite material of concrete and steel. The interaction of these two materials – the reinforcement resisting the tensile stresses, the concrete resisting the compressive stresses – is not an additive process but leads to a new load-bearing quality." Here, two materials are combined into a composite that, in the form of a specific element size, can take on a tectonic role in a load-bearing system only in its combination (Deplazes 2018). This basic principle is the guideline for observing the bond behavior of a clay matrix and biobased reinforcement.

2.1 Poured earth mixture

In the research carried out during the seed fund project, there were two pourable earth mixtures, one developed by RWTHs ibac (Figure 1) and another provided by BC materials. The mixtures are both characterised by the presence of clays, silts, sands, and gravel. The maximum grain size for the "ibac" mixture is 2 mm and the "bc" mixture is 8 mm. The sieving curves are shown in Figure 1b). The "BC materials" mixture has an additional additive consisting of a sodium salt, which acts as a clay dispersant and increases the mixture's flow for the same water content (Figure 2).

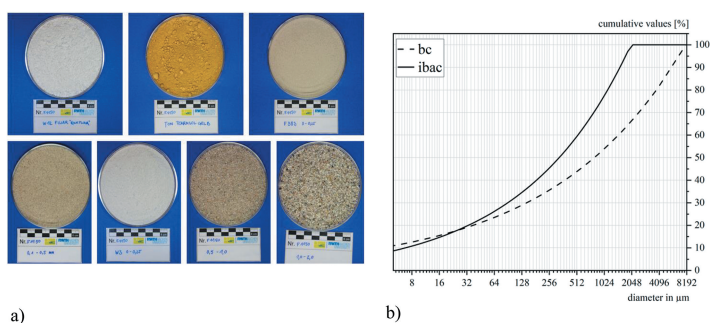


Figure 1. (a) Clay, silts, sand and gravel of the ibac mixture; (b) sieving curves of bc and ibac mixtures.

2.2 Poured earth and wood in combination

Wood and earth are natural resources that can be used as building materials with little processing. They can be combined into constructive elements or systems with complementary effects. Earth-building materials, in general, have a lower moisture equilibrium content than wood as well as better fire resistance and fire reaction; when earth-building materials are in contact with wooden elements, the capillary action of earth-building materials extracts humidity from the wood element, keeping the wood dry and thus preventing it from rot. When earth-building materials cover wood elements, the combined constructive system will generally have increased fire resistance and fire reaction compared to the wood alone.



Figure 2. Sieving and preliminary testing of the poured earth mixtures.

2.3 Tension active wood

Earth's primary limitation is its low tensile strength, similar to concrete, making reinforcement essential for resisting tensile forces in bending slabs. Wooden beams address this limitation by taking on the tensile forces. The earth matrix surrounds and bonds with the wooden reinforcement, forming a composite material capable of resisting tension and compression. Wooden beams can effectively control cracking and distribute stresses to prevent large fractures that could compromise structural integrity.

Pull-out tests are conducted on wooden rebars with varying surface geometries (see Figure 3) to optimise bond strength and ensure maximum load-bearing capacity. Adjusting rebar diameter allows for control over load-bearing capacity. Ideally, materials for wooden rebar should be readily accessible, easy to machine, and have a surface geometry that is simple to produce with minimal waste. This paper examined only the first geometric form (Figure 3_GEO 1).

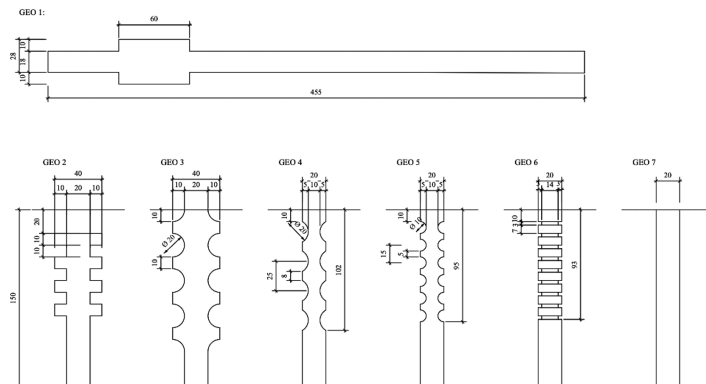


Figure 3. Wood reinforcement geometries.

2.4 Biofibres as additives in a liquid earth mixture

Biofibres, with their ability to take on tensile forces, have the potential to expand the earth's bending resistance and reduce cracking as an additive in the earth's mixture. In this paper's preliminary research, no shredded fibres have yet been added to the poured earth mixture. The addition of fibres from different sources and formats should be investigated to observe the possibility of crack and weight reduction. Biobased netting in combination with earth plaster is a state-of-the-art method that is defined in DIN 18948 "Clay boards – requirements, testing and labelling", clay boards Type A, for linear or grid-shaped sub-constructions (Claytec 2023) (DIN 18948 2022) to prevent the earth plaster from cracking and shrinking, improve adhesion, provide strength in high-stress areas and thus allow for thicker application of the plaster. The application of fibres in the poured mixture is, therefore promising and, next to the potential further substitution of wooden reinforcement by larger scale fibre reinforcement elements like ropes or netting, another mode of applying fibres in the components build-up and part of our project's next steps.

Table 1. Characteristic values of finger-jointed solid timber of selected strength classes for design in accordance with German norm DIN EN 1995-1-1: 2012-12 and DIN EN 1995-1-1/NA 2013-08 a).

Strength characteristics in N/mm ²	C24*	
Bending	$f_{m,k}$ a)	24
Tension parallel	$f_{t,0,k}$ b)	14
Tension perpendicular	$f_{t,90,k}$	0,4
Compression parallel	$f_{c,0,k}$	21
Compression perpendicular	$f_{c,90,k}$	2,7
Shear due to transverse force and torsion	$f_{v,k}$ c)	2
Stiffness values in N/mm ²		
Modulus of elasticity parallel to the fiber	$E_{0,mean}$ d)	11,000
Modulus of elasticity parallel to the fiber	$E_{0,05}$	7,400
Modulus of elasticity perpendicular to the fiber	$E_{90,mean}$	370
Shear modulus	G_{mean} c) d)	690

* Strength, stiffness and bulk density properties KVH is offered in strength class C24 in accordance with the agreement on KVH.

3 TEST METHODOLOGY

Preliminary tests with two clay mixture compositions and geometric alternatives in wooden elements were evaluated to develop basic knowledge about the possible combinations of the two material groups. These were then implemented in different wood geometries to increase the wood surface while reducing the total material volume and two clay mixtures with a maximum grain size of 8 mm (others 2 mm) and flowability so that the liquid clay mixture can completely enclose the wood elements.

The compressive strength test was carried out to determine the general strength of the systems. To observe the bond behaviour of the two material groups, the adhesiveness of liquid earth and wood was finally tested in pull-out tests comparing the two earth material mixtures in combination with different wood geometries (Figure 4).

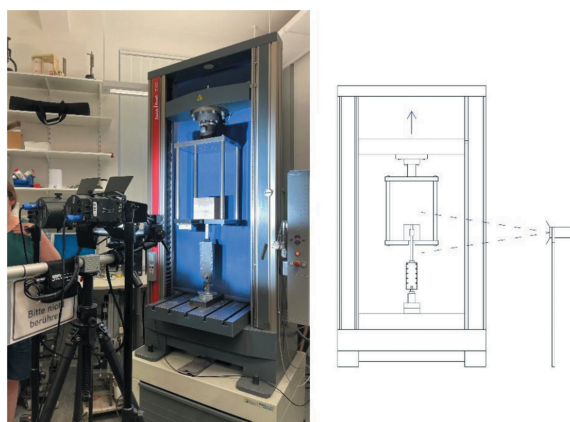


Figure 4. Pull-out test set-up.

The failure modes of the pull-out test specimens are analysed using the Aramis optical strain analysis system. The ARAMIS optical deformation measurement system from GOM was used to record crack formation and determine the crack opening of the test specimens. It is one of the 2D analysis systems for recording spatial deformation under static and dynamic

loads. For this purpose, images of the sprayed dot pattern are recorded at a pre-set frequency using the stereo camera system with the support of the GOM Testing Controller. The software divides the surface into individual facets, which are determined by their position on the surface based on the grey values of the area in question (Bochmann 2014). The software calculates three-dimensional position vectors for the facets of the dot pattern using the cameras mounted at a defined angle to each other and the previously set distance to the measurement object. If the surface is deformed, the local displacements are obtained by changing the position vectors. The pull-out tests were carried out in accordance with the bond tests from: RILEM Recommendation “RC 6 Bond Test for Reinforcement Steel - 2. Pull-Out Test”. The basic structure of the test specimen is shown in Figure 4.

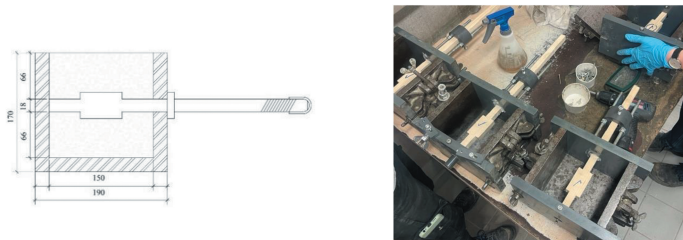


Figure 5. (a) Build-up and measurements of test specimen formwork; (b) manufacturing the pull-out test specimens with the first chosen wood geometry.

The tests were carried out with a wooden bar diameter of 18 mm. To comply with the ratio of rod diameter d_s to specimen edge length $10 \times d_s$ specified in (Rilem 1983) the specimens for the pull-out tests were manufactured with an edge length of 150 mm (see Figure 5). The uncovered wood reinforcement was not de-bonded. The compressive strength was determined in accordance with DIN EN 12390-3:2019-10 with a reduced testing velocity of 450 N/s. The solid earth density was determined with DIN EN 12390-7:2021-01.

4 RESULTS AND DISCUSSION

The initial research on behalf of the lab tests shows results on the scale of each component’s material qualities.

4.1 Compression tests

The earth test specimens exhibit the typical double-cone fracture behaviour that can also be observed in concrete. The cone is shown in Figure 6a. The strengths of the tested clay mixtures differ, see Figure 6b. The bc mixture is 2.6 Mpa, and the ibac mixture is 1.9 Mpa.

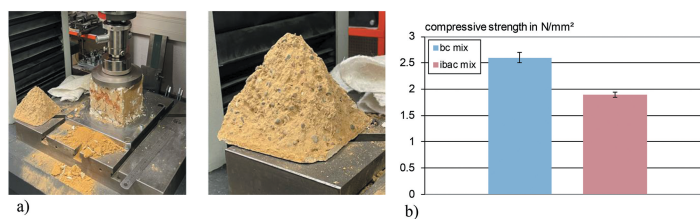


Figure 6. (a). Compression test and test specimens conic form after failure; (b) compressive strength of both tested poured earth mixtures in comparison.

4.2 Pull-out tests

In the experimental pull-out tests, two distinct failure modes emerged, with apparent differences between specimen types “bc” and “ibac” (Figure 7).

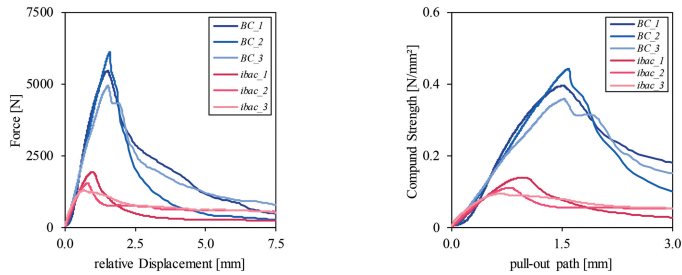


Figure 7. Compound strength of the tested poured earth mixture and wooden geometry combinations in comparison.

For “bc” specimens, all samples displayed a matrix-splitting failure mode that ultimately led to fibre withdrawal. This failure is characterised by longitudinal cracks forming within the clay matrix, extending toward the outer edges (see Figure 8). In the load-slip diagrams, the bond response shows predominantly elastic behavior, with a small quasi-elastic phase, culminating in a brittle failure point. This process unfolds in two stages: first, the matrix withstands stress until reaching its tensile strength limit, at which point, splitting cracks form. As these cracks widen, the load-slip behaviour becomes quasi-linear, with capacity gradually decreasing as slippage increases (Figure 7).

The significant slippage causes the broader part of the wooden fibre (the “tooth”) to exert compressive stress on the already damaged bond area, leading to a second failure stage. This stage involves the formation of a triangular cracked prism on the loaded end of the specimen - a geometry distinct from the cone-shaped failure typical of concrete. A brittle fracture immediately follows this stage. For “ibac” specimens, two-thirds displayed similar behaviour to the “bc” specimens, with matrix splitting followed by forming a cracking prism and fibre pullout. However, the “ibac” samples exhibited slightly lower stiffness, resulting in earlier and more brittle failure than “bc” specimens.

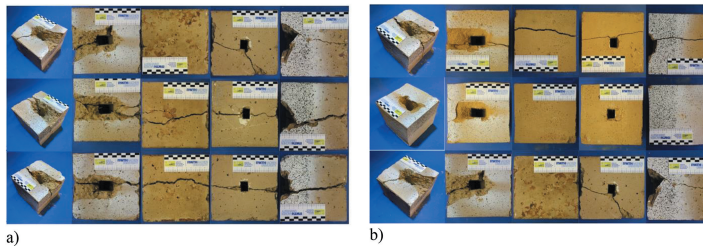


Figure 8. (a) bc test specimen after bond failure; (b) ibac test specimen after bond failure.

A different failure mode was observed in one-third of the “ibac” specimens: fiber withdrawal without significant matrix cracking. In this mode, the fibre gradually debonded from the clay matrix rather than causing prominent cracks (Figure 8). This debonding phase is visible as a non-linear section on the load-displacement curve just before the peak load. It indicates that the clay matrix provided sufficient shear and confinement strength to prevent interfacial cracks from reaching the surface. As the peak load approached, the curve showed a pronounced drop and non-linearity due to the fibre “tooth” compressing the cracked interface. This caused another triangular prism failure at the loaded end without longitudinal surface cracking, as the local tensile strength was not exceeded (Figure 7).

The ARAMIS system was used to determine the crack formation and the crack opening of the test specimens. First, the coordinate system must be defined. This was placed in the centre of the

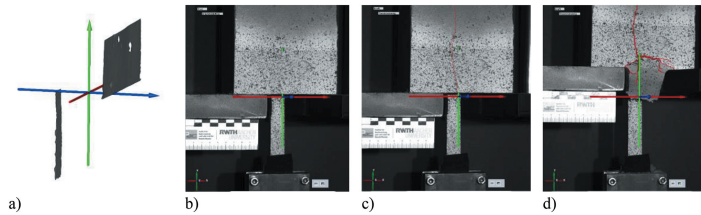


Figure 9. (a) Position of the coordinate system; (b) status before testing; (c) load case 1 crack pattern, (d) case 2 failure.

two observed surfaces, i.e. the wooden rod and the specimen surface (see Figure 9). The force-displacement curve can now be normalised with the optical crack tracing.

Figure 9 c) and d) shows load cases 1 and 2. The optical evaluations can be used in further investigations to precisely analyse different wooden bar geometries and their effect on the cracking and fracture behaviour. Figure 10 shows a detailed view of the bond zone from wood to earth after the pull-out test. This shows apparent fibre inclusions. This indicates that an adhesive bond between the wood and liquid earth mix has taken place and that there has been no previous detachment due to strong shrinkage effects, for example.

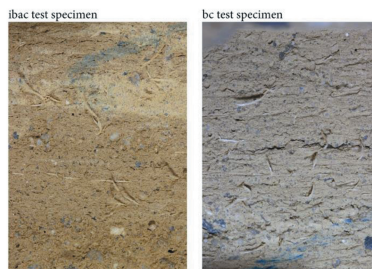


Figure 10. Representation of the interface between earth and wood.

5 CONCLUSION

A general bond behavior could be shown in this investigation. The bonding behavior is strongly dependent on the following:

- a. the Granulometry and additives in the Earth mixture
- b. the form and surface of the wooden rods.

Treatment of the tension rods by coating its surface could increase the bond. The sub-geometry of several rods can spread the tension in a grid. The potential of constructing grids from slim wooden rods with an enlarged surface while interweaving those into a three-dimensional skeleton using fibres in the form of ropes and mesh could be a promising approach. This multi-layered design of an element is currently being researched. The complexity of this element build-up is best investigated through the experimental construction of prototypes.

The initial research on behalf of the lab tests shows the capacity of earth and wood working as a composite and indicates a potential to span horizontally. The reinforcement by fibres in the form of ropes or netting and using bio-fibre husks as an additive in the liquid earth mix has yet to be tested. To build larger-scale prototypes with an exemplary build-up of a slab from liquid earth, wood, and fibre reinforcement, the following research will be further investigated:

- bending and tensile behaviour of the liquid earth and wood combination
- the adhesiveness of tension active biological materials that are underused but naturally abundant in different formats like Flax, Hemp, Sisal, Jute, Seagrass, Willow, Miscanthus or Reet, and liquid earth.

- extrusion with biofibre-netting
- biofibers as additives in the liquid earth mix to reduce weight
- floor slab design, its size and build-up: geometrical ordering principles, possible spans
- proof of the earths fire repellent capacity and the layering of different earth mixtures in the composite
- production of 1:1 Prototypes to observe applicability, scalability, and regulatory compliance by hacking existing production infrastructure

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