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Wood based fasteners to produce timber earth slabs

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ABSTRACT: This study investigates wood-based fastening methods for the robotic manufacturing of timber earth slabs, which comprise lightweight timber structures (grids or frameworks) filled with an earth mix (clay, gravel, water, and natural fibres). The timber structure provides structural support, while the earth infill enhances thermal performance and naturally regulates indoor climate conditions. Specifically, the research examines the structural effectiveness and manufacturability using beech nails, with and without adhesive, and beech dowels for fastening the timber structure, using conventional bonded intersections as a baseline reference. Push-out tests were conducted on specimens featuring two shear joints each. Displacement transducers and digital image recording capture relative displacement while the forces at each shear joint are measured. The wood failure is analysed photographically. For the minor intersections in the investigated timber earth slab, nail-bonded connections with pressure applied during nail insertion demonstrate sufficient stiffness and load-bearing capacity. Additionally, this connection method offers potential for robotic manufacturing for such lightweight timber structures, particularly regarding geometric adaptability and production efficiency, although the potential for reuse remains limited.

KEYWORDS: *timber-earth construction, timber fasteners, beech nail bonding, beech dowel, robotic manufacturing*

1 – INTRODUCTION

The investigated timber earth slab is a composite ceiling structure consisting of a lightweight timber structure filled with an earth mix. These materials are deliberately combined to act structurally and functionally as a unified system, which is explored as a sustainable construction solution. This study investigates two timber grid systems (orthogonal and diagonal) and a timber framework (see Table 1). Utilizing small timber cross-sections for the load-bearing structure enhances resource efficiency by minimizing production waste and enables flexible production of diverse slab layouts with non-standard adaptations. The lightweight and precise nature of timber, combined with accurate and flexible manufacturing possibilities, enables robotic prefabrication of the load-bearing framework, a significant advancement in construction technology. Subsequently, a heavy earth mix infill is applied between the timber structure to improve construction physics properties, including sound insulation, fire protection, and indoor climate regulation. The contribution of the different materials to the overall system is summarized in Figure 1.

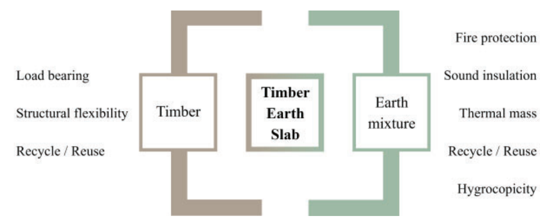
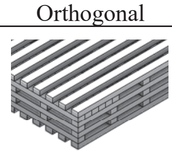
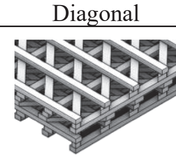
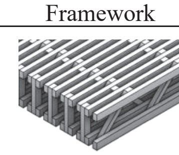


Figure 1: Combined characteristics of a timber earth slab

First prototypes of the timber earth slab (see Figure 2) were developed during a master project at the Technical University of Munich [1, 2]. The timber structure featured an orthogonal grid with conventionally bonded intersection.

Table 1: Possible timber structures for a timber earth slab

Orthogonal	Diagonal	Framework
		

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The robotic manufacturing of the timber structure previously involved laying out the grid, applying adhesive at each layer, and applying pressure either at each layer or to the entire structure for proper adhesive curing. The necessity of applying pressure significantly increases manufacturing complexity, reduces flexibility, and prolongs production time. Thus, a localized solution with fasteners capable of ensuring load-bearing capacity, durability, and suitability for robotic manufacturing is required. A fully mechanical "fast-forward" approach that eliminates adhesives altogether would significantly enhance reusability; however, this method notably reduces the structural stiffness [3]. Therefore, an alternative method involves utilizing mechanical fasteners to apply localized pressure during adhesive curing, thereby combining the benefits of adhesive stiffness and mechanical fastening efficiency. This paper specifically addresses this challenge by experimentally evaluating the structural effectiveness, manufacturability, and potential for robotic automation of various wood-based mechanical fasteners, including beech nails (with and without adhesive) and beech dowels, comparing their performance to conventional adhesive-bonded connections.

Figure 2: Prototype of a timber earth slab [1]

2 – BACKGROUND

2.1 ROBOTIC MANUFACTURING

The conventional production process of cross-laminated timber (CLT)—which closely resembles the method proposed in this paper—involves sequentially positioning individual lamella or preassembled lamella layers with adhesive applied between each layer. Once the target number of layers is reached, the assembly is transferred to a dedicated pressing station, where consolidation occurs through mechanical, hydraulic, or vacuum pressing methods. Following another relocation step, precision cutting is performed to create necessary openings for windows, doors, and building service equipment [4]. Robotic manufacturing could enhance this process by employing additive fabrication techniques that precisely place material only where structurally and functionally required. This method could eliminate the subsequent cutting operations, thus reducing material waste, minimizing handling steps, and increasing overall production efficiency. To fully leverage thes advantages, localized direct connection methods suitable for automation are required.

To leverage this approach, the layout of the timber structure is realized through a digital design tool that integrates architectural design, structural calculations, and robotic manufacturing into a streamlined workflow. A prototypical configurator calculates the optimal arrangement of the load-bearing timber layers based on the form and dimensions of the desired slab element. By incorporating additional input parameters such as timber cross-section dimensions, the number of layers, reinforcement options, and rotation of individual layers, the system flexibly accommodates various geometric requirements, static load cases, and required openings. Furthermore, the configurator automatically generates all required production parameters for subsequent robotic manufacturing. This approach aims at streamlining the production process of timber grids and is shown in Fig 3.

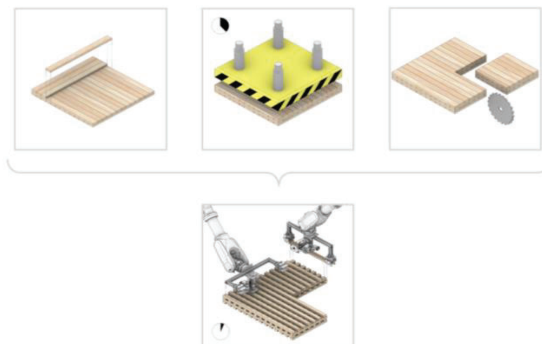

Figure 3: From a subtractive to an additive manufacturing approach.

2.2 MECHANICAL FASTENERS

According to DIN EN 1995-1-1:2010, four failure mechanisms based on Johansen's yield theory govern the load-bearing capacity of double-shear dowel-type connections. These include embedment failure of the side or main member and plastic hinge formation in the dowel [5]. The failure modes were derived for metal fasteners in timber connections. In [6], a new failure mode for wood-based fasteners is introduced, where two plastic hinges are formed at every shear plane. This failure mode has been experimentally validated, confirming its applicability in practical scenarios. The calculation approach in [6] is based on three plastic hinges for the two shear planes, differing from the European model, which assumes two plastic hinges per shear plane. Therefore, the calculation approach in [5] shown in (1) to calculate the characteristic (char.) shear resistance $F_{V,Rk}$ should be applicable for wooden fasteners. Additionally, the rope effect, which arises from friction between the fastener and the wood, is accounted for by the characteristic withdrawal resistance $F_{ax,Rk}$.

$$F_{V,Rk} = \sqrt{\frac{2\cdot\beta}{1+\beta}}\cdot\sqrt{2\cdot M_{y,k}\cdot f_{h,1,k}\cdot d} + \frac{F_{ax,Rk}}{4} \qquad (1)$$

With

$f_{h,i,k}$ … $char. embedemend\ strength$

$M_{y,k}$ … $char.\ plastic\ resistance\ moment\ fastener$

d … $diameter\ of\ fastener$

β … $\frac{f_{h,2,k}}{f_{h,1,k}}$

$F_{ax,Rk}$ … $char. withdrawal\ resistance$

For beech nails, the equation has been slightly modified. The characteristic plastic resistance moment is only considered with a factor of 1.5 instead of 2 [7]

2.3 NAIL BONDING

Nail bonding is used when conventional bonding is either uneconomical or impractical. A standard case is on-site reinforcements [8]. The quality of the adhesive joint is influenced by the type of nailing, the type and length of the nails, the type of adhesive, the wood's density, and the nail spacing [9].

Nail press bonding was regulated in the withdrawn DIN 1052-1:1988. The nails had to be 2.5 times the length of the lamellae or panel thickness to be fastened. Each nail covered a maximum area of 6500 mm², and the minimum distance between nails was 100 mm. The maximum board thickness for the component to be bonded was 33 mm, while the maximum plate thickness was 50 mm. [10] In the revision of DIN 1052-1:2008, nail press glueing was replaced by screw press glueing covering an area of 15000 mm² with a minimum distance of 15 mm. Furthermore, additional regulations regarding the length of the threaded section (> 40 mm) and a smooth shank in the component to be fastened were added. The maximum board thickness was increased to 35 mm [11].

Further regulations can be found in the current DIN 1052-10:2024. In addition to requirements for screw type and head diameter, the standard also specifies requirements for the adhesive. [12] A gap-filling adhesive of type "EN 301 I 90 GF 1.5 M w" must be used. According to [13], this limits the options in Germany to phenol-resorcinol adhesives and melamine-based adhesives. Investigated screw press bonding with one-component polyurethane adhesive leads to sufficient results. Using so-called scrails (shot in screws), no reliable results could be achieved, especially regarding wood failure. However, it was demonstrated that applying pressure during nail insertion increases the resulting contact force, thereby enhancing adhesive curing. Above a pressure of 0.11 N/mm², sufficient results were obtained for shear strength and wood failure [14]. Since the base material for bonding in a controlled environment can be more precisely prepared than on-site reinforcements, a deviation towards a non-gap-filling adhesive is conceivable. The adhesives examined in this paper are one-component polyurethane adhesives. The choice was made due to its use in standard cross-laminated timber production and the expected easier integration into the robotic production process.

3 – PROJECT DESCRIPTION

3.1 MATERIALS

The investigated fasteners are listed and shown in Table *2*. The beech nails have the same diameter but differ in the inclination angle at the tip. The nail with a flatter tip has a head and grooves. The beech dowels were cut from a round beech rod. The wood used is spruce, with a dynamically measured average modulus of elasticity of 9087.7 N/mm², an average density of 409.75 kg/m³, and an average moisture content of 8.97 M-%. Two different one-component polyurethane adhesives are examined.

Table 2: Investigated wood based fasteners

			
Product name	LIGNOLOC 4.7	LIGNOLOC 4.7 head	Round bar
Material	Beech	Beech	Beech
Length l [mm]	78	78	160
Diameter d [mm]	4.7	4.7	8/10/12/16/18

3.2 TEST SPECIMENS

Due to constraints imposed by the earth mix infill and the goal of resource efficiency, relatively small timber cross-sections (b/h = 60/40 mm) are selected for the timber earth slab. Accordingly, the connection tests are performed on specimens with identical cross-sections. Each specimen has a length of 180 mm, which is determined based on the required edge distances for the nails according to spacing guidelines typically applied for steel fastener [5]. The edge distance for the dowels is not sufficient. However, the tested conditions correspond to the conditions of the intended timber earth slab. Table 3 lists the investigated test configurations. All connections, except for the beech dowels, are tested with and without adhesives. All beech nail connections are shot in without pre-drilling using a manual nail gun. The dowels are dried and then inserted into a pre-drilled hole, which is 0.5 mm smaller than the diameter of the dowel at equilibrium moisture content. An additional investigation involves beech nails without head, where a pressure between 0.3 – 0.4 N/mm² is applied at the shear area during nail insertion and released immediately afterward. This part of the investigation is carried out using two different adhesive types. A bonded connection is produced for reference, ensuring curing pressure and time parameters adherence. The reference is created to check the test configuration and not to assess the load-bearing capacity of the adhesive bond, so only one reference is needed.

Table 3: Investigated test configurations and acronyms

Fastener type	No Adhesive	Adhesive	Pressure during insertion	Constant pressure
Beech nail	N	N_Adh1 [a)]	N_Adh1_Pre N_Adh2_Pre	
Beech nail head	NH	NH_Adh1	-	
Beech dowel	Dow_d [b)]	-	-	
No fastener	-	-	-	Adh1 Ref

a) Adh1/2 … different types of one component polyurethan
b) d … diameter of dowel in [mm]

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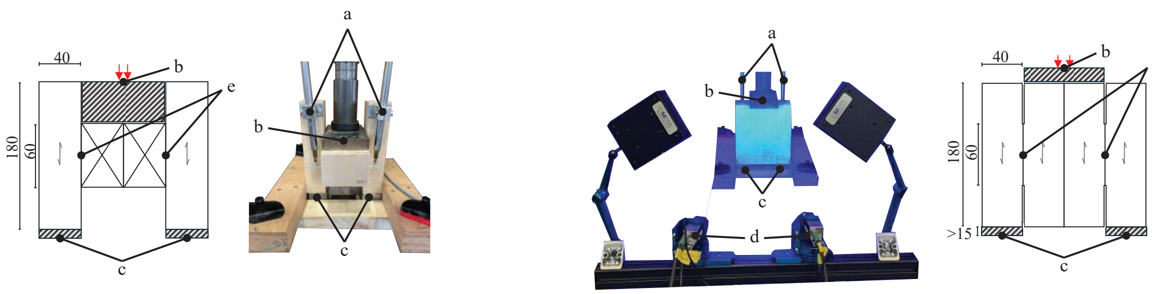

Figure 4: Test specimens and experimental setup 90° (left) and 0° (right) with (a) displacement transducers, (b) load point, (c) force measuring device, (d) digital image correlation system, (e) investigated shear plane.

The Push-Out tests were conducted in two configurations (see Figure 4). In the first configuration, the fiber angle between the two wooden components to be joined is 0°, while in the second configuration, it is 90°. In both configurations, the two middle parts were bonded beforehand to obtain a test specimen with symmetrical behavior. To achieve a similar shear area of 60 x 60 mm^2 in both configurations, the test specimens of configuration 0° were cut in. Two specimens with two shear planes were produced for each configuration and invested connection type.

4 – EXPERIMENTAL SETUP

According to DIN EN 26891, a test program is performed to evaluate the stiffness and load-carrying capacity of the different connection types [15]. The test program begins by increasing the load to 40 % of the estimated load-bearing capacity. After reaching that load, the load is kept constant for 30 seconds before being reduced to 10 % of the estimated capacity. Again, the load is kept constant for 30 seconds. Until this point, all changes are performed load-controlled. In the last step, the load is applied displacement-controlled until failure or a displacement of 15 mm is reached.

To prevent the side timbers from moving sideways, the horizontal displacement at the bottom is inhibited, creating a shear plane that stays parallel to the applied load. Using this symmetric approach, a shear plane is received, and influences from bending or pressure can be neglected.

Two displacement transducers and two load-measuring plates are installed in both configurations. This ensures a separate evaluation of the two different shear areas. Additionally, the displacement is recorded in the configuration 0° using a digital image correlation system.

5 – RESULTS

5.1 MAXIMUM FORCES

Figure 5 presents the experimentally determined maximum forces of the connections. A square represents the mean value for the 90° configuration, while the mean value for the 0° configuration is a circle. Additionally, the standard deviation is indicated by error bars.

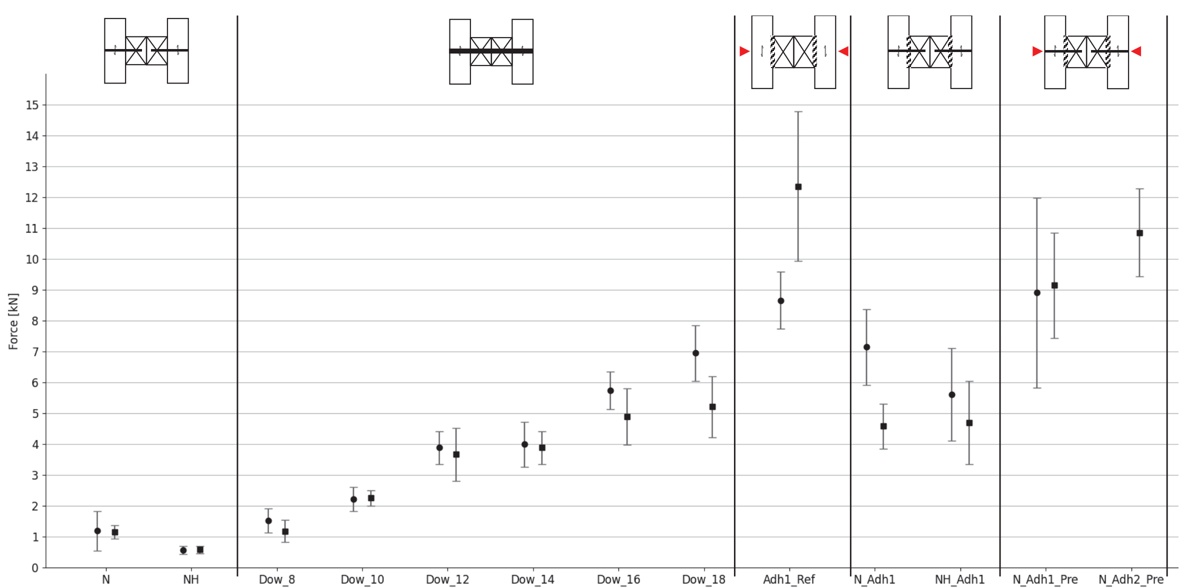

Figure 5: Mean maximum shear load and standard deviation per side in [kN] for configuration 0° (●) and 90° (■)

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The nails without head and the 8 mm beech dowels achieve comparable results regarding the load-bearing capacity. The nails with head achieve the worst results. The dowels' load-bearing capacity increases with the diameter of the dowel. Up to 14 mm diameter, there is no significant difference between the two testing configurations. For 16 and 18 mm, the configuration 0° reaches higher values than the configuration 90°. 16 and 18 mm dowels are loadwise comparable to the adhesive nail connections without pressure. Like in [6], two plastic hinges in the mechanical fasteners are visible, which can be seen in the deformed dowels and nails without adhesive in Table 4.

Despite less diameter, the 4.7 mm nail has the same maximum force as the 8 mm dowel. The beech nails with head achieve less. As an additional load-bearing capacity is achieved through the rope effect, it follows that the nail without head must have a high rope effect. The nail with head has a sharper tip, which increases the insertion speed. Comparing the timber around the inserted nails, it is detectable that the nail more or less "cuts" through and bonds with the surrounding timber as the nail with head "pushes" the fibers to the side. This effect somehow influences the withdrawal resistance and increases the rope effect.

Table 5 presents the mean values of the experimental test results combined for the two shear planes ($F_{V,Rk,calc,exp}$). For design according to [5], the characteristic plastic bending moment ($M_{y,Rk}$) for the beech dowels was determined based on three-point bending tests, while the plastic bending moment of the nails was taken from [7]. Using these as input parameters, it becomes evident that the resistance calculated according to [5] ($F_{V,Rk,calc,EC5}$) and neglecting the rope effect sometimes overestimates the actual load-bearing capacity. A calculation following the approach of [7] ($F_{V,Rk,calc,ligloloc}$) yields more accurate results. This suggests a fully plastic moment does not develop in the beech dowels before failure.

The difference between the experimentally determined and calculated forces increases with increasing diameter. The beech dowels were inserted into a hole 0.5 mm smaller in diameter, and due to the increasing circumference with larger diameters, an increase in friction can be expected, which leads to a rise in the rope effect.

For the connections with adhesive, it is visible that pressure during nail insertion improves the maximum load-bearing capacity of the nailed adhesive connections. With pressure during nail insertion, a load-bearing capacity at a level of the adhesive reference can be observed. The achieved shear strengths of at least 2.62 N/mm² for adhesive connections pressed during nail insertion are sufficient for use in a timber earth slab, as this exceeds the characteristic rolling shear capacity of the designated softwood by approximately factor 3.

Table 4: Deformed dowel and nail connections after testing

8 mm	
10 mm	
12 mm	
14 mm	
16 mm	
18 mm	
Nail without head	
Nail with head	

5.2 STIFFNESS

The resulting stiffness values are listed in Table 6. As before, the stiffness of the bonded connections exceeds that of the mechanical fasteners, with the difference in stiffness being more pronounced. The pressure applied during nail insertion enhances stiffness, though it remains below the adhesive reference. Since the displacements are significantly minor, high standard deviations are observed, and as a result, the findings primarily indicate

Table 5: Comparison of calculation approaches for the mechanical wood connectors

Fastener type	d [mm]	$M_{y,Rk}$ [Nmm]	$F_{V,Rk,experiment}$ [kN]		$F_{V,Rk,calc,EC5}$ [kN]		$F_{V,Rk,calc,ligloloc}$ [kN]	
			0°	90°	0°	90°	0°	90°
Beech nail	4.7	2247.00	1.91	1.99	1.69	1.52	1.47	1.32
Beech nail head	4.7	2247.00	1.29	1.24	1.65	1.51	1.42	1.30
Beech Dowel	8	4364.62	3.13	2.51	3.12	**2.86**	2.71	2.48
	10	8313.93	4.37	4.58	**4.70**	4.26	4.07	3.69
	12	13243.01	8.33	8.35	6.66	5.96	5.77	5.16
	14	22731.55	8.65	8.08	**8.66**	7.72	7.50	6.69
	16	42579.87	11.35	10.04	**12.39**	**11.14**	10.73	9.65
	18	55283.87	14.94	12.57	14.58	12.76	12.63	11.05

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Table 6: Mean stiffness and force and standard deviation (SD) for the investigated connections and different configurations

Fastener type	Diameter [mm]	Adhesive type	Stiffness [N/mm] mean | SD		Force [kN] mean | SD	
			0°	90°	0°	90°
Beech nail	4.7	-	2.37 | 2.29	2.06 | 1.72	1.19 | 0.64	1.15 | 0.21
Beech nail head	4.7	-	1.59 | 1.57	1.09 | 0.62	0.56 | 0.13	0.57 | 0.11
Beech Dowel	8	-	1.73 | 0.53	1.18 | 0.51	1.53 | 0.39	1.18 | 0.36
	10	-	4.28 | 1.08	1.57 | 0.74	2.22 | 0.39	2.25 | 0.25
	12	-	1.35 | 0.70	1.38 | 0.47	3.88 | 0.54	3.66 | 0.86
	14	-	5.06 | 1.16	3.00 | 1.80	3.98 | 0.72	3.88 | 0.54
	16	-	4.24 | 1.38	3.19 | 0.76	5.73 | 0.61	4.88 | 0.91
	18	-	4.71 | 1.64	3.32 | 0.25	6.94 | 0.90	5.21 | 0.99
Beech Nail Adhesive	4.7	1	29.75 | 11.07	23.03 | 12.70	7.14 | 1.23	4.58 | 0.72
Beech Nail Adhesive and Pressure	4.7	1	37.10 | 22.81	34.50 | 10.14	8.91 | 3.07	9.14 | 1.70
	4.7	2	-	33.72 | 3.28	-	10.86 | 1.42
Beech Nail Head Adhesive	4.7	1	21.28 | 8.04	16.16 | 15.32	5.60 | 1.50	4.70 | 1.34
Adhesive Reference	4.7	1	74.36 | 22.12	51.44 | 20.05	8.66 | 0.92	12.35 | 2.42

trends rather than definitive results

The digital image recording results for a 16 mm dowel and a bonded connection with a beech nail inserted under pressure are presented in Figure 6. A consistent displacement difference is visible between the left and right sides of the connection's shear plane in both configurations.

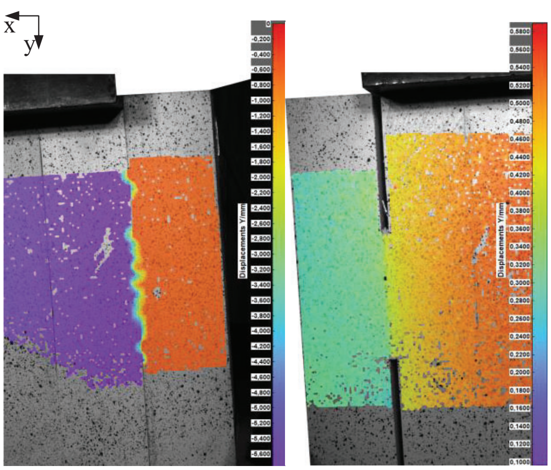


Figure 6: Digital image recording displacements y [mm] in test configuration 0° for a 16 mm dowel (left) and for beach nail Adhesive 1 (right) with pressure close to the failure point

A displacement gradient across the middle wood can be observed for the bonded connection. Evaluating stiffness directly at the shear plane yields lower values compared to physical displacement sensors. However, due to the minimal displacements, this difference is negligible and does not affect the reliability of the stiffness assessment, as the standard deviation is inherently high. Since acquiring and analyzing digital image data involves more steps than using physical sensors, its application in this specific case is mainly limited to checking the presence of moments and the desired force flow. For example, the presence of y-values in the side wood of the connections can be verified by evaluating the x-values, indicating a rigid body motion to the left during testing.

5.3 WOOD FAILURE

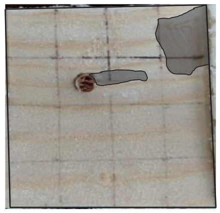
As the stiffness and load-bearing capacity of the bonded connections does not vary significantly, the wood failure is an indicator to check the quality of the adhesive strength. The wood failure in percentage is defined as the area of the shear area where wood failure is detectable and is visualized in Table 7 and Table 8. It can be obtained that the wood failure varies significantly between the different connection methods. Pressure during insertion enhances the wood failure, correlating with the results in [14].

Table 7: wood failure percentage

Fastener type	Adhesive type	Wood failure [%]	
		0°	90°
Beech Nail Adhesive	1	0/36/0/27	16/19/6/9
Beech Nail Adhesive and Pressure	1	46/78/85/90	39/75/87/38
	2	-	100/100/60/95
Beech Nail Head Adhesive	1	0/60/23/0	0/65/2/3
Adhesive Reference	1	100/100/99/100	87/98/93/100

If the wood failure exceeds 50 %, it can be assumed that the adhesive bond strength surpasses the wood's [16]. The adhesive's bonding capability and manufacturing process must be adequate to achieve a sufficient adhesive bond. Since the adhesives used are approved, their bonding capability is ensured. Therefore, the observed wood failure indicates that the manufacturing method, which includes initial pressing during the insertion of the beech nail, constitutes a proper production technique.

Table 8: Comparison of wood failure percentage exemplary for three test configurations

Beech Nail Adhesive (9 %)	
Beech Nail adhesive and pressure (75 %)	
Adhesive Referenz (100 %)	

6 – CONCLUSION

6.1 CONNECTION

Due to the high number of nodes, the fastener stiffness significantly influences the system behavior of the timber earth slab. In a finite element simulation, a comparison for a 6 m spanning timber earth slab with an orthogonal grid was calculated using the stiffness at the connection points of a 16 mm dowel and an adhesive connection with pressure during nail insertion. Using 16 mm dowels increased the deformation compared to the bonded connection by 60 %. It follows that using purely mechanical wood fasteners (nails and dowels) is not adequate for a timber earth slab, as the low stiffness prevents the overall system from achieving adequate rigidity with respect to the limit state of serviceability.

Bonding with beech nails achieves sufficient strength and stiffness under the condition that pressure is applied during the insertion of the nail. Additionally, the observed wood failure is within a range that indicates a reliable manufacturing process. The shear strength of the connection exceeds the rolling shear strength of the wood used. Therefore, the application of this method appears promising for the robotic manufacturing of a timber earth slab.

Additionally, it was observed that beech dowels do not develop a fully plastic hinge mechanism following the need for reduction values in calculations.

6.2 MANUFACTURING PROCESS

The results of the fastener investigations lead to conclusions on how to best set up a manufacturing process for the load-bearing timber structure of the timber earth slab. The manufacturing procedure includes three main robotic steps carried out at a single workstation: positioning the lamellas, applying adhesive, and inserting nails. A preliminary step involves the preparation of wooden lamellas, which can be robotically prepared or supplied already prepared.

Preparation and cutting of the lamellas

The wooden lamellas must be accurately prepared according to the intended geometric layout. This step can either be performed directly by the robot or completed separately, with prepared lamellas supplied to the robotic station.

Positioning of the lamellas

Guided by the digital model, the robot picks up the pared lamellas and positions them precisely, starting with the bottom layer. Precise positioning ensures accuracy and structural integrity throughout the assembly process.

Applying the adhesive

Once the bottom layer is positioned, the robot applies adhesive specifically at the intended connection points. This targeted application optimizes adhesive usage within its effective open time.

Insertion of nails

Immediately following adhesive application, the robot positions the subsequent lamella layer and inserts nails using controlled pressure to locally secure joints during adhesive curing. This method avoids the necessity of large-area pressing like vacuum pressing.

6.3 OUTLOOK

Connection-wise, delamination testing is necessary for the bonded connections to verify durability. In the case of the beech dowels, it must be determined if swelling causes the dowel to crack the spruce or if shrinking results in friction loss.

Manufacturing-wise, future advancements in robotic automation and material technology could further enhance timber construction efficiency, precision, and sustainability. Integrating innovative fastening techniques and improved material usage may reduce waste while enabling more complex and customized structures.

7 – ACKNOWLEDGES

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