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Biaxial spanning flat solid wood slab

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Abstract

The reduction of carbon dioxide emissions is one of the priority environmental policy goals and the building sector is responsible for a significant part of these emissions. This paper shows a possibility to substitute point-supported and biaxially spanned reinforced concrete slab with one made of solid wood only. In this way, one of the largest emitters within the load-bearing structure can be substituted to become a significant store of $C0_2$. In addition, the advantages associated with a flat slab, such as improved conversions and potentially longer service life, can be preserved.

The approach takes up a historical design principle and, with the help of digital planning tools, transfers it to the desired load-bearing effect, which resembles a reinforced concrete flat slab. It describes a way of using an algorithm to generate the desired spans through a patchwork-like spatial arrangement and an interlocking of smaller cross-laminated timber (CLT) elements.

Keywords: Timber construction, computational design, digital fabrication, optimization composite system

1. Introduction

The building sector is responsible for a significant part of these emissions. Since the oil crisis in the 1970s, the share of emissions resulting from operation has been continuously reduced, but now the focus is increasingly on emissions resulting from production and dismantling. To classify the impacts associated with specific construction methods, regulations such as DIN EN 15804 [1] can be used for analysis.

Due to the cumulative accumulation of CO_2 in the atmosphere and the only short time frame until the 1.5° target set in the Paris Agreement 2015 [2] is reached, immediate savings are required. This paper shows a possibility to substitute point-supported and biaxially spanned reinforced concrete floors with one made of solid wood only. In this way, one of the largest emitters within the load-bearing structure can be substituted to become a significant store of CO_2. In addition, there are the advantages associated with a flat ceiling, such as the improved usability of a building and thus the extension of its service life.

2. Topic and Approach

Timber ceilings, designed in solid wood or with beams, usually have a single axis span. The elements usually lie on beams between columns or walls. Free floor plans or organically shaped ceilings are often very difficult or impossible to realize with a one-way slab.

Flat slabs, as known since the beginning of the 20th century in reinforced concrete, can transfer loads to punctual support points and transfer loads biaxially through cross-distribution effects.

[7]. The supports do not necessarily have to be arranged in a grid; they can be positioned more freely. With one-way slab, often more supports are required, especially in free-form floor plans, as the axes

cannot run parallel and a uniform and material-saving shaping of the downstand beams can hardly be realized.

Structural depth. Without downstand beams, the structural depth of the slab can also be significantly reduced. Over several storeys, this can save material and reduce the height of the building. In taller buildings in particular, the same floor area can be accommodated in a significantly lower overall height Figure 1.

Repurposing. Conversions can be realized much more easily with beamless slabs. In addition to bracing walls and cores, columns remain as a limiting or space-forming element. A predetermined and restricted sequence of rooms can be avoided by using a flat ceiling, which also increases flexibility in terms of the use of space.

Ducting. The routing of building services supply lines often has to be adapted when changing the use of the building. If the underside of the ceiling is even, the installation lines of the building services systems can be placed freely Figure 1. It is often not feasible to make additional openings in load-bearing beams and laying pipes underneath existing joists further reduces the clear room height Figure 1.

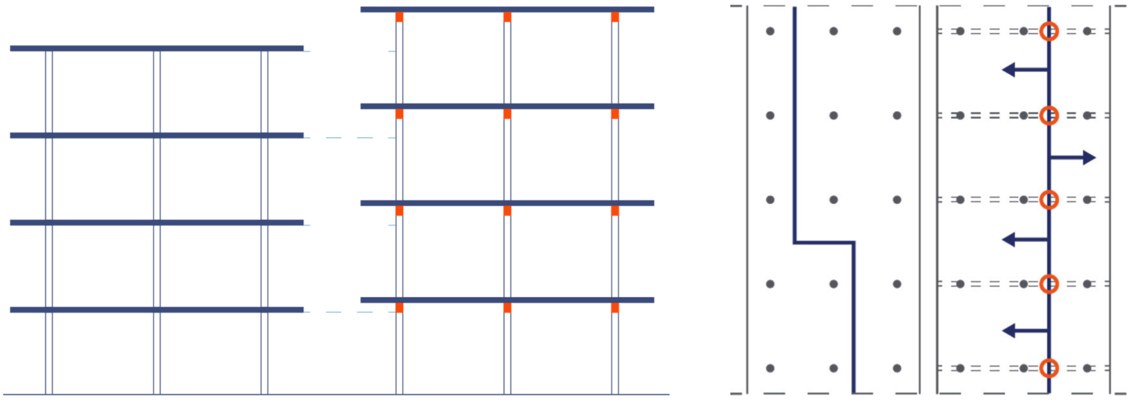


Figure 1: Qualitative comparison: left: structural depth, right, ducting and repurposing

Flat ceilings are also popular to planners because of the perception of the room. In large, open rooms, beams form visual boundaries and thus clearly divide the room.

In order to be able to use the described advantages of flat slabs in solid timber construction, a biaxial load transfer must be realized on the one hand and punching in the area of the punctual support points must be avoided on the other [7]. The present work initially focuses on the realization of biaxial load transfer and aims to realize this with timber connections. The punching shear problem is also being solved in timber construction. By using solid wood, the approach differs from the solution presented by Schramm et al [3], which pursues a similar objective. The flat ceiling made of solid wood described in this paper can also increase CO_2 storage and improve building physics parameters. The calculations should be able to be carried out on the basis of known wood-wood connections in order to enable a rapid transfer into practice and achieve the targeted CO_2 savings in the short term.

2.1 Construction principles and transformation

The concept is based on the principle of interlocking or doweled beams (Figure 2). This shear-resistant connection between two superimposed beams significantly increase their load-bearing capacity and span, which can thus exceed the length of the individual beam several times over. This type of beam connection can already be found in drawings of ancient Roman wooden bridges [4]. The Swiss craftsmen and brothers Grubenmann used this connection to assemble smaller beams into a large statically viable one and build bridges with spans of up to 70m [4]. An advantage of this method is the reversible connection of its individual parts.

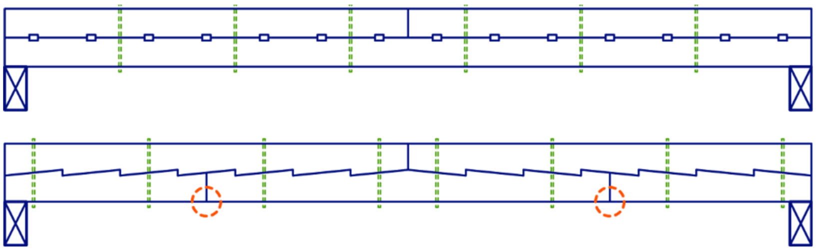


Figure 2: Principle of interlocked or doweled beams.

The present approach takes up this design principle previously used for beams and transfers it with the help of digital planning tools to the desired biaxial load-bearing effect using two layers of CLT panels to create a solid flat slab made of wood.

In order to transfer the effect to a panel, the positioning of the joints and the arrangement of the dowels was translated from two to three dimensions, as shown in Figure 3.

Figure 3: Layers of CLT plates. Left: upper Layer three parts, right: lower layer three parts.

The positioning of the joints is crucial for the performance of the system. In the upper layer, the joints were positioned in the center of the field, as this way they are located in the zone subject to compressive stress. The joints in the lower slabs, on the other hand, were positioned near the support points. Joints can also be placed in the area of the moment zero point.

The interlocking is placed in particular in the areas with the highest shear forces between the two slabs in the area of the supports. For interlocking, wooden strips were arranged in several rows depending on the shear force amount.

For the positioning of joints and dowels, the slab was initially analyzed with irregular contours and support spacing Figure 5 using Karamba3D [9]. Based on the results, an evolutionary multi-objective optimization plugin Wallacei [5] is used to generate different layouts for the joints and impact points. In a second script, the arrangement of the dowels is calculated based on the shear forces of the first calculation. The results of the two scripts are combined at the end to generate the final digital models of the individual parts.

2.2. Life cycle assessment

The life cycles A1-A3 (production) and C3 (waste recycling) were calculated according to DIN EN 15804 [6]. Phase D (recycling potential) was also calculated but is not included in the overall assessment. The values were determined using the life cycle assessment tool "eLCA" [7]. A 50-year lifespan was assumed. It is noticeable that all ceiling systems that contain wood have negative CO_2 emissions during production but emit a lot of CO_2s during recycling. As timber components are usually thermally recycled, the CO_2 (A1) stored during the growth of the trees is released back into the atmosphere during recycling [8].

Concrete slabs systems emit a lot of CO_2s during their production, as cement production is very energy intensive. Recycling, on the other hand, has little impact on the balance, as concrete is usually processed into recycled gravel, and hardly any CO_2 is emitted during this process.

In life cycle D (potential for reuse, recovery, and recycling), wooden components again have a better balance. The reuse of the material and the resulting avoidance of thermal recycling is one of the main reasons for the very positive numbers. Wood is easier to reshape into a new usable form than concrete. Wooden construction elements can be easily separated and reused, as long as they are not glued, or they can be sawn into new, smaller pieces from large cross-sections. Concrete components, on the other hand, can either be reused in one piece or crushed into gravel. This is usually used as a substructure in road construction or as an additive for recycled concrete. However, this requires energy-intensive cement again.

Figure 4 shows once again the difference that phase D makes to the overall balance of wood. For components made of concrete or steel, the influence of the last cycle is almost negligible.

This illustrates that the good climate balance of timber ceilings and timber components is further improved compared to concrete components if thermal utilization can be avoided. Extending the life cycle of timber components should therefore be the goal in the further development and redesign of construction.

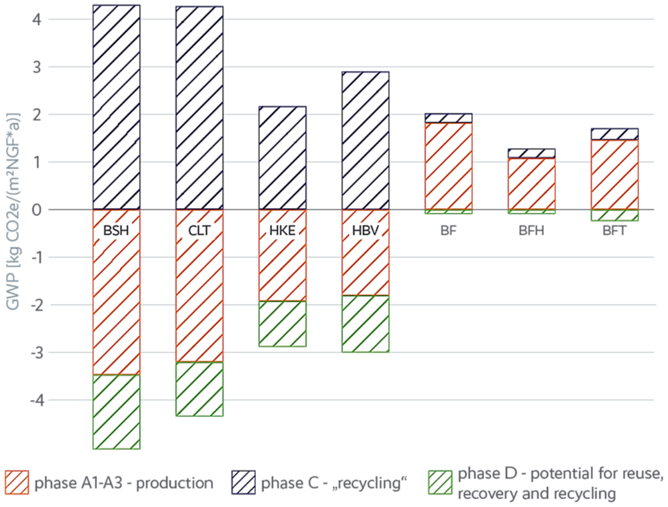


Figure 4: LCA-comparison of different ceiling systems: BSH- Glulam timber, CLT- Cross laminated timber, HKE- Hollow box element, HBV- Wood-concrete composite, BF- Concrete flat ceiling, BFH- Concrete honeycomb ceiling, BFT- Prefab concrete elements [8].

3. Setup and investigations

The test structure of the biaxially spanning solid timber slab has no stairs or other openings, as it is intended as part of a larger building. Different spans and irregular column positions were used, which [9] usually cannot be realized satisfactorily with a conventional timber floor system.

3.1 Initial calculation

An FEM calculation was created in real time using the Karamba3D plug-in [9] and visualized using the reference points of the columns and the outline of the slab (Figure 5). This allows a quick and easy check of whether there are sufficient supports, where there are weak points or whether a support is redundant. If changes or adjustments are made, a new calculation and a new result are provided immediately. In addition to the self-weight of the monolithic slab, a surface load of 5kN/m² was also applied. This first calculation serves as the basis and reference for all further calculations.

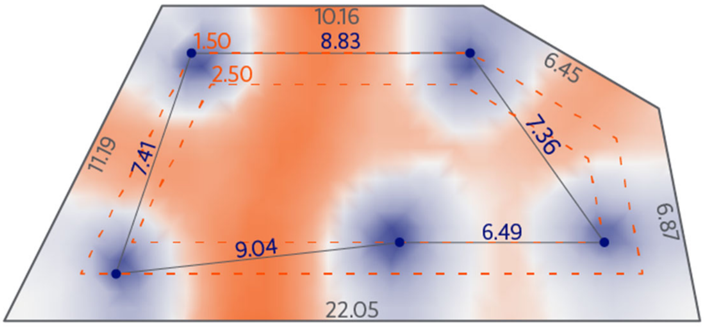


Figure 5: Reference model shows a visual representation bending moments.

3.2 Positioning connection points

For the arrangement of the panel joints on the top and bottom sides, the panel is divided into parallel strips. Figure 6 shows hatched zones and there are defined for both the upper and lower layer. These zones are located in the areas with the high bending moments (e.g. middle of the span), in the upper layer in the areas with the lowest moments (above the supports). If a joint intersects such a zone, a plate is arranged transversely there automatically, bridging the area like a crossing.

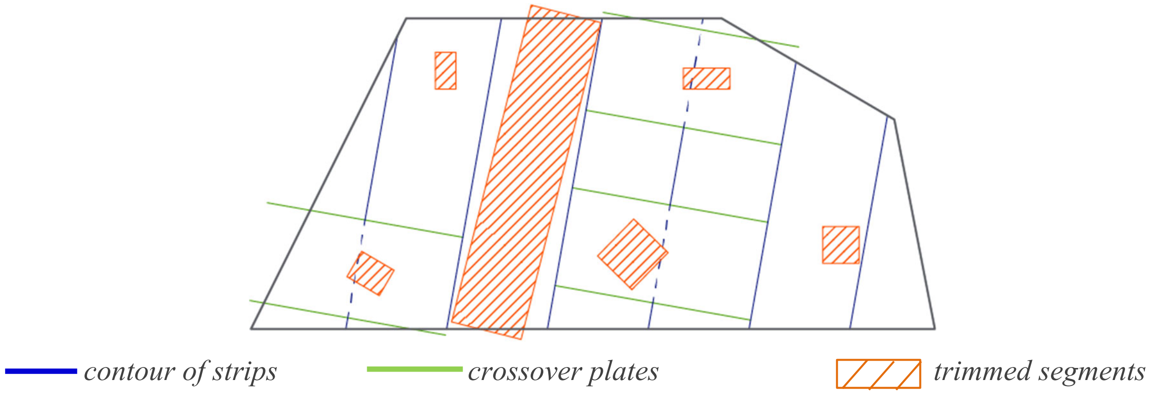


Figure 6: Definition of the positioning of slab joints.

There are numerous options for aligning and stacking the individual elements. In order to quickly find an optimized arrangement with regard to load transfer, the evolutionary optimization plug-in Wallacei[5] was used to perform an automated alignment and prevent collisions, as well as to determine the stress from bending moments and their deviation and to minimize them. Optimization is carried out step by step using the plug-in mentioned above, with evaluation and classification according to the specified criteria. The optimization process began with a free cutting of the panel edges. The waste was minimized by using only parallel edges and elements of the same width Figure 7.

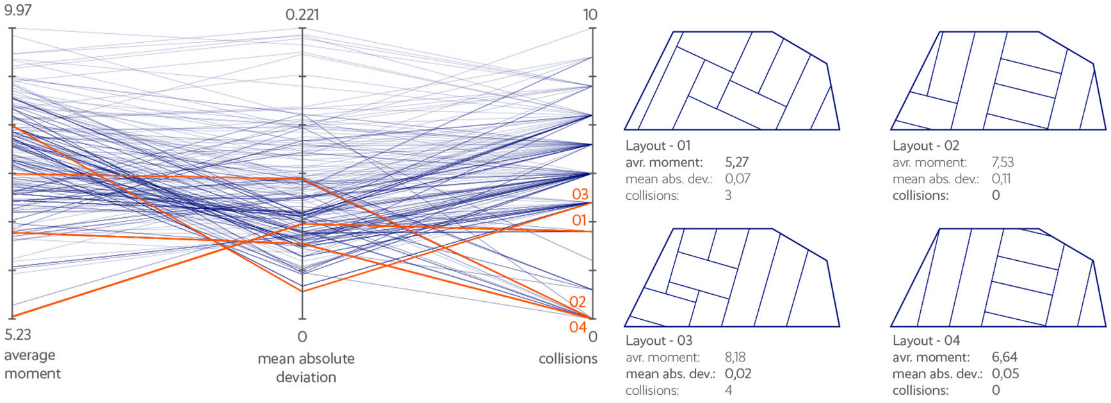


Figure 7: Optimization process for nesting the CLT plates: different layouts for the bottom layer.

3.3 Dowel strips

Several rows of dowels are used for interlocking in the area around the support points. These are arranged polygonally at different distances around the supports. The orientation of the dowel bars results from the direction of the forces that run parallel to the connection between the lower and upper slab element. These forces running in the joint plane were recorded at regular intervals and combined to form a resultant force. The orientation of the longitudinal axis of the dowel bar is perpendicular to the resultant force. The resulting lines are automatically combined to form a closed polyline. These curves were then offset by the thickness of the dowel bar to create a surface Figure 8. The volume dowel bars were created in a first step by offsetting each curve by half its thickness upwards and by extrusion.

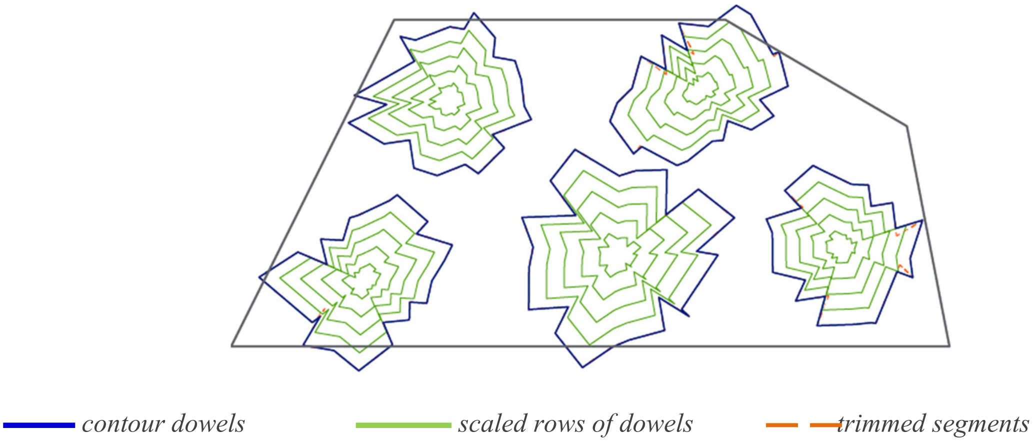


Figure 8: Dowels contour and scaled rows of dowels.

To secure the panels in an orthogonal direction, cylindrical dowels are inserted at up to 45° to the surface in addition to the strips described above, whereby the upper and lower panels are connected to each other in a grid pattern and secured against lifting.

3.4 Composite System

Particular attention must be paid to finding a suitable composite system between the CLT-layers. The effectiveness of the shear connection has a direct influence on the required material consumption. It must meet high requirements in terms of accuracy of fit so deformation due to slippage is minimized and uniform stress on all shear connectors ensured. It should also be sufficiently rigid, and load bearing to limit the required number of connectors and thus reduce production costs. Currently, the aim is to achieve a bond via form-fit, similar to the notch, as known from the timber-concrete composite [10] [11] or based on historical or modern composite constructions with hardwood dowels [12, 13]. The composite system prevents relative displacements between CLT layers and thus enables the layers to work together to form an overall cross-section.

In form-fit timber-concrete-composite systems or traditional carpentry timber joints, the fasteners are arranged in such a way that the forces are transferred into the timber component as parallel to the grain as possible. The anisotropy of wood results in very different material properties depending on the direction of the grain. For example, the characteristic strength of a solid wood of grade C24 [14] in the longitudinal direction with $f_{c,o,k} = 21$ N/mm² is more than eight times higher than the strength transverse to the grain ($f_{c,90,k} = 2.5$ N/mm²). For the stiffnesses, this factor is almost 30 ($E_{0,mean} = 11{,}000$ N/mm² and $E_{90,mean} = 370$ N/mm²) [12].

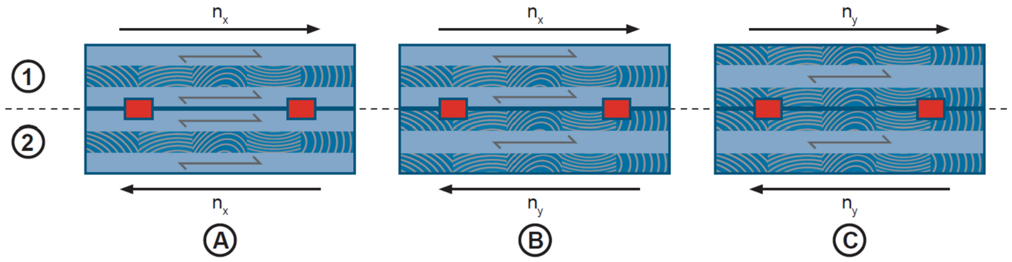
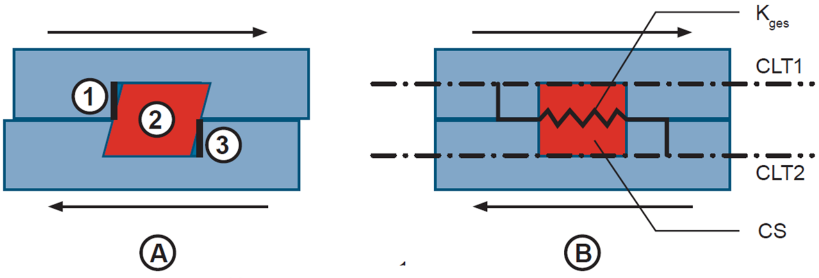


Figure 9: Composite System between top ① and bottom ② CLT-layer: Principle of different load to grain angles in the composite joint (Ⓐ: 0°-0°; Ⓑ: 0°-90°; C: 90°-90°)

The two CLT-layers run at an angle to each other in ground plan. This results in shear forces in the joint with a load to grain angle. The known approaches from EC 5 [15] can be used to interpolate the intermediate values for strength and stiffness. In addition, the intermediate layers of the CLT elements must be considered, which themselves also exhibit a certain shear softness. This is largely determined by the rolling shear stiffness of approx. 10% of the shear stiffness [16]. These parameters can be integrated into the overall parametric model as input values for initial estimates.



$$Kges = 1/(\frac{1}{KCLT1} + \frac{1}{KCS} + \frac{1}{KCLT2}) \qquad (1)$$

Figure 10: Composite System Ⓐ: Principle of the mechanical spring model Ⓑ for K_{ges} (1): Tensile stiffness of the notch end faces (① and ③) and the shear stiffness of the dowel strip ②.

One way to consider the stiffness of the composite connectors between the layers is through a spring model connected in series (Figure 10). The tensile stiffnesses (EA) of the notch end faces of the CLT elements are considered as well as the shear stiffness of the dowel strip (GA). Figure 10 clearly shows that the orientation of the CLT layers in relation to each other has a major influence on the bond quality. In the worst case, the stiffness can drop to below 4% (Table 1).

Table 1:

Composite System - Influence of the load to grain angle: Simplified example with three variants (Figure 9) using the tensile stiffness of the notch end faces according to Figure 10.

			Variants of load to grain angle acc. Figure 11		
			0°- 0°	0° - 90°	90° - 90°
CLT1	E-Modul	*N/mm²*	11.000	11.000	370
CLT2	E-Modul	*N/mm²*	11.000	370	370
	K_ges	*N/mm*	5.500	358	185
		%	**100**	**6,5**	**3,4**

Experimental investigations should be carried out to validate the analytically determined parameters. The parameters of the composite material can be well examined based on small-scale shear tests [10, 17] While the slip-block-test is a single shear test, the push-out has a double shear test setup. They are based on testing the shear strength of solid wood [17] and on composite steel and concrete joints [18] [16]. Figure 11 shows possible setups for the composite system considered here.

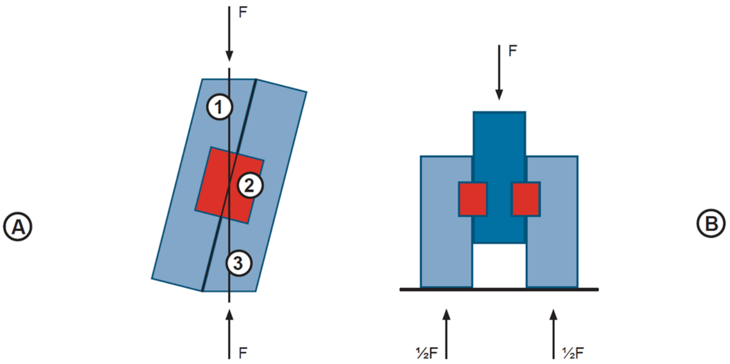


Figure 11: Principle of small-scale shear test setups: Ⓐ slip-block-test acc. to DIN EN 408 and Ⓑ push-out-test acc. to EC4 (① and ②: test specimen as CLT-layer; ③: composite system, f_e. hardwood dowel).

3.4 Mock-up

A mock-up in the shape of a table was created and loaded to check the functionality and to record the manufacturing influences, such as tolerance.

The model, which can be seen in Figure 11 has the following dimensions: 1.8 meters long, 1 meter wide and consists of seven 18 mm thick plywood panels. These boards are connected to each other in two ways: firstly with 6 mm thick wooden dowels, which are arranged in a grid of 12 x 12 cm where possible, and secondly with plug-in connections made of wooden strips with a cross-section of 1 x 1 cm^2.

Figure 12: Mock-up: Assembling and testing the construction principle with 100kg of Sand.

4. Conclusion

The developed system demonstrates a way of constructing flat slabs made of wood with wide spans. The slab, in this case consisting of two 18cm thick CLT elements, are of a size suitable for transportation and can be joined together on site so that they look like a continuous slab. The requirements for airborne and impact noise insulation can be met by adding e.g. 6cm of cement screed, 3cm impact sound absorbing subflooring and 6cm non-bonded chippings. It therefore appears to be possible to construct timber buildings without beams, thereby achieving flexibility of use and saving CO_2. The present investigations demonstrate that the proven design principle can not only be used for linear elements, it can also be transferred to a surface. It is possible to significantly increase the section modulus and the surface moment of inertia through the described interlocking, in that the total height resulting from the interconnection can have an exponential effect. On the one hand, this can significantly improve the load-bearing capacity with the same amount of material, and on the other hand, the interlocking and the elimination of the previously obligatory downstand beams offers more design freedom and possibilities for conversion. The high tolerance requirements are one of the challenges. These will be investigated as part of a funding project with an industrial partner. In addition to questions relating to assembly and manufacturing tolerances, a new approach to punching in the support area is also to be explored. The experimental and analytical investigations also serve to obtain more precise information about the composite behavior and deflections.

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