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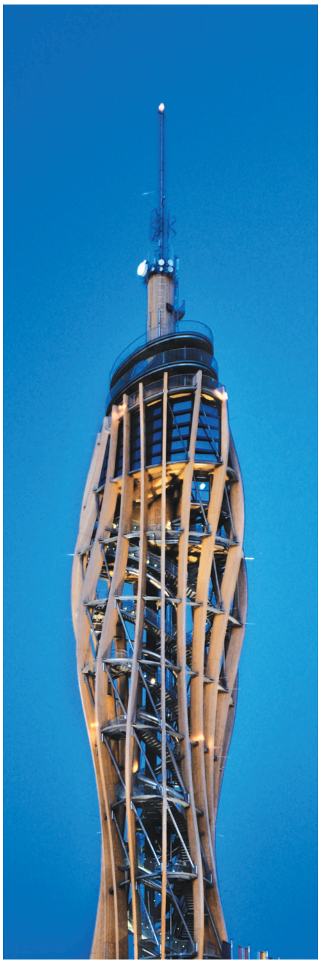

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A 3D CUTTING METHOD FOR INTEGRAL 1DOF MULTIPLE-TAB-AND-SLOT JOINTS FOR TIMBER PLATES, USING 5-AXIS CNC CUTTING TECHNOLOGY

Christopher Robeller[1], Yves Weinand[2]

ABSTRACT: Integral Mechanical Attachment (IMA) uses features in the form of components for their connection. In addition to the transfer of forces, locator features are used as integral assembly guides. Prismatic, single-degree-of-freedom (1DOF) joints only allow for a single assembly motion and therefore a simple, rapid and precise assembly. In modern timber construction, such CNC-fabricated 1DOF joints are commonly used in frame structures. Recent research is investigating the application of similar techniques for the joining of timber plate components, inspired by traditional handcrafted joints from cabinetmaking. The method presented in this paper builds upon previous research, allowing for new geometric variations such as non-orthogonal 1DOF plate joints and a simplified cutting process using a 5-axis simultaneous cutting technique. In addition to the use of milling tools, the method is compatible with 5-axis laser cutting and 5-axis waterjet cutting. Advantages and disadvantages of the different methods are being discussed.

KEYWORDS: Timber plate joints, 5-axis CNC fabrication, Dovetail joints, 5-axis laser cutting, 5-axis waterjet cutting

1 INTRODUCTION AND STATE-OF-THE-ART

Integral Mechanical Attachment (IMA) is known as the oldest method of joining. It uses features in the form of parts for the connection, instead of additional fasteners or adhesives. *Connector Features* are used to transfer forces, and *Locator Features* are used for a rapid and precise assembly. [1]

IMA used to be common in traditional timber construction, but was widely replaced by mass produced mechanical connectors during the industrialization. A Renaissance of IMA has begun with the introduction of numerical controlled machine technology. With the proliferation of automatic joinery machines, IMA was repatriated to timber frame structures, bringing back joints such as mortise and tenons. These joints are so-called prismatic, or *1DOF-joints*, where the form of the joint constrains relative movements between the parts to a single remaining motion path. In addition to the mechanical features, such 1DOF joints are used as guides for a simple, rapid and precise assembly. Other joints with multiple DOF, such as 3DOF finger joints are the subject of related research. [5]

For plate-shaped wood components, 1DOF integral connectors such as dovetails have been used in traditional cabinetmaking rather than carpentry. Instead of single tabs and slots, plate joints are using multiple tabs and slots (MTSJ). These joints were used for the joining of solid wood boards, for furniture such as cabinets or drawers and their use was limited to plate edges which are oriented perpendicular to the wood fibers (Figure 1, bottom right). Analog to the use of CNC-fabricated 1DOF joints in timber frame structures, recent research is investigating the application of 1DOF-MTSJ for the assembly of cross-laminated timber plates. Due to the quasi-orthotropic behavior of cross-laminated panels, joints can be applied to both sides of the plates. Figure 2 shows how this allows for various new applications, such as box girders or hollow wall or roof elements.

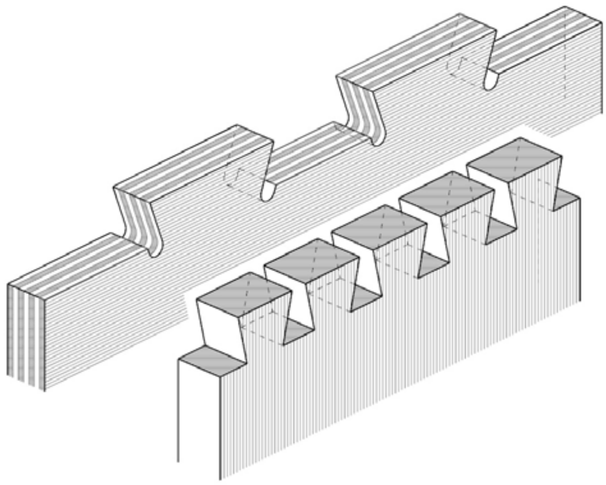

Figure 1: *1DOF-MTSJ, top left: CNC fabricated on cross-laminated wood veneer plate, bottom right: Handcrafted on solid wood*

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In 2010, the application of 3-axis CNC cut dovetail joints on plywood, for the production of furniture has been examined by Simek and Sebera [2]. A first application of dovetail-jointed CLT panels in an experimental building structure was demonstrated in the Curved Folded Wood Pavilion in CH-Mendrisio in 2013, where the joints were combined with adhesive bonding. [3]. A self-interlocking folded-plate structure, made of 1DOF-MTSJ jointed laminated veneer lumber (LVL) plates, without adhesive bonding, has been examined by Robeller et al. in 2014 [4], followed by a study of the semi-rigid behavior of 1DOF-MTSJ on LVL composite box girders (Fig. 2) by Roche et al. in 2015 [6], and the examination of the rotational stiffness of 1DOF-MTSJ on LVL by Roche et al. in 2015 [7].

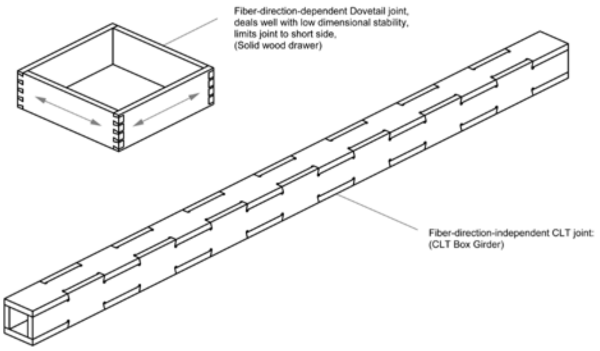

Figure 2: *Application of 1DOF-MTSJ connectors for the construction of LVL composite beams.[6]*

1.1 PREVIOUS 2D CUTTING METHOD USING 3-AXIS SIDE-CUTTING AND SPOT-FACING

State-of-the-art methods for the CNC fabrication of dovetail joints [2] use CNC routers with three translational axes. Figure 3 illustrates this method, where the *tail part* of the joint is using side-cutting, with the milling tool positioned normal to the plate surface, while the *pin part* is cut using spot-facing, with the tool positioned normal to the side face of the plate.

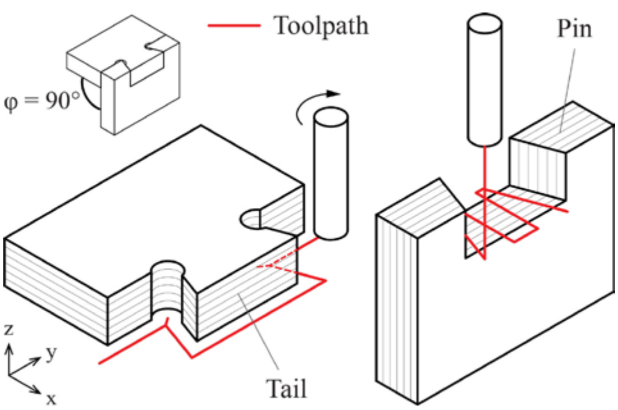

Figure 3: *Fabrication of dovetail joints with 3-axis CNC technology, limited to orthogonal joints between plates.*

This method allows for the cutting of the typically 10-20° inclined faces on the pin part with a 3-axis machine, but it also results in several constraints, such as the vertical clamping of the pin-part, which is difficult with flatbed routers. Furthermore the method requires the re-clamping of parts where multiple edges are to be jointed and it allows only for the joining of plates at a dihedral angle of 90°:

- **Vertical clamping:** The vertical clamping (YZ-plane in figure 3) of parts is time consuming and it is more difficult to properly clamp the cantilevering work pieces, avoiding vibrations which reduce the cut quality and feed rates. The vertical space (z-axis height) of CNC flatbed routers is limited for plate cutting; larger parts cannot be fixed vertically.

- **Re-clamping:** When applying joints to multiple edges on one plate, the part must be released, rotated and fixed again. This requires a new referencing of the work piece and causes imprecision. This problem may be solved with an additional rotational table, synchronized with the machine [2], however it only works well with circular or quadratic shaped plates, and a sufficient clamping is difficult to achieve.

- **Dihedral Angle φ:** Traditional dovetail joints were used for the joining of plates where the dihedral angle is $\varphi = 90°$, such as the drawer in figure 1. Recent research projects have demonstrated the use of 1DOF MTSJ with non-orthogonal dihedral angles [3][4][7][8]. This is not possible with the previous method.

2 3D SIDE-CUTTING METHOD USING 5-AXIS MILLING TECHNOLOGY

The cutting method presented in this paper takes advantage of 5-axis flatbed CNC routers (Figure 4), which are already used by many larger wood processing companies. Figure 5 shows that in addition to the usual three translational axes X, Y and Z, 5-axis enabled machines are equipped with two additional, cardan rotational axes (here A and B), which allow to orient the tool along directions n_{tool} which are not perpendicular to the machining table (XY-plane). With such rotations of the tool, we can fabricate integral 1DOF MTSJ joints, while the work piece is simply clamped on the machining table.

Figure 4: *5-axis CNC router with automatic tool changer*

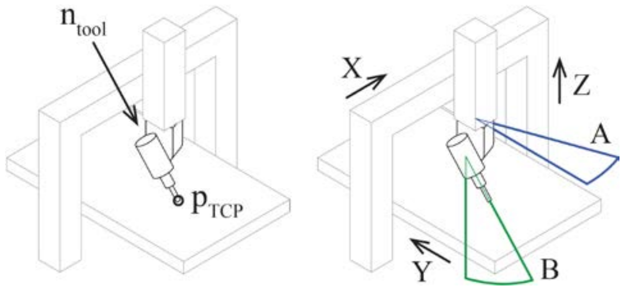

Figure 5: *5-axis CNC router schematic with axis notations*

The maximal tool inclination β_{max} that can be achieve with our method depends on the plate thickness t_{plate}, the geometry of the cutting tool (cutting length, protrusion) and the geometry of the tool holder and spindle, as shown in figure 6. Larger inclinations can be achieved with longer cutters and tool extensions, but the feed velocity V_F needs to be reduced accordingly. In our experiments, we have cut with cutter inclinations of up to $\beta_{max} = 60°$.

The right side of figure 6 shows how the minimum and maximum possible dihedral angle φ_{min} and φ_{max} result from the maximum tool inclination β_{max}. With an inclination of $\beta_{max} = 50°$, we can fabricate dovetail joints for folds with dihedral angles ranging from $\varphi_{min} = 40°$ to $\varphi_{min} = 140°$.

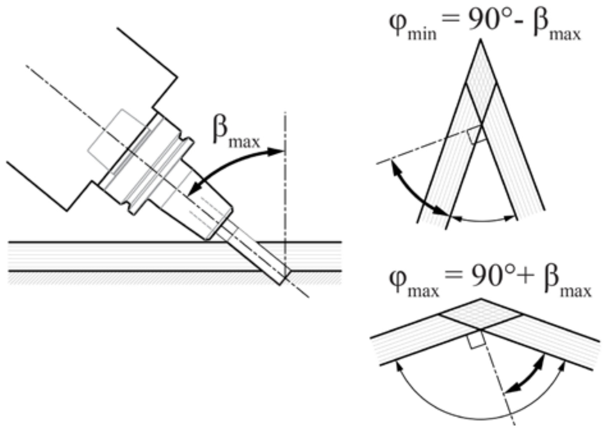

Figure 6: *relationship between maximum tool inclination and minimum / maximum producible, variable joint angles.*

Polytonally shaped plates with multiple 1DOF MTSJ joined edges can have both positively and negatively inclined joints on the same work piece. We want to fabricate these parts without re-clamping or reversing of work pieces in order to achieve precisely fitting joints. Figure 7 shows a cross-section schematic drawing of the tool position on a positive (regular) and negative (undercut) inclination. The tool center point p_{TCP} lies above the flatbed router XY-plane for regular cuts, and below it for undercuts. This is taken into account for the maximum possible inclinationβ_{max}, which we adjust accordingly.

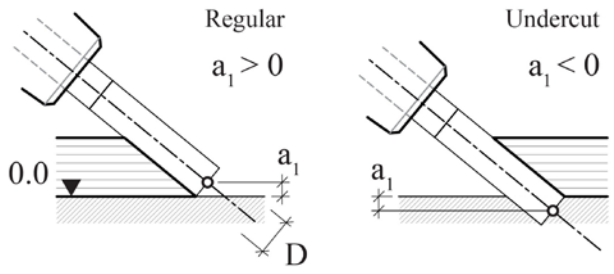

Figure 7: *vertical shift of the tool center point during inclined cutting, positive for regular cuts and negative for undercuts.*

The manual programing of 5-axis CNC cutting with standard computer aided manufacturing software (CAM) is not adequate for the fabrication of MTSJ. The manual programing of hundreds or thousands of tabs and slots with various 3D rotations and custom details would be too time consuming. We have therefore developed a custom algorithm for the generation of the G-Code (ISO6983) machining instructions, which are sent to the CNC router.

2.1 CUTTING OF CONCAVE CORNERS

The fabrication of MTSJ requires the cutting of polygonal shapes, for which we use tungsten steel shank-type cutters with a diameter D of 10-20mm. The polygons include various concave corners or slots (cut-outs within parts). In contrast to convex corners, such sharp, concave corners cannot be cut with a shank-type cutter, as its radius will remain as a fillet. We solve this problem through additional notches (sometimes referred to “Mickey Mouse Ears”), as illustr ated in figure 8.

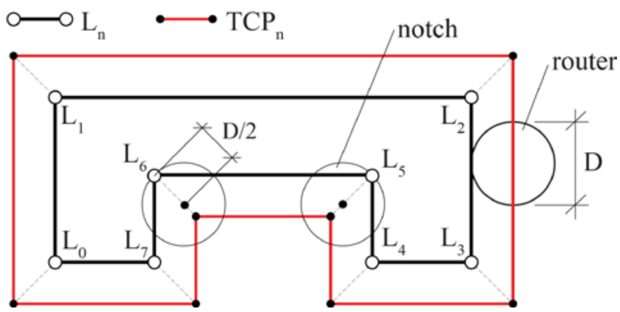

Figure 8: *FSS made from LVL using open-slot MTSJ* [2]

The figure shows a schematic tool path offset around a polygon L, at a distance equal to the milling tool Diameter D. Notches must be added at the concave corners L_5 and L_6. Such notches are required for the assembly of the MTSJ; also they reduce the notch stresses compared to sharp corners. However, the notches also reduce the important contact surfaces of the joints. We therefore minimize the size of the notches through the use of tangential circles, see figure 9, option c. Also our algorithm will cut the notches in a final pass, using a smaller diameter tool than for the nesting and cutting of the joints.

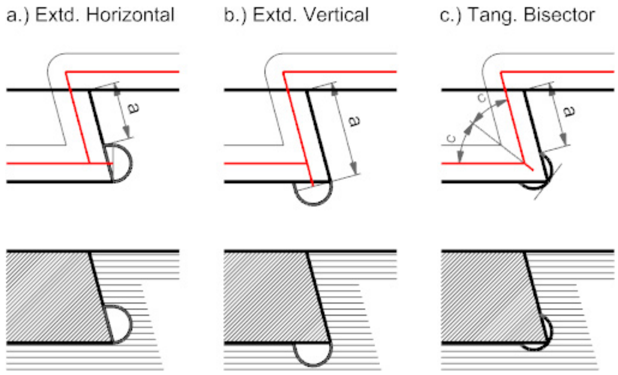

Figure 9: *Different types of notches possible with the side-cutting method with cylindrical milling tools. Depending on the type of notch, different contacts of the joint are reduced in size. Our 3D method uses tangential bisector notches (c.), similar to [2], adapted to the aligned 3D cutting process.*

Figure 9 illustrates how different types of notches reduce the contact surfaces (a) of the joints in size. We have chosen the tangential bisector notch (9c) to minimize this problem. Generally, the ratio between notch size and plate thickness decreases with thicker plates. Let the ratio between cutter diameter and cutter length (protrusion) be 1:7.5, and we require a protrusion of 90mm to achieve a 3D tool inclination of $\beta = 50°$, the cutter diameter must be $D = 12mm$. In consequence the notch radii, and therefore the loss of contact surfaces is critical for thin plates (such as in the fabrication of scale models with plate thicknesses of 8-15mm) but greatly reduced for thicker plates (21-39mm) in building construction applications.

2.2 AUTOMATIC TOOL PATH GENEARTION

For the 3D cutting, we define the shape of plates through pairs of polygons, as shown in figure 10a. There is a lower polyline L_n and a top polyline T_n in every pair, each consisting of a list of points. The 3D geometry of the part is described through a loft surface between these pairs of polylines. A plate with cut-outs (e.g. slots) within the outer contour is described through additional pairs of polylines for each cut-out, where the orientation is clockwise, while outside contours are oriented counter clockwise. Figure 10a shows a pair of polylines, describing the pin part of a dovetail-type MTSJ, with a single slot. As explained in figure 7, the tool center point must be offset three-dimensionally, in contrast to a 2D offset, as shown in the schematic figure 8. We therefore process the pair of polygons in segments, where each segment (representing a joint face) is described by 2 points on the lower polygon L_i, L_{i+1} and 2 points on the top polygon T_i, T_{i+1}. The line, on which the tool center point p_{TCP} of a cylindrical tool with the radius r_{tool} will translate, is defined through a point p_{offset}, which is offset from L_i along the vector n_i, which is the cross product of $n_{path} = \widehat{L_{i+1} - L_i}$ and $n_{tool} = \widehat{T_i - L_i}$, multiplied by the tool radius $r_{tool} = D/2$.

$$p_{offset} = L_i + (n_{path} \times n_{tool}) * r_{tool}$$

The tool center point must pass through this point, in the direction $n_{toolpath}$. The start and end points of the tool path, which both lie on this line, are found through the intersection of the line with two bisecting planes. The planes are bisecting between the plane of the current joint face, and the neighboring ones before and after. The figure 10b shows how the tool center point transits on these planes, between the tool path lines of joint faces with different, three-dimensional inclinations.

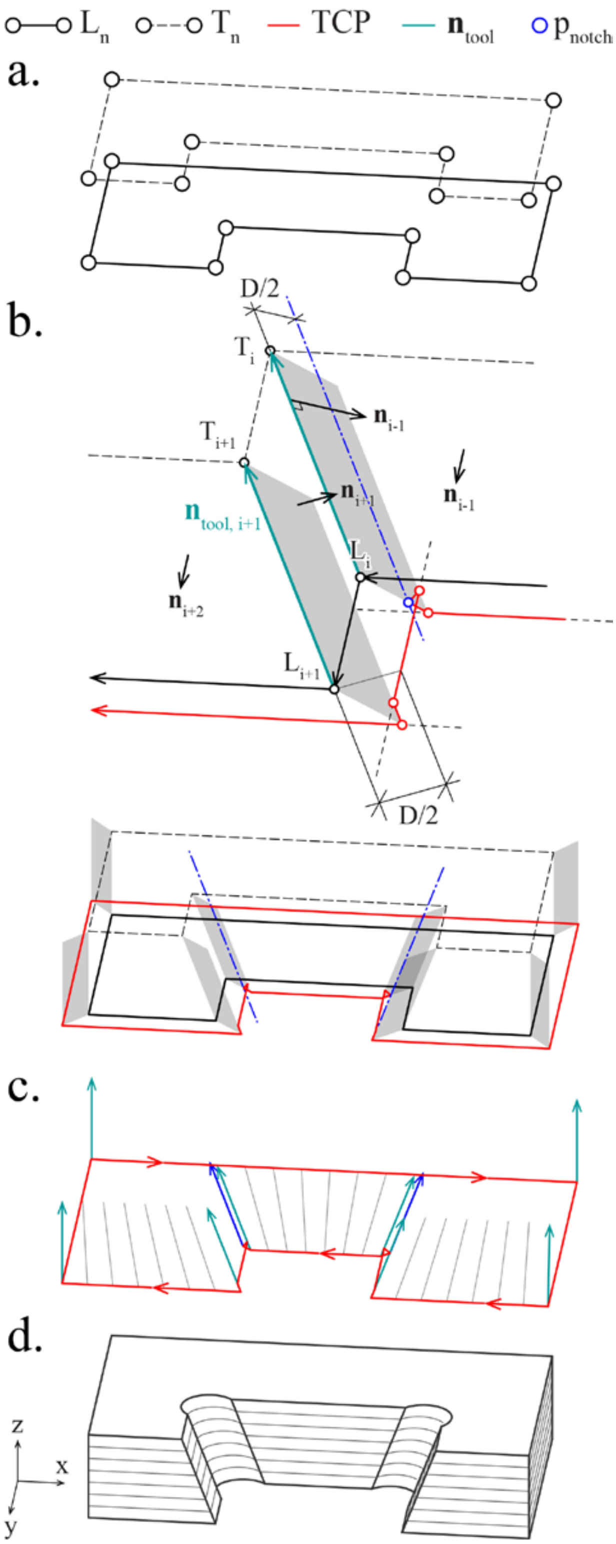

Figure 10: *new 5-axis milling algorithm using 3D offset*

On concave corners, which can be identified through a negative cross product $n_i \times n_{i+1}$, we add a *tangential notch*, as described in section 5.1. In 3D, we find the center axis of this cylinder (shown as a blue line in figure 10b) defined through the point $p_{notchaxis} = L_i + ((n_i \times n_{i+1})/2) * r_{tool}$ and the vector n_{tool} at this point.

Figure 10c shows the simultaneous translation and rotation of the tool, in segments where the tool orientation n_{orient} at the start point of the segment is different from the one at the end point of the segment.

A pseudo-code algorithm for the generation of such a 3D tool path is given in Figure 11:

```
function CONCAVEPOLY 2DCUT(points L_n, tool diam. D)
    for i in size(Points L) do
        n_0 ← |L_{i+1} − L_i|                    ▷ Vector last segment
        n_1 ← |L_{i+1} − L_i|                    ▷ Vector next segment
        n_bisec ← |(n_0 + n_1)/2|                ▷ Vector Bisector
        α ← 90° − VectorAngle(n_0, n_1)
        d_1 = tan(α) * (D/2)                     ▷ Regular offset
        d_2 = D/2                                ▷ Notch offset
        p_tcp ← L_i + (n_bisec * d_1)            ▷ tool center point
        Append p_tcp to TCP                      ▷ add to TCP
        n_3 ← n_0 × n_1
        if n_3[2] ≤ 0 then                       ▷ if concave corner
            p_tcp ← L_i + (n_bisec * d_2)        ▷ notch point
            Append p_tcp to TCP                  ▷ add to TCP
        end if
    end for
end function
```

Figure 11: *Pseudo-Code Algorithm for 3D cutting*

2.3 IMPLEMENTATION IN 3D CAD

We have implemented the previously described automatic G-Code generator algorithm as a plug-in for a visual programing environment in a commonly used 3D CAD system. Figure 12 shows that the plug-in consists of individual components for functions such as 3d cutting or drilling, which we have used for fixation holes for the clamping of parts. Input parameters include a hatch-selected and automatically sorted and processed list of closed polyline pairs defining the polygonal plate contours, as described in section 3.2., as well as adjustable values for the tool radius, security and retreat planes, the number of vertical passes and separate tool feed rates for horizontal and vertical movements. The automatic cutting of tangential notches in the final pass can be activated and de-activated. On the right, output values side, the figure shows that we instantly obtain the G-Code file, including various automatically generated comments, which are skipped by the CNC control system, but allow for simplified reading and checking of CNC files. Changes in the input parameters will appear directly in the G-Code display.

A third algorithm, visible on the output parameter side in figure 12, is used for the real-time visualization of the tool paths in the CAD software. Figures 14 and 15 show the display the tool paths, and how the motions of the machine can be simulated to check for collisions with the tool, tool holder or spindle.

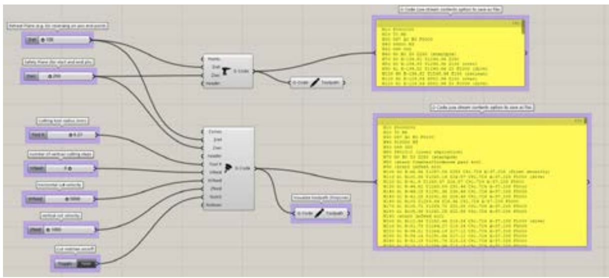

Figure 12: *Automatic G-Code Generator CAD Plugin. Left: input / cutting parameters, middle: separate components (functions) for predrilling (clamping) and 1DOF MTSJ side-cutting, right: live G-Code display with comments.*

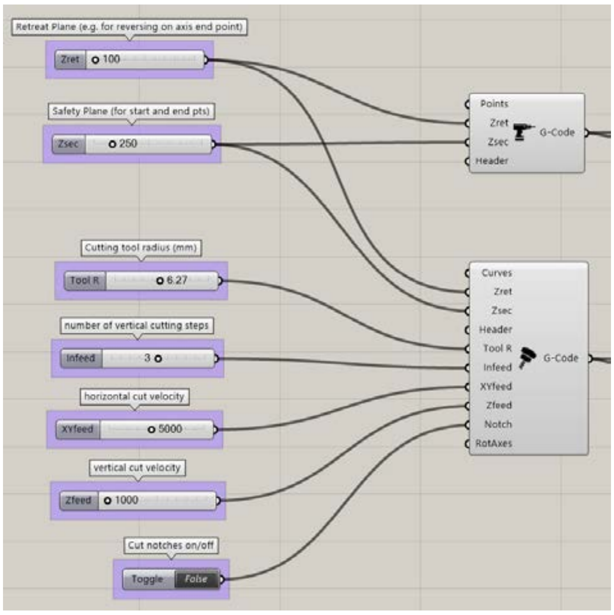

Figure 13: *Detailed view of 1DOF MTSJ side- cutting function inputs top to bottom, 1. Curves: hatch-selected list of closed polyline plate contours, which will be automatically sorted into pairs. 2. Zret: retreat plane, 3. Zsec: security plane, 4. Header: Editable G-Code header, 4. Tool radius, 5. Number of infeeds, 6. Horizontal feed rate, 7. Vertical feed rate, 8. Notches on last infeed on/off, 9. Rotational axis letters*

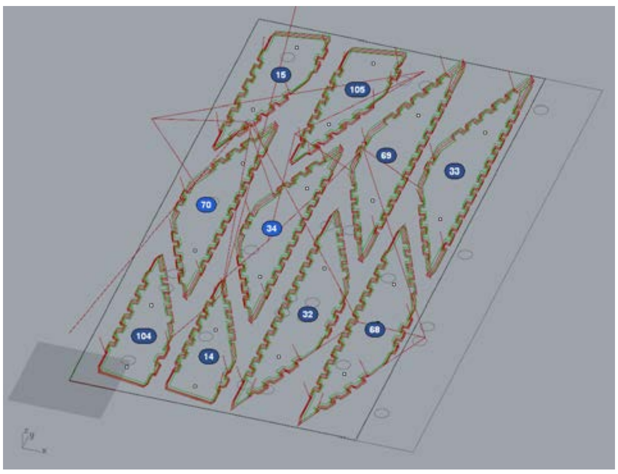

Figure 14: *Display of tool paths and tool orientation for 3D cutting of 1DOF MTSJ in the CAD software [5]*

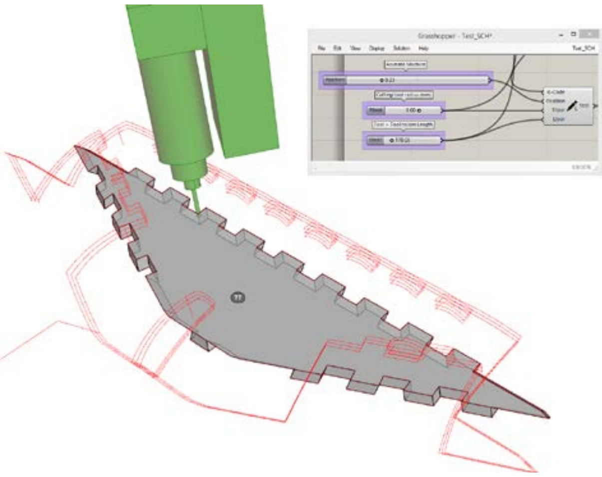

Figure 15: Integrated Machine Simulation to check for collision points (Tool path display in this figure is without tool length offset G-Code function G49). [4]

2.4 FABRICATION OF FREEFORM SPACE STRUCTURE PROTOTYPES

While the LVL composite box girder in Figure 2 shows the application of the 1DOF-MTSJ for a simple orthogonal plate assembly, the methods allows producing non-orthogonal joints for the fabrication of freeform space structures such as single-layered Folded Surface Structures [4] (Figure 14), curved-folded surface structures [3], double-layered Folded Surface Structures [8] (Figure 15) or segmented Curved Shell Structures [9] (Figure 16). The figures show both photos of the final prototype structures and schematic drawings of the plates, which are defined through polygon pairs, as explained in section 3.2.

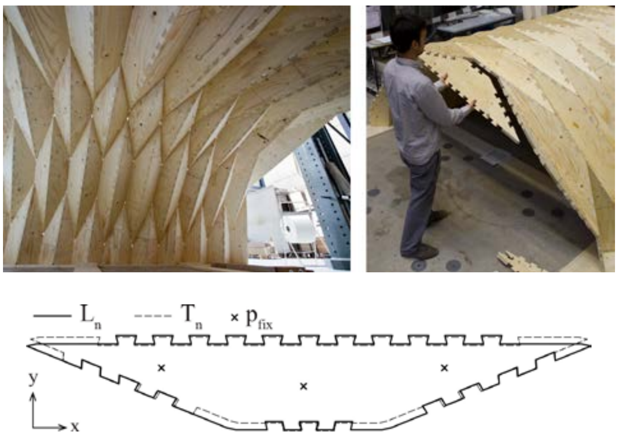

***Figure 14:** Single-layer Antiprismatic Folded Surface Structure made from LVL using open-slot MTSJ, 2014 [4]*

These experimental structure prototypes combine the generally advantageous properties of wood, such as its sustainability and favorable weight-to-strength-ratio, with the particular easy machining of the material with the dimensional stability and quasi-orthotropic behavior of cross-laminated veneer lumber, and the widely available 5-axis enabled CNC technology in the wood processing industry, which allows for the efficient production of large series of individually shaped parts. This enables the efficient design and fabrication of self-supporting thin shell structures, where the structurally beneficial global shape of the structures is achieved through incremental changes in the shape of the individual plates. In addition to the load-bearing performance of the 1DOF MTSJ joints through integral *connector features*, the integral assembly guides in the form of *locator features* are essential for the rapid and precise assembly of freeform structures.

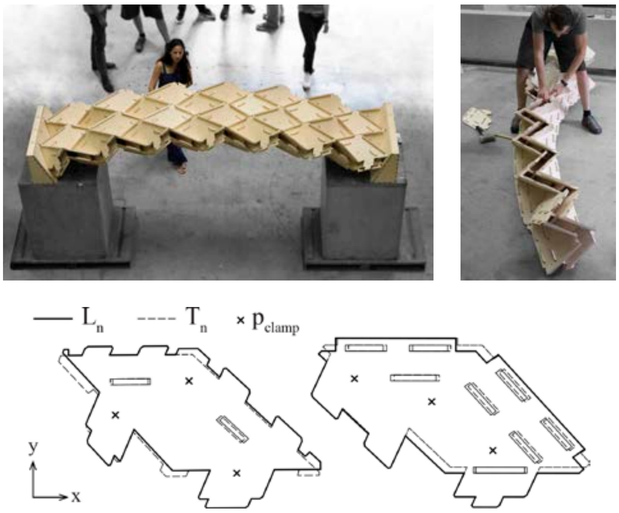

***Figure 15:** Double-layer Miura-Ori Folded Surface Structure made from LVL using closed-slot MTSJ, 2015 [8]*

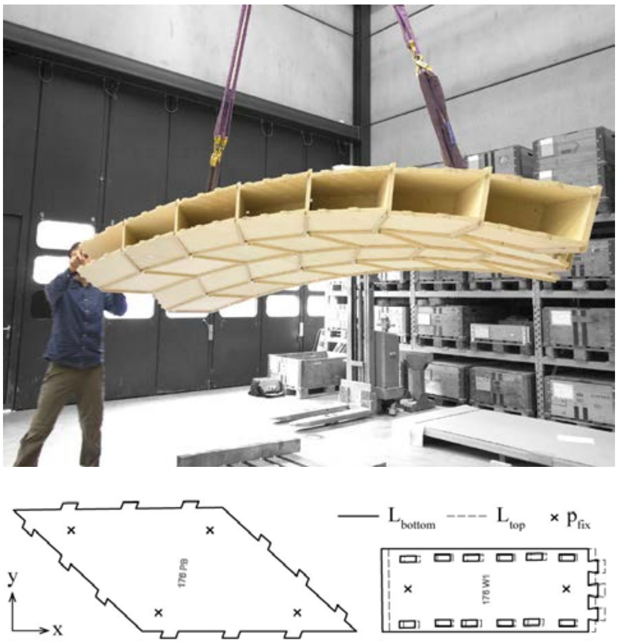

***Figure 16:** Double-layer segmented curved shell structure made from LVL using closed-slot MTSJ, 2016* [9]

2.5 DRAWBACKS OF CNC MILLING

The fabrication of integral 1DOF MTSJ requires the cutting of polygonal contours with concave corners and slots. Such cuts are not possible with saw blades. Instead, cylindrical shank-type cutters must be used, which results in multiple drawbacks, such as the need for notches and increased waste and emissions such as dust. The dust contains particles from both wood and the adhesives used for the lamination of the veneer layers. On 3D cutting systems, such as the 5-axis machine for our tests, the extraction of the dust is particularly problematic due to the large motion space of the cutting spindle. The motion space is extended even more through long cutting tools, which are required for the cutting with a large tool inclination β, in order to avoid collisions between parts of the machine and the workpiece.

Another challenge is presented by the clamping of work pieces on the table of the flatbed CNC routers. The milling with shank type cutters creates vibrations, which are influenced by the machine feed rate, tool geometry and the clamping of the work piece, requiring compromises. Standard cutting tools are typically designed for perpendicular, not inclined cutting, and nesting cutters also create traction forces normal to the plate for the dust extraction, requiring rigid clamping of the work piece. Rigid clamping is particularly challenging in large batches of individually shaped plates such as in the prototype structure examples [3][4][8][9].

$$V_c = \frac{D * \pi * n}{60 * 1000} \frac{m^{-1}}{s} \qquad f_z = \frac{V_f * 1000}{n * z} mm \qquad V_F = \frac{f_z * n * z}{1000} m/min$$

From the above equations, we see that a high tool rotational speed $n\ m^{-1}$ is required to achieve a sufficient cutting speed V_C. It results from this that also a high machine feed rate V_F is required, but these required feed rates cannot be realised with standard cutting equipment and tools, due to the polygonal shape of the plates with MTSJ. In consequence, cutting too slowly, cut quality is reduced while tool wear and emissions are increased. We have cut our parts with a feed rate $V_F = 6\ \mathrm{m/min}$ and multiple vertical passes (infeeds). The cutting parameters are provided in table 1:

t_{plate}(mm)	21	27	39
w_{cut}	12	12	20/10
n_{infeed}	2	3	4
$V_{F,EFF}$ (m/min)	**3**	**2**	**1.5**

Table 1: *Effective cutting speed using 3D milling*

3 ALTERNATIVE 3D CUTTING TECHNOLOGY 1: 5-AXIS LASER CUTTING

The 3D side cutting method that we have used with the 5-axis enabled CNC milling machine is compatible with our 5-axis enabled flatbed cutting systems, which we have investigated as alternative cutting technologies. The first alternative cutting technology which can be used with the method and algorithm are 5-axis laser cutting systems, such as the one illustrated in Figure 4, which is commonly used in the automotive industry.

In state of the art literature, the laser beam for woodworking purposes such as separating parts is considered as a possibility, but infeasible due to a lack of efficiency, caused by its excessive energy use [10]. However for our application, the cutting of polygonal 3D contours with concave corners, the laser system provides advantages. The cut width of the laser system is only 0.6 mm, which allows for the cutting of LVL plates with a thickness of up to 39 mm. In contrast to the milling system, this low cut width is greatly reducing waste and cut offs, and the previously introduced notches on concave corners are not required (see Figure 19).

Figure 17: *5-axis Laser Cutting System*

The system peak power consumption of the 5-axis milling system used for our tests was 19.5 kW; the one of the 5-axis laser system used for our tests was 96 kW. The high power consumption on the laser system is largely due to its external cooling system. However, the cutting of up to 39mm LVL with the laser system was performed at $V_{F,EFF} = 11\ \mathrm{m/min}$ in one pass. With the milling system, we have cut 21mm LVL with $V_F = 5\ \mathrm{m/min}$ in two passes, resulting in an effective feed rate of $V_{F,EFF} = 1.5\ \mathrm{m/min}$. The comparison shows that the laser system allowed for precise 3D cuts at a feed rate which was more than four times faster than the one on the 5-axis CNC milling system.

Figure 18: *5-axis 6kW CO2 laser system setup for LVL cutting*

Table 1 shows that on a milling system, the number of vertical passes n_{infeed} increases with an increasing thickness t_{plate} of the LVL plates. Therefore the effective feed rate $V_{F,EFF}$ is reduced. Table 2 shows our tests using a 3D laser cutting system, where cutting is always performed in one infeed. We have cut spruce LVL plates of up to 39mm with a feed rate of $V_F = 11\ \text{m/min}$.

t_{plate} (mm)	21	27	39
w_{cut}	0.6	0.6	0.6
n_{infeed}	1	1	1
$V_{F,EFF}$ (m/min)	**11**	**11**	**11**

Table 2: *Effective cutting speed using 5-axis laser cutting*

While the effective feed rate is greatly improved with the laser system, the system peak power consumption for our two testing systems is 19.5kW for the milling and 96kW for the laser system. The 4.9 times higher energy consumption of the laser system is balanced by the 3.6-7.5 times faster effective machine feed velocity we observed in our test cuts with 21-39mm cross-laminated spruce LVL plates. On the 5-axis laser-system, cut quality was independent from the cut inclination β, which was tested up to $\beta_{max} = 45°$.

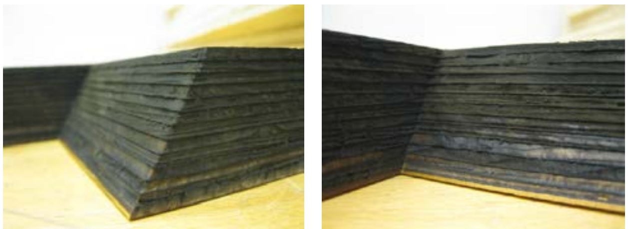

Figure 19: *5-axis 30° inclined laser cut of a convex (left) and concave (right) corner on 13-layer 39mm spruce LVL plates.*

With its cut width of 0.6mm, a major advantage of the laser system is presented by its ability to cut sharp concave corners (or with very small radii), allowing for cutting MTSJ without notches or "Mickey Mouse ears". (Figure 19). As previously discussed this is particularly relevant for the cutting of thin plate thicknesses, where the notches would be relatively large and reduce the contact surfaces considerably.

3.1 Drawbacks of 5-axis Laser Cutting

Two major drawbacks of the laser cutting system are the burning or charring of the cut edges (Figure 19) due to the high temperature cutting process, which is mainly a visual, aesthetic problem, as well as the burnt odor of the final work pieces. Hazardous emissions are presented by the fumes generated during the laser cutting, as well as the laser light. Provided a class 4 visible-light, continuous-wave laser system, which was used for our tests, even scattered light can cause eye or skin damage. Therefore, a complete enclosure of the machine is required. For the hazardous fumes, extraction and filtering systems are used. For the cutting of LVL, the fume emissions are higher than for the laser cutting of metals. Particularly powerful extraction systems and measures for fire protection are required for such applications.

4 ALTERNATIVE 3D-CUTTING TECHNOLOGY 2: 5-AXIS ABRASIVE WATERJET CUTTING

The second alternative cutting technology compatible with the previously presented side-cutting method are abrasive waterjet cutting machines that are equipped with an additional tilt axis (see figure 20). We have performed our tests with a system where the tilt axis can be rotated up to a maximum of $\beta_{max} = 59°$, which allows for the fabrication of non-orthogonal 1DOF MTSJ with a dihedral angle ranging from $\varphi_{min} = 41°$ to $\varphi_{min} = 139°$.

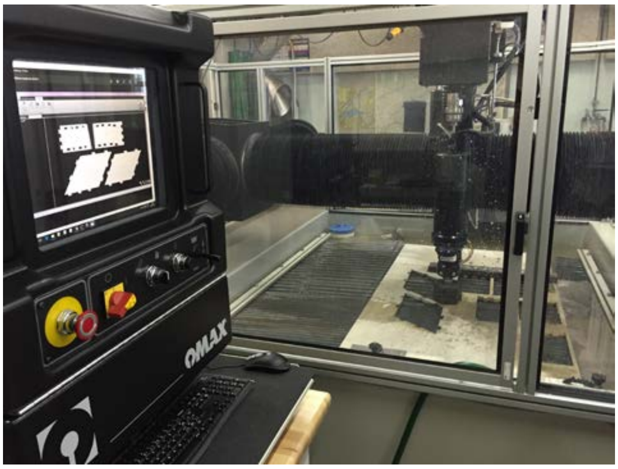

Figure 20: *Abrasive waterjet cutting system equipped with an additional tilt-axis*

The cut width of our water jet cutting test setup was 0.6mm, for spruce and beech LVL plates with a thickness of up to 39mm, which is identical to the 5-axis laser cutting system (Table 3). The same applies for the number of vertical passes, only a single cut is needed to separate the pieces. With the values provided in table 3, high edge quality was achieved, as shown in figure 21. Similar to the laser system, the cutting speed is not greatly affected by the thickness of the plates.

t_{plate}(mm)	21	39
w_{cut}	0.6	0.6
n_{infeed}	1	1
$V_{F,EFF}$ (m/min)	**2**	**1.5**

Table 3: *Effective feed rates using 5-axis waterjet cutting*

Identical to the laser cutting system, the low cut width of 0.6mm allows for the cutting of concave corners without or with very small additional notches. As explained in section 3.5, this is particularly important for thin plate thicknesses. Similar to the laser cutting system, the clamping of workpieces is simple. Only small clamps (figure 18) or even only weights (figure 20) provide for sufficient clamping. There are no hazardous emissions such as dust and fumes, only noise protection is required.

Figure 21: 15mm thick plates for a CSS [7] scale prototype, cut with a 5-axis equipped abrasive waterjet cutting system. Due to the cut width of only 0.6mm, no notches are needed.

	Milling(1)	Laser(2)	Waterjet (3)
kW_{max}	19.5	96	22
$V_{F,EFF}$	1.5	11	1.5

***Table 4:** Peak power consumption and effective feed rates for the cutting of 1DOF MTSJ with our side-cutting method and our systems used for testing: 1. Maka mm7s, 2. Trumpf TruLaserCell 7040/TruFlow6000, and 3. OMAX 5555/30HP.*

4.1 Drawbacks of 5-axis Abrasive Waterjet Cutting

Waterjet cutting is performed with the work pieces over water basin. The work pieces are either completely submerged (10mm under the water surface), or just above the water surface, for splash and noise protection. For the second case of cutting just above the water level, we have still observed the work pieces getting wet due to water splashing.

5 CONCLUSION

The 3D side cutting method introduced in this paper allows for the rapid and precise fabrication of single-degree-of-freedom (1DOF) integral timber plate joints, such as dovetail joints or through-tenon-joints. In contrast to time consuming manual programing with CAM software, the automatic geometry processing allows for a rapid generation of machine code for CNC milling, laser or waterjet cutting. Unlike in previous methods, it is not necessary to position the cutting tool normal to the side face of the plate. The method therefore allows for the use of standard flatbed routers without any technical modifications, and it allows for the processing of parts of any size that fits on the flatbed table of the CNC machine. Instead of positioning the tool normal to the side face of the plate, inclined faces are cut with the tool inclined at an angle β, which is possible with modern 5-axis enabled CNC routers. For the milling with shank type cutters, the maximum tool inclination β_{max} is determined through possible collision points with the tool, tool holder or spindle and the work piece. With standard CNC cutting tools, we have found this limit at 60°. The 5-axis abrasive waterjet system used for our tests is constrained to a maximum rotation $\beta_{max} = 59°$. With the laser system, we have successfully cut inclinations of up to $\beta_{max} = 45°$. Unlike previous methods, the variable inclination of the tool allows for the fabrication of 1DOF MTSJ (such as dovetails), where the dihedral angle φ between two joined plates is not constrained to $\varphi = 90°$. Instead we can fabricate joints with a large range of dihedral angles. While a fixed rotation of $\beta_{max} = 15°$ would be sufficient for the fabrication of orthogonal assemblies with inclined dovetails, such as the box girder presented in section 1, a large variable range of angles is required for the fabrication of freeform shell and spatial structures built from timber plates, where the global curved shape is achieved through incremental modifications in the shape of a series of individually shaped plate elements.

In the last two sections of the paper we have discussed the drawbacks of 5-axis CNC milling, and presented two alternative side cutting technologies, which are compatible with the method and algorithm presented. While the mechanical behavior of 1DOF MTSJ produced with 5-axis milling machines has already been studied [5][6], further research is required to investigate the behavior of 5-axis laser and 5-axis waterjet cut joints.

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