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Robotic Joining of Oblique Dowels – Precision Analysis and Calibration

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Abstract

Aiming at the further reduction of material consumption in multi-storey timber constructions, this paper focuses on the anchoring of interlocking dowel joints. They are an integral part of a new construction system for load-bearing plywood walls. The presented research analyses the feasibility and sensitivity of their production process as well as whole wall elements accessing the interlocking effect of the dowels and proposes a production concept for their precise and automated, yet time- and space-saving manufacturing. To make use of the form-fit effects of diagonally positioned beech dowels, versatile robotic manufacturing was necessary. Resulting single wall samples were incorporated in several explorative load-tests concerning the influence of the dowel anchoring and positioning on the performance of the presented construction. The resulting observations allow for comparative considerations of alternative wall construction methods such as timber frame and solid construction.

Keywords: robotic manufacturing, design for disassembly, timber based structure. mono-material construction, resource efficiency, interlocking joints, beech dowels, wooden nails

1. Introduction

The Interlocking Dowel System (IDS) is a novel, mono-material and resource-saving lightweight timber construction method (Schmidt-Kleespies et al. [1]). It differes from the load-bearing behaviour of the established timber frame construction by activating the surface layers of the structure as the primary load-bearing structure. Cylindrical wooden dowels arranged at skew-whiff angles connect these load-bearing layers. The resulting hollow space in between the panels serves as insulation layer that can be filled with various pressure-resistant thermally insulating materials. An example of the interior of such a wall element shows *figure 1*. As a system based almost exclusively on wood, IDS elements are completely separable and recyclable.

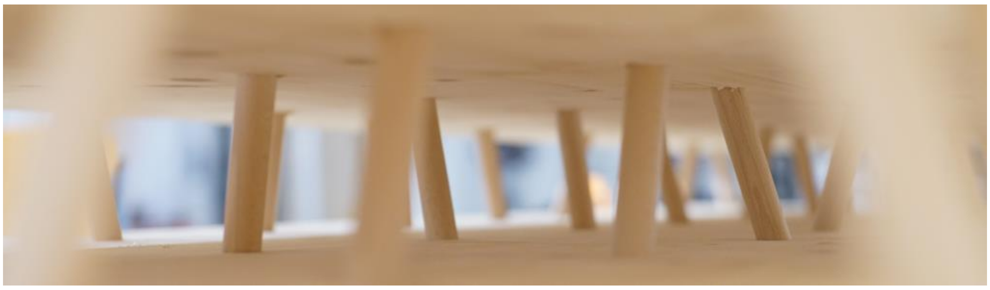

Figure 1: Insight in the interspace of a test specimen

3.1. Impact of dowel connectors on the performance of IDS wall elements

Preliminary FE analyses of the presented wall construction concept show that the type of anchorage of the dowels has a major influence on the load-bearing behaviour of the resulting walls. The analysis was conducted with consideration of non-linear effects by large deflections, path-controlled loadsteps and an orthotropic-elastic material model. The resulting load-deflection curves (*fig. 2)* are heavily influenced by imperfections.

It is assumed that they are tightly controlled during the load tests and therefore considered with a maximum pre-deformation of just 1,25 mm to predict estimated values. A control of the influence of imperfections (factor 10) is included in said graph as well. Therefore, the analysis can predict the relative influence of the dowels and their connections on the loadbearing capacity. In the FE model, a vertically loaded wall slab fails at 140 kN when a vertical load is applied with hinged joints, but reaches 225 kN with rigid connections of the dowels. Without any - or loosely connected - dowels, it is predicted to fail at 85 kN. This leads to the following thesis: The performance and range of applications of the IDS depends largely on the interaction of the two panels and thus on the coupling effect of the dowels.

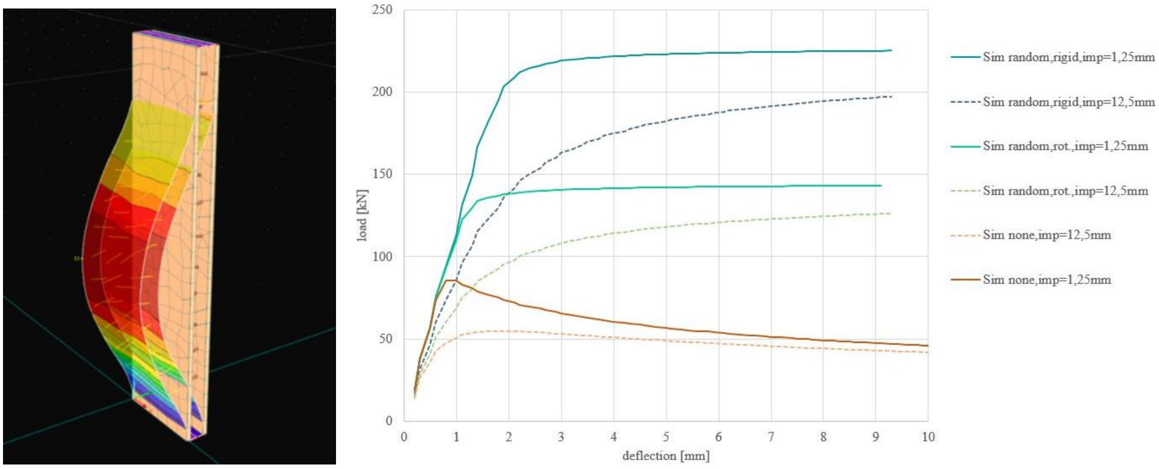

Figure 2: FE-Model and visualisation of the resulting deflections (not to scale) (left), load deflection curves of simulated specimen W9 with rigid or hinged dowels and without dowels (right)

Dowels can easily be anchored using glue. However, such a connection is not reversible and would contradict the principle of mono-material construction. The presented work tries to find an alternative way by implementing glue-free, purely mechanical dowel anchoring using robotic production tools while determining its limits. Here, a press-fit is created either via the commonly known swelling effects of certain types of wood (Thoma [2],[3]) or via a nail that spreads the dowel (Graubner [4]).

Interlocking timber structures have the potential to improve recyclability and simplify construction and manufacturing steps (Bucklin et al. [5]; Robeller et al. [6]). Even when the adhesives within the plywood are still prohibiting a strictly mono-material construction, the presented form-fit plug-in connections represent a significant step towards eliminating metal fasteners from conventional timber panel construction.

2. Fabrication workflow

The following robotic manufacturing steps are necessary in order to fabricate mechanically anchored, interlocking dowel connections: preparatory milling (1), drilling (2), insertion of dowels (3) and press-fitting of the dowel ends (4). The equivalent effectors used are a high-frequency spindle, a drilling tool with high torque rate (>100 Nm), a pneumatically controlled gripper and a pneumatic coil nailer for wooden nails. (*fig. 3*). The effectors can be swapped automatically. The changing process takes approx. 2 minutes. In order to shorten the production time, the number of changes should be kept as low as possible.

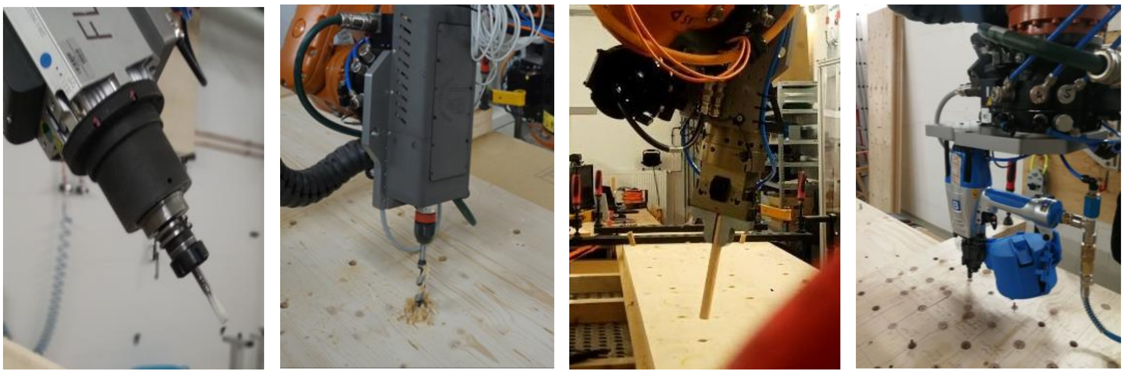

Figure 3: Effectors used in the fabrication Workflow, from left to right:
milling tool, drilling tool, gripper, coil nailer

Measuring the individual durations of the manufacturing operations, made it possible to compare the respective costs of individual production steps with the benefits regarding the rigidity of the resulting connection. The average production time for a single double anchored dowel joint, using a Kuka KR60 robot, is 1:33 min. The drilling and insertion processes are especially time-consuming but – other than milling and press-fitting – cannot be avoided.

Table 1

procedure	milling	drilling	insertion	press-fitting
duration	7 sec	56 sec	25 sec	5 sec

3. Production related Sensitivity Analysis

First, inclined bores and deep-hole bores (with a depth ten times larger than bore diameter) with varying inclination angles and drilling tools were drilled and their nominal values (position and inclination angle) were compared with the actual measured values. In the second step, the pull-out resistance of robotically inserted non anchored dowels was measured and compared with that of mechanically anchored dowels. Finally, large-scale load tests were carried out and compared to the predictions of the FE calculations.

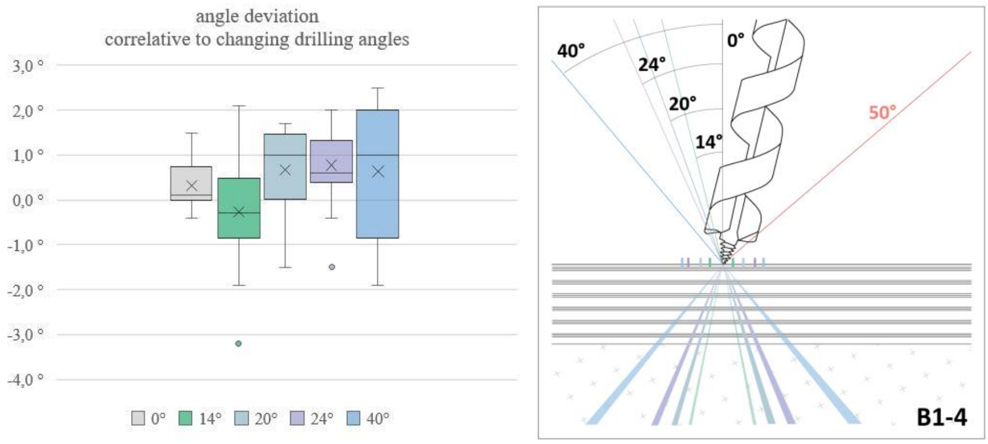

Figure 4: Degree of deviation with different inclinations of the drilling axis from 0°-40°

3.1. Deviations

Drilling in wood as such is a manufacturing step that is associated with imperfections (Baldauf el al. [7]). Precise robotic drilling with a drilling axis inclined to the normal of the workpiece surface poses a major challenge (Garnier et al. [8], Pereira et al. [9]). This is due to the fact that the robot arm usually has to move all six axes simultaneously in order to trace a straight line. More precisely, it moves along a sequence of lined-up circular arc segments. As a result, there are inherently slight deviations between the digital target values and the physical results implemented by the NC system (industrial robot).

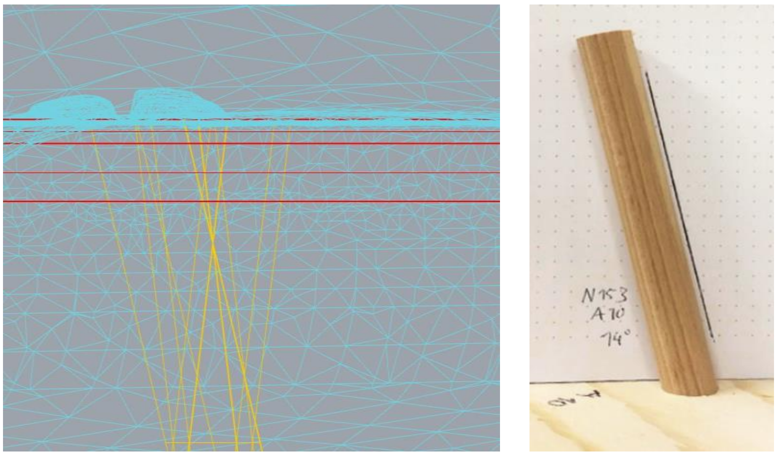

Figure 5: Comparison of the drill axis inclination in the digital model and 3D scan parallel (left) with the measured values on the test specimen (right)

As all four, previously described production steps use the same coordinates, deviations can quickly lead to conflicts. For example, if the driller slips out of position by some millimetres due to a certain fibre direction and low rigidity of the tool, the coil nailer effector does not hit the dowel on its axis. Therefore, in a first step the degree of possible deviations must be determined in more detail and then looked at again in a sensitivity analysis comparing the respective production steps.

3.1.1. Experiment set-up

Therefore, a series of tests was initiated. It included eight repetitions of drilling inclined holes for a total of four different drill bit types (B1: 20mm/265mm auger drill bit; B2: 16mm/255mm auger drill bit; B3: 14mm/440mm auger drill bit, each as a single-lip drill bit and B4: forstner drill bit with extension and 15mm/345mm mandrel, as a double-lip drill bit). With those drill bits 16 cm – 20 cm deep holes were drilled at 0°, 14°, 20° and 24° and 40° inclination to the plate normal. The holes were drilled at a feed rate of 7.5 mm/sec and a speed of 300 rpm (B1+B2), 480 rpm (B3) and 360 rpm (B4). The drill hole positions were then recorded using 3D scanning (ArtecLeo) (*fig. 5*).

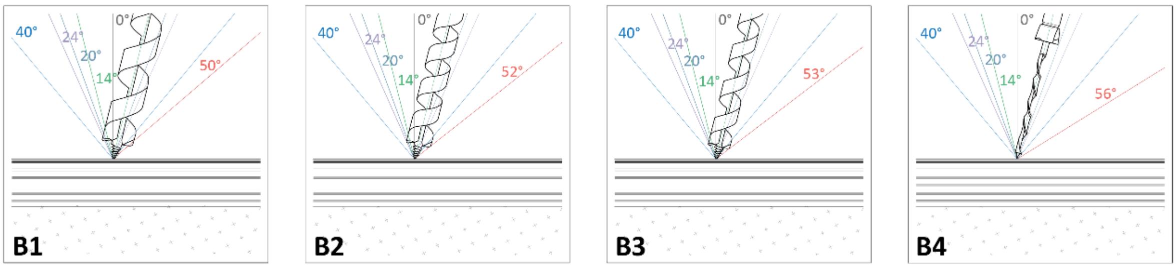

Figure 6: Drill types

To measure the resulting degree of inclination of the drilled holes, round wooden rods were driven into the hole reveal and the protruding pieces were measured in relation to the panel normal (*fig. 5*). In addition to the series of tests on drill holes in laminated veneer lumber boards (LVL), a technically equivalent series of tests on drill holes in glue-free, pressed biofibre boards (*fig. 7*) was carried out. The selected biofibre boards consist of 70% beech fibres and 30% spruce fibres. They have a relatively high bulk density of 1000 kg/m³. The angle of rotation of the drill around the panel's alignment was not varied in this test setup, as there is no oriented fibre direction.

Figure 7: biofibre plate with a homogeneous, rough surface and stainer marks (left); auger on the top layer of an LVL board made of spruce wood (right)

3.1.2. Evaluation

While the shifting between measured, real drilling position and the digitally prefabricated nominal value at an inclination of 14° was hardly recognizable, particularly steep inclinations of 24° and 40° showed deviations of up to 11mm. These values can lead to problems, particularly in the edge areas of the wall elements. In a further pass, the inclination of the drilling axis was rotated by 30°, 60° and 90° relative to the grain direction of the top panel veneer. It was noticeable that the degree of deviation at steep drilling inclinations depends heavily on the direction of the grain on which the drill is placed. The maximum deviations (15 mm / 1.9°) between the target value and the measured value always occur when the drilling axis is parallel or only slightly inclined (<30°) to the grain direction (slipping of the drill tip/mandrel). For drilling orthogonal to the fibre direction, the average deviation is only 2 mm / 0.5°, but is characterized by outliers of up to 20 mm / 1.9°, which are to be traced back to spontaneous hopping of the drill mandrel when it hits the transverse fibres of the LVLs covering layer.

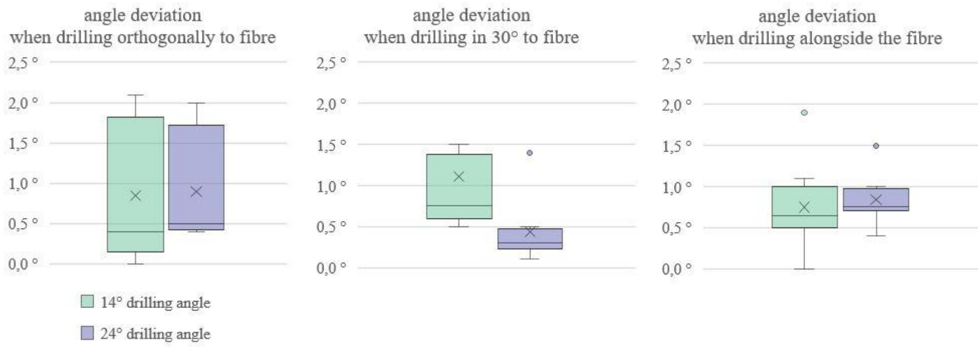

Figure 8: Distribution and degree of deviation depending on the inclination of the drill axis

This deviation of the drilling position is less critical, than the resulting increase of the inclination angle by 0.1-2.1°. If it is 1.5° shallower than calculated, the desired hole depth is not achieved. There is a difference of 2 mm 1.76 mm perpendicular to the panels surface. This also affects the dowel length to be selected and the associated subordinate production steps of driving and spreading. In extreme cases, the bottom of the blind hole moves so close to the surface (top layer) that the dowels can no longer hold on to it.

When comparing the two-test series (LVL and biofibre), it is noticeable that the degree of deviation in the drill entry point and thus also in the resulting, shifting inclination of the drill axis is strongly dependent on the materiality of the surface layer into which the drill dives in. While the average deviations in homogeneous pressed biofibre boards (Funderplan) are 5 mm deviation of the drill hole position or 1.2° inclination, they are slightly lower for LVL boards at 3 mm and 0.5°.

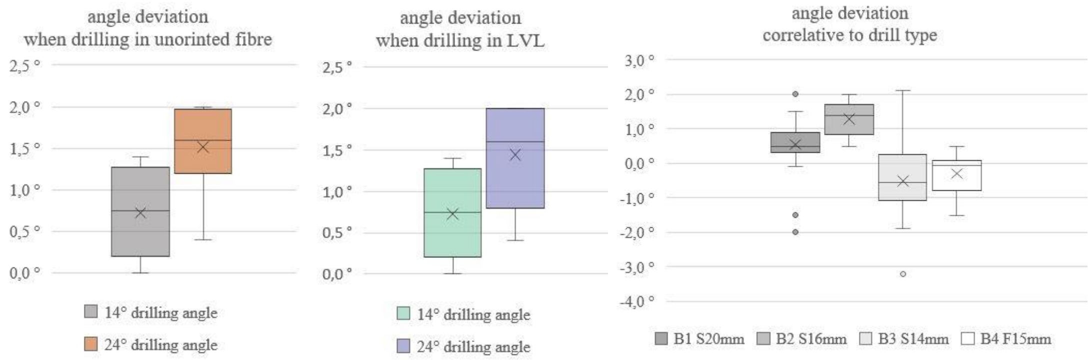

Figure 9: Comparison of angle deviation when drilling in non-oriented fibre (left) and LVL (centre); angle deviation correlative to drill type in unoriented fibre and LVL

B4 (Forstner drill bit with extension) shows the best results in terms of precision. The median of the measured values is 0.0°. Beyond this, there are hardly any outliers. B1 also shows acceptable values with an average deviation of 0.5°.

B3 and B4 perform the worst, while drilling with an extended Forstner drill (B4) yielded particularly favourable results in terms of drilling precision (process compliance) and surface quality of the bearing stress. The deviations here turned out to be mostly in the negative range, i.e. inclined more shallowly to the plate normal than desired, but therefore less problematic in terms of a potential emergence of the blind hole bottom.

3.1.3. Summary of the test results:

(a) the shallower the entry angle of the drill axis, the higher the deviations
(b) the longer the drill bit, the higher the deviations
(c) the steeper the inclination of the drilling axis to the grain direction, the higher the deviation
(d) the more pointed the drill bit mandrel, the more precise the hole
(e) the fibre direction of the material has less influence on the deviation than its raw density

3.2. Solutions for reducing deviations

The following conclusions concerning the manufacturing and design concept of the wall panels can be drawn from the test results:

A conflict arises between the depth of the hole and thus the maximum wall thickness of the load-bearing wall core and the desired precision of the respective holes. The deeper the hole, the longer the drill must be, but the softer it becomes. This creates an increased risk of slipping at the hole entry point and thus a change in the angle of inclination. Inclination angles >14° should be avoided to guarantee sufficient embedment depth.

Steep holes parallel to the fibre should be avoided. In the range of 60° - 90° to the grain direction, the resulting deviations are average. 2 mm/ 0.3° can be neglected. To be able to comply with the conventional guidelines (EuroCode) for minimum edge distances for fasteners, an additional increased safety distance of 50 mm should be set between the desired hole reveal and the edge of the component.

Possible solutions for increasing drilling precision in deep (longer than 10 x drill diameter) drilling include making pilot millings (3.2.1), a slight (3 mm) orthogonal immersion of the tool centre point (TCP) and then bending the drilling axis in the material (3.2.2) or an additional top layer of insulation with a low bulk density (<500 kg/m³) like soft wood fibre (3.2.3).

3.2.1. Pilot milling

One way to reduce the deviations of the hole entry points and inclinations is to incorporate ramp-like pilot millings to the top layer of the wall panel (Schwinn et al. [10]). The ramp must be aligned perpendicular to the drilling axis and be wide enough to accommodate the cutting edge of the drilling tool. That way, the drill hits the LVL plate perpendicularly and is less likely to slip, even on steep inclines and the influece of the grain orientation can be avoided. The 3D scan (ArtecLeo) of such connections shows a deviation of <1 mm (*fig. 11*) in the drill position or <0.3° difference in inclination of the drill axis. This dimension is below the usual tolerance limit in timber construction.

Figure 10: Pilot milling (left); drilling (right)

Milling a 24° inclined ramp (8mm milling cutter with two cutting edges, with feed of 125mm/s and a speed of 7000 rpm) requires an average of 12 seconds of production time. A pilot milling for 20° inclined holes only takes an average of 9 seconds to complete. For one square metre of wall surface with 20 dowel connections at a 24° inclination, an additional 2 minutes of production time and another 2 minutes are necessary for changing the effector. However, with practical element dimensions of 3m x 8m (24m²), this would already lead to a delay of 50 minutes per wall element if constructed in the prototypical setup.

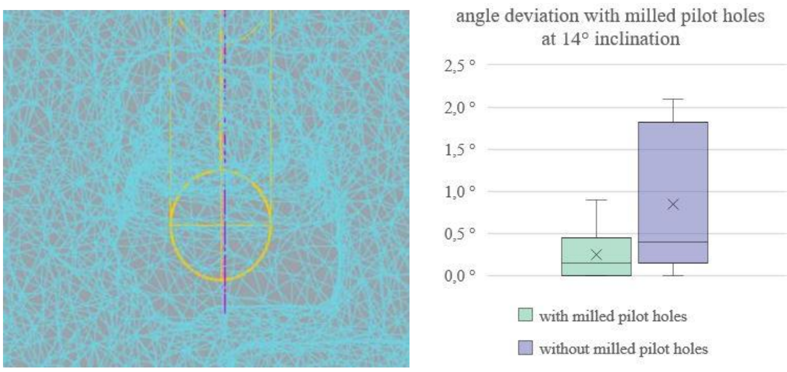

Figure 11: 3D scan with measured dowel axis (violet) and target value (yellow)
(left) and angle deviation with and without milled pilot holes (right)

3.2.2. Bending the drill around the tool-centre-point

Another solution to prevent the drill tip from skipping or sliding is to dive the drill tip vertically for just two milimeters and then realign the drilling axis arround the TCP (*fig. 12*). However, corresponding robotic production tests showed that the median of the resulting deviations due to the reorientation of the drill tip is even higher (1.2°) than with the direct angled orientation of the drill tip on the panel surface layer (0.5°).

3.2.3. Additional top layer with low bulk density

An additional layer of insulation on the top of the work piece or the outside of the wall not only improves the physical properties of the system (shifting the condensation point to the outside). Additionally, it has a positive effect on the precision of the drill holes, as it acts as a guide and reduces the effect of the drill tip sliding along the top layer of the load-bearing (dense) material layer. Accordingly, the measurements only show average deviations of 0.2°.

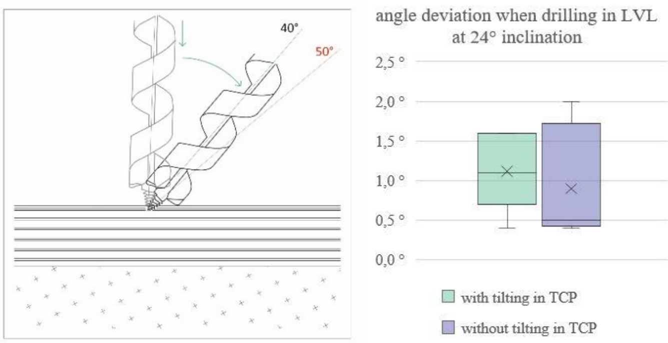

Figure 12: tilting after dipping in the covering layer (left); comparison of the deviations when drilling with and without tilting when drilling with BT1 in an angle of 24°

3.3. Press fitting

Pull-out tests of different dowel connections showed that the press-fitting of the dowels via hardwood nails (LignoLoc F44) can improve its pull-out resistance significantly. Aiming for maximum of homogeneity within the measured values of the pull-out resistance, it must be ensured that the dowels do not split when spread by the nail. To guide the expansion, the dowel heads were prepared with pilot holes or slots. The corresponding pull-out tests showed that the clamping effect of slotted anchors decreases with increasing slot depth. As the risk of splitting does not decrease with deeper slots either, the shallowest possible slot leads to the best bond with this kind of preparation.

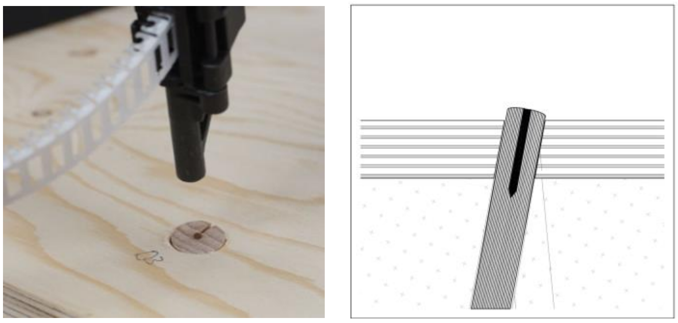

Figure 13: Coil nailer spreading test specimen (left), schematic sketch of the nail position in the dowel (right)

With the pre-drilled anchors, there was no enhancement on the clamping effect measurable. The dowel-to-hole diameter ratio showed to have a greater impact on the pullout strength than different types of guide drilling or slitting. Dowel connections with no preparation for expansion guidance achieved the best pull-out strengths (2,1 kN), as they have the largest cross-sectional expansion, while only a few (<5%) of the dowels were damaged. The prepared anchors achieved on average only three-quarters of these values. The heads of the dowels used for the load tests were therefore not processed any further before inserting the nails.

3.4. Load-bearing behaviour

In explorative load-tests of 20 specimen of IDS walls (*fig. 14,15*) with varying anchor types and dowel positions were vertically loaded (*fig. 16*), while measuring the displacement of single dowels and of the whole walls. The mechanical anchoring of the dowels shows a positive influence on the load-bearing behaviour of large-format wall panels. Walls with mechanically anchored dowels reached values of up to 195 kN before failing. This is above the limit of hinged dowel connections predicted by the FE analysis. The effects of swelling and the resulting press fit of the dowel in the bearing holes turned out to be comparable (190 kN) and therefore can be used for the innovative wall construction method as well. However, this requires more preparation time, as the dowels must be dried beforehand and driven in short-termed.

Also, there was a tendency measurable that walls (W11, W15) with clustered dowel patterns performed better than such with randomly arranged dowel patterns. Walls (W9, W14) that were exclusively connected with long wooden nails (160 mm x 4,5 mm), without any dowels at all, failed at 100 kN.

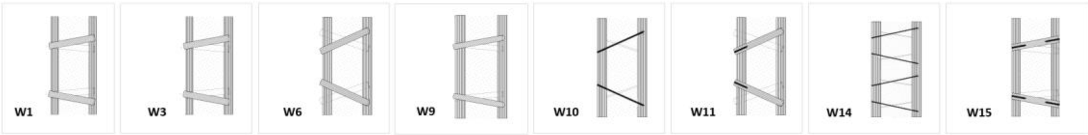

Figure 14: configurations of the different dowel connections of W1-W15 in a horizontal section

Figure 15: Specimen W1, W3, W6, W9, W10, W11, W14, W15 (from left to right)

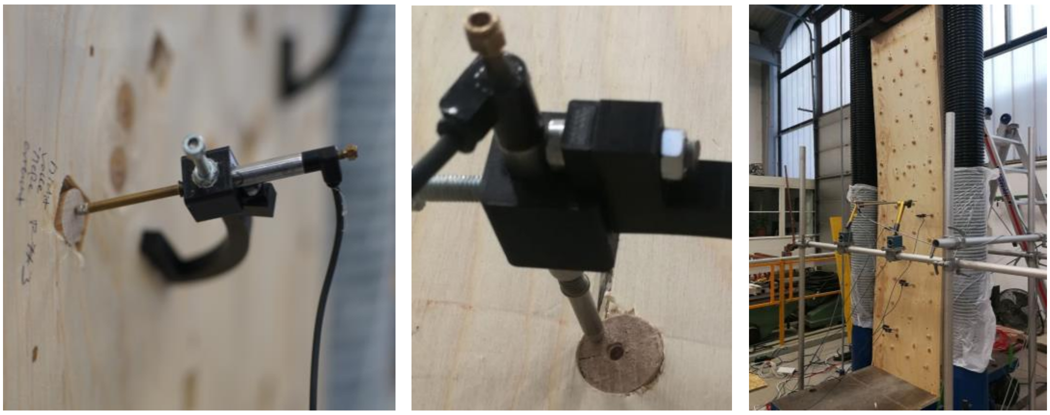

Figure 16: Displacement transducer on dowel (left and centre),
deformation of the wall specimen W20 under vertical loads in experimental setup (right)

4. Conclusions and Outlook

IDS wall units with mechanically anchored dowels can be produced fully automatically using an industrial robot with a linear unit. The use of adhesives is not mandatory and there is no need to flip over the walls to reach a press fit anchoring of the oblique dowel connections. Additional soft covering layers or pilot milling countervail against possible deviation when drilling inclined holes. The construction method seems particularly suitable for medium-sized timber construction companies with a small number of employees (<10) that use small-format numerically controlled production stations for the fast production of wall panels.

As the load affine positioning of the dowels lead to a further improvement of the load-bearing behaviour of the structure, the expected field of applications might be higher than expected. Further research is needed to investigate issues such as detailed mechanical performance, durability and fire safety of the system. A follow-up project intended to shorten the resulting computing processes by implementing machine-learning algorithms has just started.

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