Realization of a Double-Layered Diamond Vault Made from CLT

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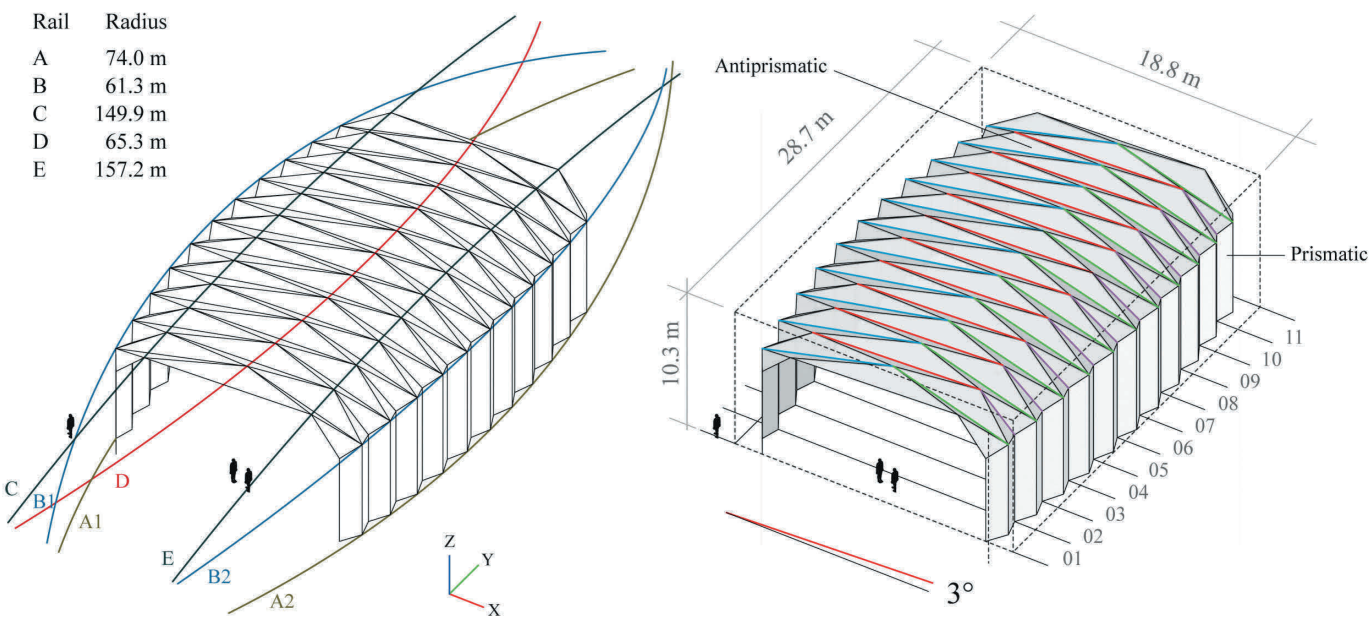
Constraint-aware design for assembly, for the first integrally attached Timber Folded Plate lightweight structure, covering a column free span of 20 meters with only 45 millimeter thick CLT plates.



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ABSTRACT

The use of digital design and fabrication technology for the integration of joints into timber plate structures has been the subject of recent research in the field of architectural geometry. While most of research has been focused on joint geometries, assembly sequences, and the fabrication of smaller prototypes, there have been few implementations in buildings. This paper illustrates the challenges for such a process and offers our solutions for implementing it at a building scale through the example of a theater hall built from cross-laminated timber plates. The building achieves its column-free span of 20 meters with a plate thickness of only 45 mm through a form-active lightweight structure system. It combines prismatic and antiprismatic folded surfaces and a double-layered cross-section with integrated thermal insulation.

1 Target manifold, rail curves, roof slopes, building sections. Image: C. Robeller

INTRODUCTION

Folded Plate Structures

In the group of form-active structures, folded plates are part of the surface active typologies. They allow for the creation of large-spanning, column-free roof structures from planar elements. The combination of multiple oblique plates into a structural entity combines three different load-bearing actions: a plate action (of a horizontal plate), slab action (of a vertical plate), and frame action (being rigidly clamped on each end). The principle was discovered and first published by Craemer (1929). Until the rise of pre-stressed and precast concrete elements in the 1970s, the principle of folded plates was commonly used for column-free, self-supporting roof structures.

Timber Folded Plates

While few concrete folded plate structures have been built in recent years, the structural principle has been the subject of research in architectural geometry by using new structural composite lumber materials. A first timber folded plate (TFP) structure was built for a music rehearsal hall in Thannhausen near Augsburg in 2001 (Schineis 2004), followed by an experimental Miura-Ori origami-inspired TFP barrel vault made out of plywood (Buri and Weinand 2008) and the chapel of St-Loup, using cross-laminated timber plates (CLT). Further research was focused on curved folded CLT and advanced joining methods using digital design and fabrication technology.

The use of integral multiple tab-and-slot joints (MTSJ) allowed for more complex freeform TFP structures using laminated veneer lumber (LVL) (Robeller and Weinand 2015a). The load-bearing behavior of MTSJ was studied by Roche et al. (2015a), showing that a stiffness equivalent to screwed joints can be achieved. Subsequent developments were the use of closed-slot MTSJ through-tenon joints instead of open-slot MTSJ dovetail joints, because they provide a higher rotational stiffness, which is a critical performance issue for use in timber folded plate structures (Roche et al. 2015b). A first experimental Miura-Ori type TFP structure using closed-slot MTSJ was shown by Robeller et al. (2016a). Here so-called double-through-tenon joints (DTTJ) were first introduced for the fully integral connection of double-layered TFP structures, taking particular advantage of the possibility of joining thin cross-laminated plates with MTSJ.

Developable and Non-Developable Geometries

The TFP structures in the previous section all belong with the group of developable geometries. This is generally the case for so-called prismatic folded plates, which are straight extrusions of a single profile curve. If multiple prismatic folded plates are rigidly attached to each other, this can result in globally developable assemblies such as the chapel of St-Loup (using so-called reverse folds between prismatic segments), or globally non-developable shapes such as the music rehearsal hall in Thannhausen, which uses mirrored folds between the prismatic segments. While the developable shapes may have certain benefits, such as ideal nesting of plate shapes, non-developable shapes have structural benefits which are the subject of ongoing research (Stitic et al. 2015).

Computational Generation of Folds

Various methods have been developed for the generation of freeform folded surface geometries, most notably by Tomohiro Tachi, who published various advanced methods for developable manifolds (2009). A method targeted for the design of non-developable geometries based on freeform NURBS surfaces was described in Robeller et al. (2016a), which evaluated and shifted a point grid for Yoshimura or Miura-Ori folded shapes, the latter of which included a post-planarization using the ShapeOp solver (Bouaziz et al. 2012).

FOLDED SURFACE DESIGN

Project Context

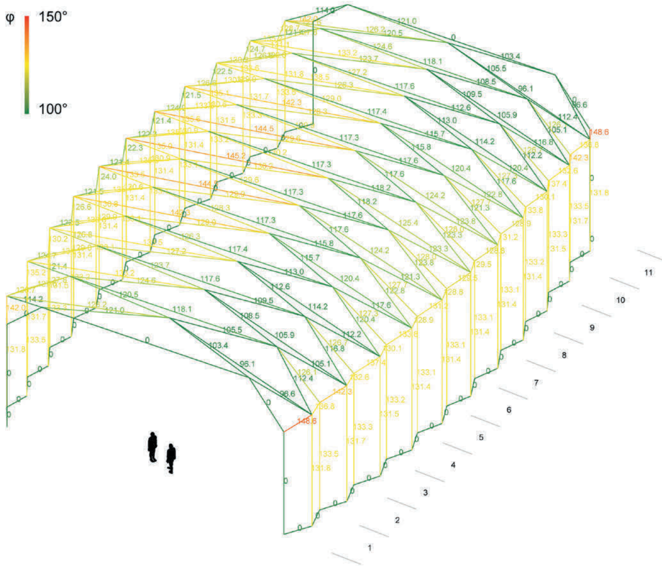
While previous experimental structures have demonstrated timber folded plates with non-developable shapes, double-layered constructions and double-through-tenon joints, the project in the present paper—a new hall for the Vidy-Lausanne Theater—is the first building-scale structure to implement many of these new methods. The project has been commissioned by the Theater, which is located directly at the shores of Lake Geneva in the west of Switzerland, at the French border. The Theater currently uses a building that was designed for the Swiss National Exhibition in Lausanne in 1964, which is known for multiple experimental structures (Bill 2000; Graf 2002), as well as a temporary tent structure which is now being replaced with this new folded plate structure.

Building Geometry

With a length of 28.7 meters, a width of 18.8 meters and a height of 10.3 meters, the new building covers an area of 540 square meters. The structure consists of three distinct sections: two 10.3 x 28.7 m folded vertical wall sections (each with a 232 m^2 surface area) and one 18.8 x 28.7 m doubly curved folded roof section (649 m^2 surface area). While the wall sections are based on straight-extruded zig-zag polylines, the roof section is a Yoshimura fold, also known as diamond fold. Our design process can be split into three separate steps: 1. the target manifold generation, 2. the plate and joint generation and 3. the fabrication data generation.

Target Manifold Generation

The target manifold generation acts as the global design model.



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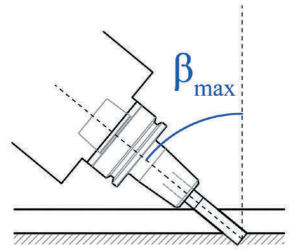

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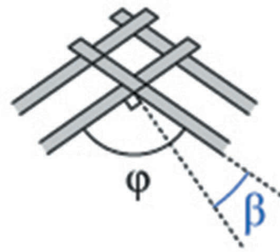

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2 Isometric view illustrating the fabrication-constrained fold angles of the construction. Image: C. Robeller

3 The maximum tool rotation β max results from the plate thickness and first point of collision on the tool holder. Image: C. Robeller

4 From the maximum tool rotation β max, we obtain the most obtuse possible fold angle φ max. Image: C. Robeller

5 Building section 04, roof element. Insertion vectors for top layer plates. Image: C. Robeller

The output of this step is a polygon mesh, representing the interior surfaces of the final structure. Each interior plate is represented by a mesh face. The use of a doubly connected edge list (DCEL) data structure (Botsch 2010) provides the information for the algorithmic processing in the next step, the plate and joint generation. The folded geometry of the Vidy theater is generated through the intersection of seven rail curves, as depicted in Figure 1. The building's geometry is based on a reference frame, which lies in the center of the building, with the XY plane on top of the base concrete plate.

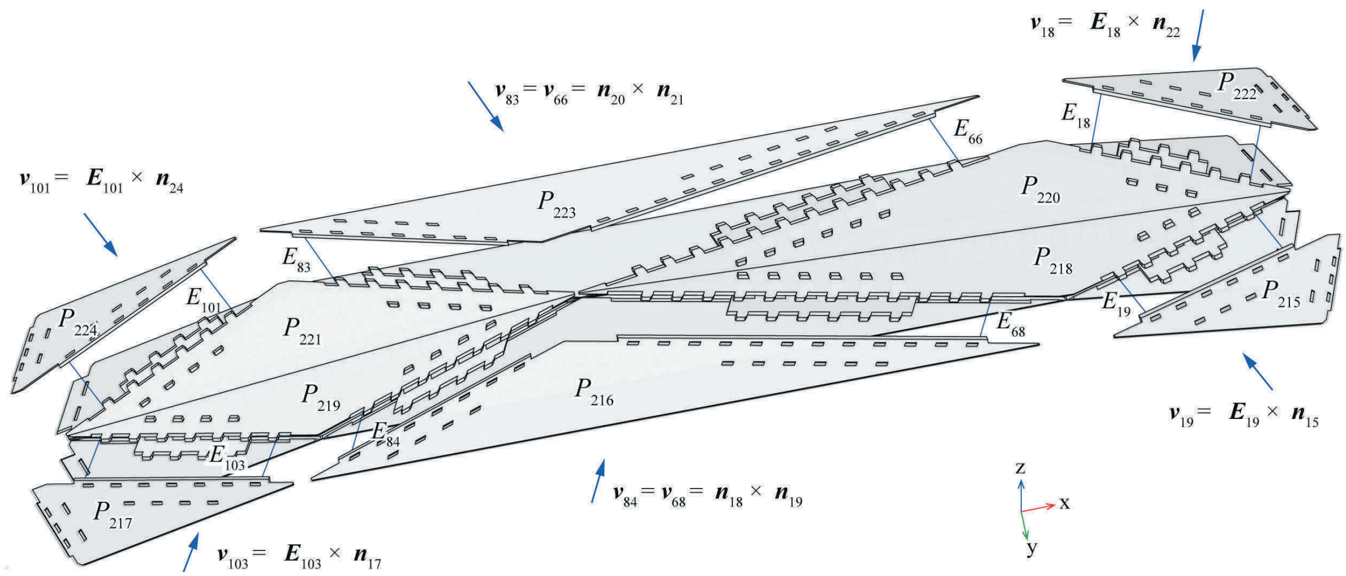
The construction is partially symmetric around the XZ plane: The sections 07–11 are mirrored versions of the sections 01–05, while the center section 06 is unique. The symmetry was originally planned for the production of the plates with a special CNC machine, which can produce two identically shaped parts simultaneously.

We have intersected the rail curves with 24 planes, which are all parallel to the reference frame's XZ plane (Figure 1), with a spacing of 2.6 m along the Y-direction. From these plane-curve intersections we obtain a point grid for the prismatic and the fold. Through the rail curves, the geometry of the building can be adapted to the architectural and structural constraints. The rail curves A1 and A2 are circles, which lie 0.3 m below the XY plane, as the structural timber plates in the vertical wall sections overlap with the concrete slab on the ground, which has been cast along the zig-zag shape of the polylines for this purpose. This way, the concrete slab is invisible after the building's completion. The wall sections end on the rail curves B1 and B2, which are circles on diagonal planes. The roof spans column free between these two rails and is sub-divided by three more rail curves. The circles C and E both lie on planes parallel to the reference frame's YZ plane. Curve E is positioned higher, which creates an asymmetric roof shape, resulting in a slope of 3° for the red lines in Figure 1. These ridges would otherwise be horizontal, which must be avoided due to the rainwater runoff.

Fold Angles

The fold angles, which we will describe as dihedral angles φ between the polygon mesh faces, are critical for the realization of the project (Figure 2). The folded roof has 110 plate segments. Its dihedral angles range from 96.1° to 145.2°, with an overall median of 122.53°. The edge lengths, which are relevant for transport and assembly, range from 1.6 m to 12.2 m. The prismatic folded walls have 11 plate segments each; their dihedral angles range from 131.4° to 133.5°. The edge lengths range from 1.6 m to 7.9 m. Globally the median dihedral angle is 125.97°, which results in an average tool inclination of β = 35.97°. The fold angles have been optimized to satisfy our fabrication constraints: from the dihedral angle φ, we obtain the required tool inclination angles β for the oblique cutting of the plates as $\beta = \varphi - 90°$. Due to our cutting technology, β must be kept below 50°, therefore the dihedral angles must be less than 140°. A detailed explanation of the relevance of the cutting angles is given in the fabrication chapter.

From a structural performance point of view, dihedral angles



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of 90° would be ideal. On the diamond fold roof of the theater, these angles are influenced by three main parameters: 1. the number of segments in the X direction (4), 2. the span-to-rise ratio (8.2), and 3. the segmentation length in the Y direction (2.6 m). The average fold angles could be decreased through more segments in the X direction, a lower span-to-rise ratio and a smaller segmentation length in the Y direction. However, the span-to-rise is set by the architectural requirements and efficient use of the space. A smaller number of segments in the X direction exceeds the size of the special edge-bonded CLT plates (see Brandner et al 2013), which can only be produced up to 15 m length at our factory. Finally, a smaller segmentation in the Y direction would result in thin triangles, which would not work with the double-layered DTTJ, as this reduces the ability to intersect through both plate layers.

SPATIAL STRUCTURE GENERATION

Surface Offset

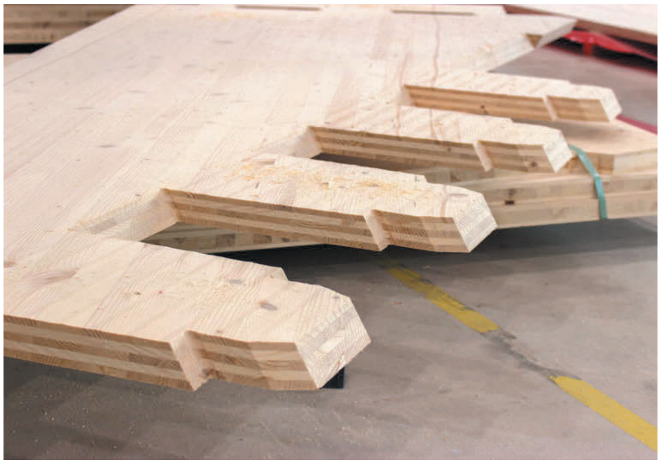
The first step for the generation of the spatial structure system is the offset of the target manifold. The total distance between the visible interior side of the CLT plates and the exterior side of the second plate layer is 300 mm. The plate thicknesses of 45 mm for both layers is offset to the inside, leaving a hollow space of 210 mm for thermal insulation made of recycled paper. This ecological, injected insulation was decisive for the project's double-layer construction technique. For the complexly shaped roof, a solid insulation material would have required costly 3D cut elements.

Geometrically, offsetting a diamond vault manifold is subject to multiple constraints. We have kept our offset of 300 mm constant throughout the structure. Our algorithm for the exterior plate generation offsets all interior edges to the outside, along the bisector of the adjacent face normals. New, offset triangles are then reconstructed from intersections of these edges. A special situation occurs on the 12 building section planes (see Figure 1), where the prefabricated elements connect on site. These section planes are kept parallel to the XZ plane with miter-joined edges. In these cases, the exterior edges are offset along a bisector of their own face normal and a vector mirrored on the XZ plane.

Plate and Joint Generation

From these interior and exterior triangles, the algorithm now generates the 3D plate geometries and joints, as shown in Figure 5, which illustrates the plates of building section 04. The double-layer assembly sequence follows the 4-step procedure previously published by Robeller (2015b). For this project, the joint types and assembly directions were defined for each target manifold edge through an Excel spreadsheet. Here, each edge ID was assigned a joint type (regular, vertical end, horizontal end). For regular-type joints, two insertion vectors were assigned.

Figure 5 shows the constraint-based calculation of these insertion vectors: for example, plate P_{223}'s unique insertion vector only allows for simultaneous attachment with the neighboring plates P_{220} and P_{221} (in the 3-digit plate ID numbers, the first number indicates the layer, 1-interior 2-exterior, while the other two numbers indicate the plate segment). This unique vector is found as the cross product of the normal vectors of the plates to attach to: n20 × n21. For other plates, which must not be simultaneously attached to multiple neighboring plates at different



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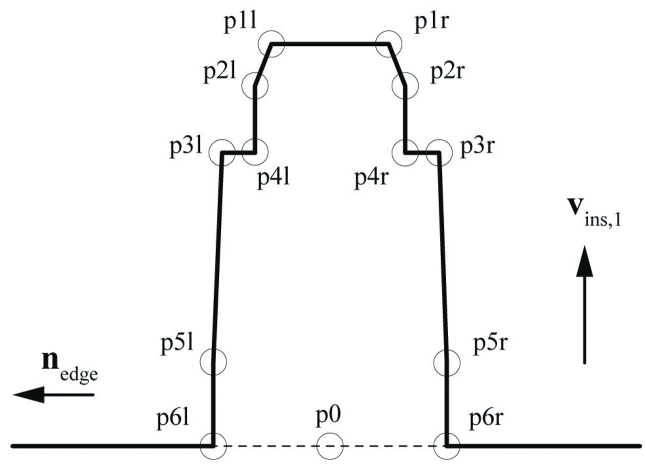

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rotations, the insertion vectors are calculated as the cross-product between the plate edge and its own normal (e.g. P_{222}).

Figures 6 and 7 show the DTTJ connectors, which are generated for all regular-type edges in the structure. The length of the joints always depends on both the dihedral angle φ of the fold, and for plates which are attached to multiple neighbors simultaneously, on their additional, secondary rotation. The base points of the DTTJ p0 are spaced at a distance of 500 mm. The base width is 270 mm, the tip width 250 mm. The through-tenon on the tip, which connects to the second plate layer, has a width of 170 mm.

Fabrication Preparations

After generating all plate geometries, the geometry is output to either the 3D position in the building model, or to a matrix of plates on the XY plane (Figure 7). The latter is done through a plane-to-plane transformation. Each 3D plate is assigned a reference frame. It is located at the center point of its underside, with the X direction facing along the long edge of the plate. The spacing of the plates on the XY plane is determined by the maximum plate length and maximum plate width.

FABRICATION

Due to the 456 individually shaped edge joints in the structure, it was not feasible to produce the parts using manual CAM programming software. Instead, a dedicated algorithm was developed for the fabrication, custom-designed for the CMS NC-PMT/190-TUCU/ISO40 5-axis CNC machining center with an OSAI series 10 control system. This machine was equipped with a 28.5 m X axis and a 3.5 m Y Axis. The G-Code generator was programmed in Visual C# and compiled as a Grasshopper add-on.The fundamental concepts of the cutting algorithm had been previously used for the production of smaller prototypes in an experimental environment. With the theater being produced in industrial wood processing facilities, the production times were critical for the project cost. Hence, several efforts were made to speed up the fabrication processes.

Contour Polygons

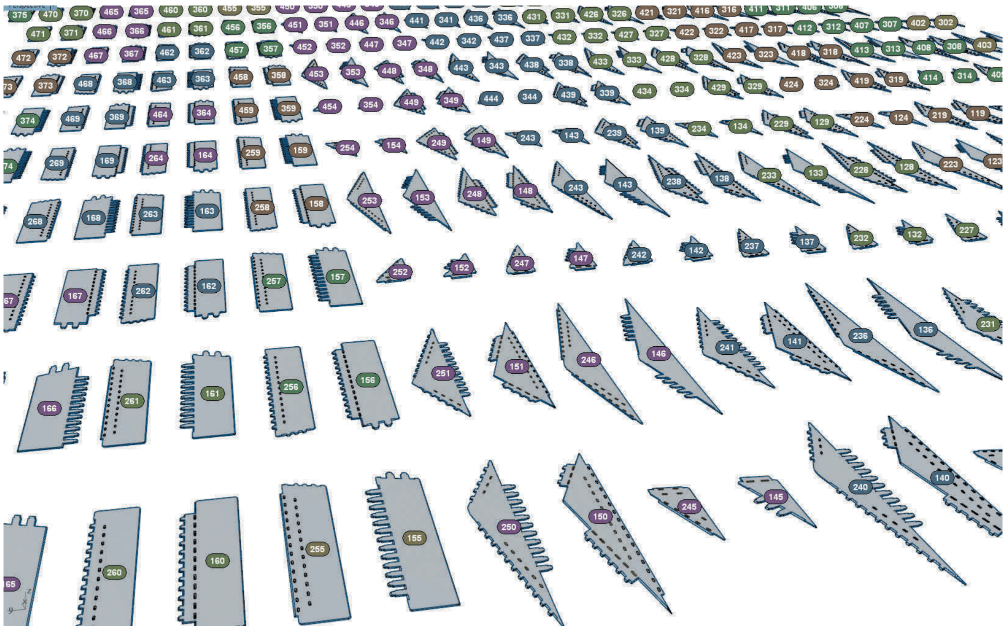
The geometry of each of the 304 plates of the building is defined through top/bottom pairs of contour polygons: one set defines the outer contour of the plate, while multiple additional pairs represent the interior cutouts for the oblique double-through-tenon joint slots. The cutting algorithm distinguishes between these exterior and interior curves through their orientation. While exterior contour polygons are all counterclockwise, interior contour polygons are clockwise.

Cutting Faces

Within a polygon contour pair, the number of segments on the bottom and the top contour must be identical, which allows the cutting algorithm to create quadrilateral cutting faces. Triangular faces are also needed for the DTTJ connectors at the start and end of each plate edge. Here the connection changes from a miter-joint to a butt-joint geometry, which requires one triangle face each. These triangle faces are approximated through two close points at the tip of the triangles, at a distance of 0.1 mm. From this we obtain a number of quadrilateral planar cutting faces for each contour pair. Figure 9 shows how the cutting algorithm processes these faces. The procedure minimizes the 5-axis cutting segments.

Contour Shape

The leftmost column shows a fundamental distinction between four different situations in a plate contour polygon. While iterating over the vertices of these polygons, we can distinguish between concave and convex points through a



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6 Double-through-tenon joints (DTTJ) on a 5-layered CLT plate. The thickness of the plate in the area of the joints has been milled down to exactly 45 mm. Photo: C. Robeller

7 Schematic view of the computationally generated DTTJ connectors, based on an insertion vector, edge vector, dihedral angle phi and plate thickness. Image: C. Robeller

8 Automatically laid-out plates of the Vidy theater on the world XY plane. Image: C. Robeller

vector cross-product with the previous vertex and the next vertex. Therefore, each face is either convex-convex (CV-CV), concave-concave (CC-CC), concave-convex (CC-CV), or convex-concave (CV-CC). This distinction is important for the cutting, since for CV-CV faces, it is possible to cut with a saw blade.

Saw Blade Cutting

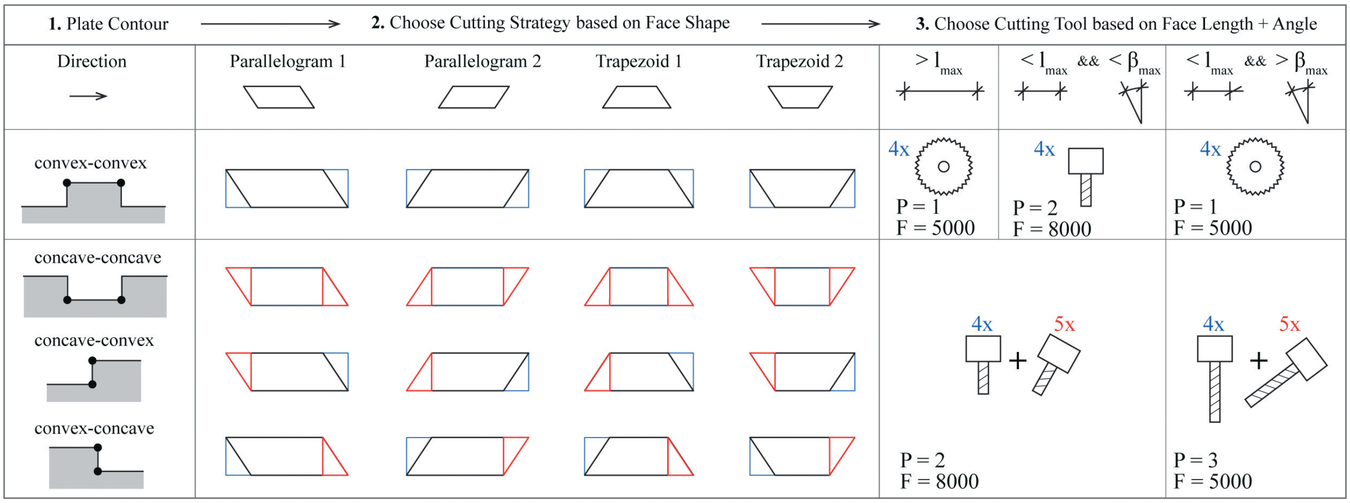
This is generally the fastest and most efficient option, due to the tool's large diameter, rotational speed and number of teeth, which optimizes the cutting force and cool-down of the blades. However, this is only possible for CV-CV faces, and only feasible for longer segments, which are defined through an input parameter lmax in the algorithm. If the face length lies above this threshold value, the saw blade (with a diameter of 500 mm) will be used, instead of a shank-type cutter. Up to a tool inclination of β=60°, the saw blade can cut the CLT plates with a thickness of 45 mm in a single pass P=1, while the shank-type cutter needs 2-3 passes to cut through the plate. Therefore, the use of the saw blade reduces the production time drastically.

Avoiding Epsilon Tool Rotations

A 5-axis tool rotation (epsilon) is required for non-rectangular CC-CC faces, and cut extensions are not possible on either the start or end point. Here, we require an additional epsilon rotation of the tool, which lies on the plane of our planar quad. When the tool is rotated at this angle and we move the cutting tool's center point along the bottom line of the quad, there will be a considerable amount of traction at negative angles and compression at positive angles. Generally, shank-type cutters are designed for perpendicular cutting, with a spiral angle for the evacuation of the wood chips out of the plate. This will create a small amount of traction normal to the plate. However, if we require larger tool inclinations around the epsilon angle, this will create much more traction, which will cause vibrations in the machine and the work piece. This is particularly problematic when work pieces are badly clamped on the machine table, which is usually the case in timber plate processing. Different techniques exist for this clamping, mostly using vacuum suction elements and screws (both were used for this project), but in either case, the clamping will be only at certain points with larger insufficiently clamped, cantilevering areas in the plates. It is therefore particularly important to avoid unnecessary traction, and therefore to avoid epsilon tool rotation angles wherever possible. Our solution to this problem is shown in red in Figure 9, as we minimize the cutting paths with epsilon rotations through changing the tool rotation within the plane of the planar faces during the cut.

Simulation

While it would have been possible to directly generate and supply G-Code files for the factory, this type of data exchange would have not allowed for flexibility on the side of the factory, such as changes in the nesting of the parts, changes in the order of the production and especially simulation of the previously described 5-axis motions of the shank-type cutters and saw blades. Therefore, the Grasshopper add-on supplied to the factory included a dedicated machine simulation, which is illustrated in Figure 10. This simulation visualizes all tool paths, as well as the machine geometry, based on a 0.0–1.0 value that indicates the line position within the G-code file. This allows



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for browsing through all machine motions, while the G-Code line number and machine rotation angles are simultaneously displayed in the command prompt of the CAD software.

Prefabrication Assembly

Following the cutting of the plates, the pre-assembly and thermal insulation injection of the 22 wall modules and 11 roof modules was also carried out in the factory. This allowed for rapid, precise and simple assembly in a controlled interior condition (see Figure 9). Parts were produced entirely without gaps; however, the insertion was much aided by the chamfers of the joints, as illustrated and described in Figure 5. One of the main benefits of the project and its new construction system is not needing falsework for the building process. However, the four custom-made supports in Figure 9 were needed for the joining process. On the two inner supports, the top end could be fixed at different lengths, allowing for this setup to be used for all 11 roof elements. For the wall elements, a similar simple support was used for the assembly. On the wall elements the additional exterior wood cladding was also pre-installed off-site.

On-Site Assembly

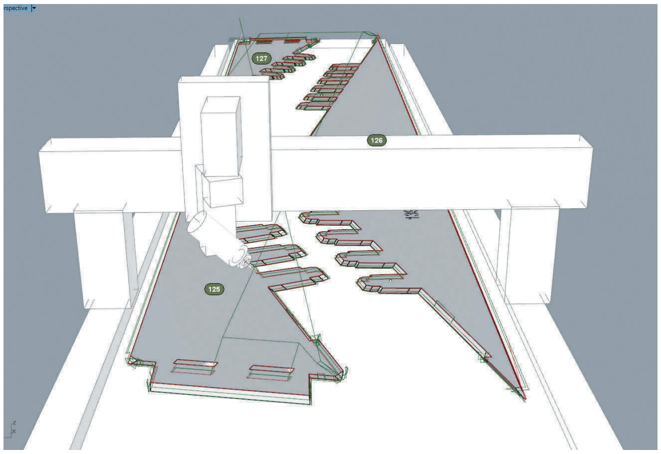
The prefabricated elements were transported to the site with trucks. The 2.6 m wide roof elements were up to 20.9 m long and up to 3.85 m high, which required costlier special transport for these parts. On site, the wall elements were installed first, and connected in groups with one another. Afterwards, the roof elements were lowered on top of the vertically facing DTTJ connectors on the wall elements (Figure 10). Being assembled on site, these 44 wall-to-roof connections are a special case within the building. Normally, the DTTJ assembly principle does not allow for the insertion of two plates along the same vector, which interlocks the plates and allows only for a plate-by-plate disassembly. This is impossible for the connection of the prefabricated walls and the prefabricated roof element, which must be carried out in one single motion. Therefore, the lower plates on the roof elements have no through-tenon joints that connect to the outer plates in the walls.

Finally, Figure 16 shows an interior view of the building sections 07–11. DTTJ connectors are visible within the prefabricated elements. In the sections 03–09, the roof elements were secured with tensile cables for transportation and on-site assembly. These cables were removed after the complete assembly of the structure in May 2017.

CONCLUSION

The Vidy theater builds upon previous research into the computational design, assembly and fabrication of timber folded plate structures. While previous experimental prototypes had demonstrated the double-layered integral attachment, it was first realized in a built structure in this project. In addition to the challenges in the geometry, joining and fabrication, the production on a factory processing line presented two major challenges.

A special G-code generator was custom developed for the factory, allowing for the simple and rapid programming of the 456 individually shaped plates with thousands of integral DTTJ connectors. This program allowed for G-Code generation by the factory personnel, while taking care of project-specific details which are unfeasible for manual CAM programming. The developments of such project specific “apps” is new to the building industry, but may become much more common in future projects, similar to other industry sectors. The fabrication efficiency and speed had to be increased drastically over previous versions of the algorithm, which were used for the production of experimental prototypes. This was achieved through the parallel use of a saw blade and different shank-type cutters, as well as the



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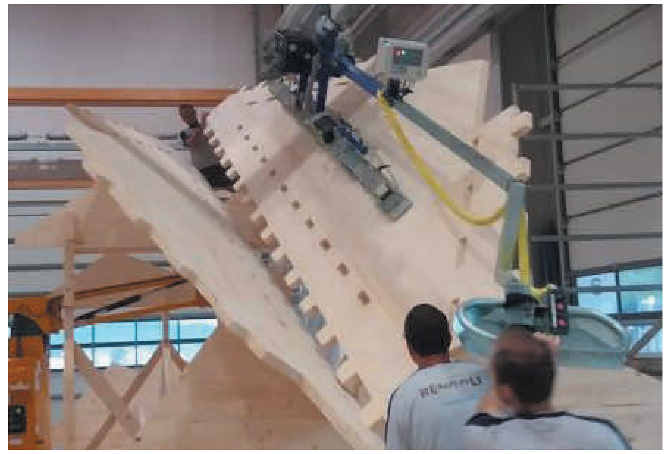

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9 Plate cutting algorithm. 3 different tools are used. 5-axis cutting is minimized. Image: C. Robeller

10 Production of the plates with a 5-axis gantry-type CNC router (Simulation tool for the factory). Image: C. Robeller

11 Prefabrication assembly. Plates are handled with vacuum grippers. Photo: D. Riggenbach

12 One of the eleven prefabricated roof elements, assembled on a minimal, re-used support structure. Photo: C. Robeller

reduction of tool rotations.

The integral DTTJ connectors served two main purposes in the structure. First, their single-degree-of-freedom shape allows for only one correct assembly position of the elements. In this project, the DTTJs also define the correct spacing between the two layers through their shape. They therefore fully embed the assembly information into the shape of the parts, which allows for rapid, precise and simple assembly. This principle was used for the pre-assembly of components in the factory and for the assembly on-site. Second, the DTTJ connectors were used as structural joints, transferring stresses not only in between neighboring plates, but also in between the two layers of the structure.

Key achievements of this new system include the construction of a self-supporting, column-free structure that spans over a distance of 20 meters, using CLT plates with a thickness of only 45 millimeters. It is currently the largest built timber folded plate structure, the first that uses integral joints and the first with such a double-layered construction that includes integrated thermal insulation between the two structural layers. With the exception of a simple support structure for the pre-assembly of the roof elements, no falsework was required for this construction.

Computational tools for design and production allow for the realization of advanced form-active structural typologies. The integral joining strategies in the present project demonstrate the importance of advanced assembly strategies for such designs, especially considering the large amount of individually shaped plates and joints that result from the freeform shape of the building.

The Vidy theater illustrates the great potential of novel, digitally inspired assembly methods, joint geometries and construction sequences. The resulting architectural design is shaped by project-specific assembly constraints, which are reflected in both its global form and its details. Timber folded plates are structurally efficient and elegant structure systems, which are rarely built due to technical challenges. However, engineered wood materials such as CLT provide an ideal, sustainable lightweight material for such designs. The joining remains a challenge, but also allows for new rapid-assembly solutions, an increased level of automation

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in building prefabrication and enables structurally efficient shapes.

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13 Vertical wall segments were installed first, then the roof elements were placed. Photo: C. Robeller

14 The prefabricated roof elements were lowered onto the through-tenon joints and double-through-tenon joints along the Z axis. Thermal insulation was pre-installed, only the tarboard was added on top of the roof on site. Photo: I. Kramer

15 Image of the finished building. The exterior ventiated facade was also fully pre-installed in the factory and transported with the wall elements. Photo: I. Kramer

16 Interior view of the theater. The photos were taken from the north side mezzanine. The steel cables were used for transportation and removed after the building was completely assembled. Photo C. Robeller

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IMAGE CREDITS

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Figure 11: D. Riggenbach

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