Moritz Niebler, Sylvain Usai, Martin Antemann, Fabian Scheurer, Evy Slabbinck

Bent-on-Site Flat-Pack Delivery of a Timber Shell

Abstract: Wisdome Stockholm is an extension to the Stockholm's Technical Museum due to open in December 2023 featuring an innovative timber roof. The free-form gridshell overarches 24 by 47 meters, consists of five crossing layers of doubly curved beams and is completely prefabricated from laminated veneer lumber (LVL). Beam segments were bent and twisted on-site from 2,190 flat, CNC-cut LVL-lamellae and locked in shape by 3,500 wooden dowels to form a stiff structure. Several challenges arose during the 1.5 year of planning, most of them induced by early design decisions such as material choice: despite being less common than glued-laminated (glulam) beams for doubly curved timber gridshells, the use of LVL was mandatory from the start. Furthermore, time and budget constraints did not allow for lamination and machining of doubly curved beams. The beams of the gridshell are composed of five layers of individually CNC-cut LVL-lamellae, thin enough to twist and bend. Only the lowest beam layer was pre-laminated to create a stiff base while the remaining lamellae were shipped to site flat-packed and bundled for assembly. The entire roof was parametrically planned in 3D. Lamellae were digitally unrolled, mapping all detailed connections from the twisted center surface to the flat lamella, and all were nested for 5-axis fabrication. The constructive system and digital process robustness was tested and validated using demonstrators as early as one month into the project, putting an early emphasis on fabrication and assembly. This paper discusses the workflow and problem-solving strategies implemented during the execution stage.

Keywords: timber structure, gridshell, laminated veneer lumber, free-form, digital planning, design-for-manufacture-and-assembly, digital fabrication

1 Introduction

The Wisdome Stockholm exhibition space, designed by Elding Oscarson Architects, permanently sits in the courtyard of the Tekniska Museet and houses a wooden dome dedicated to visualization technology. The insulated roof features a $24 \times 47 \times 18$ meters freeform timber gridshell (see Fig. 1 left and right) built from CNC milled Laminated Veneer Lumber (LVL) lamellae. As the roof's edge is standing on 4 to 9-meter-high columns, loads normally transferred tangentially from the roof surface must be brought down vertically through reinforced "stilts".

On behalf of the timber contractor Blumer-Lehmann AG along with the structural engineers SJB Kempter Fitze and Création Holz, Design-to-Production was responsible

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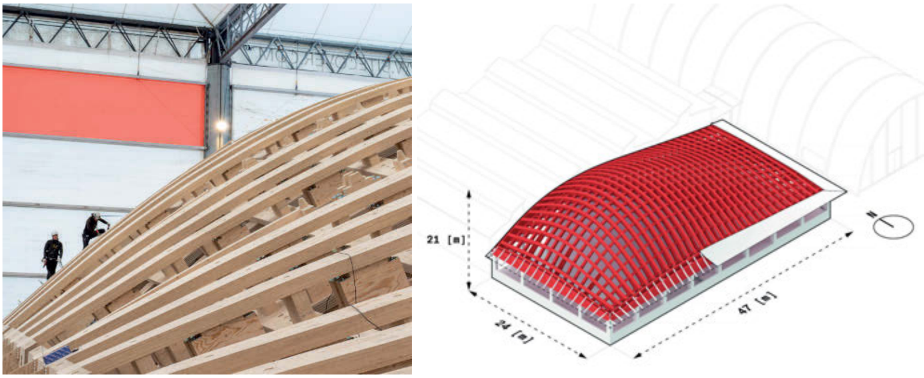

Fig. 1: Left: Wisdome Stockholm during assembly; Right: Axonometry of the roof.

for timber consulting, project management support and digital planning. The team already had extensive shared experience with freeform timber projects (Nine Bridges Golf Club in Yeoju, Venlo Casino in Venlo, Swatch Headquarter in Biel) using CNC milled glulam beam segments. However, the sponsoring of material by Stora Enso meant that the project was to pioneer the use of LVL panels in complex timber structures. Making a doubly curved blank from LVL panels and milling it afterwards to the final shape would not have been cost, material and time efficient. Instead, beams would be milled from a standard flat panel and mechanical-laminated.

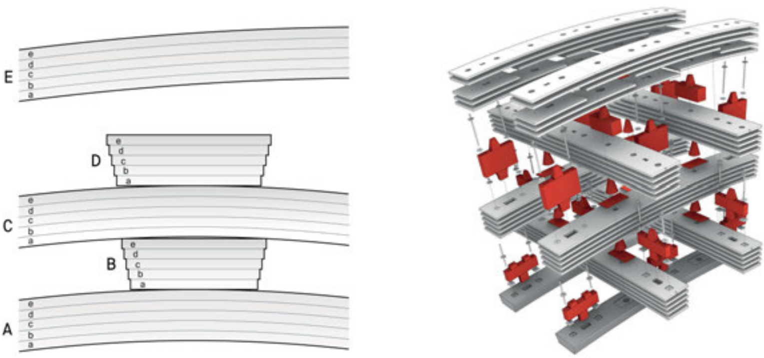

Fig. 2: Left: Beam layers composing the roof; Right: detailed roof build up.

The gridshell is composed of five beam layers running in two alternating directions (see Fig. 2, layers A to E). The beams are made of five stacked LVL lamellae, stacked and bent-on-site. Each lamella is 31 mm thick. Lamellae are held in shape and position by screws and wooden dowels, effectively turning two or three “parallel” beams into a Vierendeel truss. In order to be produced from a flat material, lamellae were digitally unrolled, including their complex detailing, and nested onto raw standard panel. Only the lowest beam layer is glued and pre-assembled off-site in order to precisely define the beam grid's shape and act as a stay in place falsework for all layers above. This paper discusses the digital process and methodology driving the modeling and production of fabrication data, the use of demonstrators to validate assumptions on structural, fabrication, and assembly concepts, the reconstruction of precise reference geometry as well as the parametric segmentation, nesting, detailing, and unrolling of all the individual lamellae.

2 Timber gridshells: state-of-the-art

There has been an increase in the design and construction of innovative and advanced wooden gridshell constructions over the past decade (Chilton and Tang 2017) (Lara-Bocanegra et al. 2018). Computational form-finding process or physical hanging-model method allows to determine the shape of elastic timber gridshells (Tomei et al. 2022). Most built gridshells use slender and thin elements, e. g. Multihalle Mannheim, Weald and Downland Open Air Museum and PEMADE gridshell (Tomei et al. 2022). By reducing the width of the elements, the geometric torsion is reduced (Slabbinck et al. 2017). Elastic timber gridshells often constitute the continuous façade of a building, starting at ground level and covering all wall and roof geometry, to be able to handle horizontal forces keeping the gridshell bent. Contrary to this, the Savill Garden gridshell is solely a roof on columns with a ring beam transferring the forces to the inclined steel columns, as in the Flimwell Woodland Enterprise Centre, while timber columns are used to transfer the loads to the ground in the tangential direction of the roof (Chilton and Tang 2017; Harris and Roynon 2008).

Following advances in digital fabrication, gridshell design has shifted away from bending elements on-site as a method of assembly. The evolutions of CAD, CAE, CAM and CNC technologies enables the production of precisely shaped curved beams from glulam blanks. This expands the design solution space while freeing the designer from the inherent difficulties associated with the design and construction of elastic gridshells (Lara-Bocanegra 2022). Alternative timber gridshell systems were developed using glulam beams, among others: Zollinger system (Toskana Thermal Springs), use of lap joints (Swatch Headquarters), hierarchical beam directions of beams (French Pavilion Expo 2015) and the use of timber dowels (Centre Pompidou Metz) (Chilton and Tang 2017).

In an effort to overcome the limited design freedom, construction constraints and complexity of the design, research has developed further by bending continuous elements in timber gridshells in a novel way. The use of single curvature locally in the elements was enabled in the bent-plate gridshell like the 2010 ICD/ITKE research pavilion (Quinn 2018). Ribbed and cross-ribbed shells, use false-work to construct the designed geometry and dowel or nail the elements together (Gliniorz et al. 2002). Or by using the hygroscopic qualities of wood to form surface-active plates like the Urbach Tower (Bechert et al. 2021).

In timber construction, the use of a single material for joint and structural members speaking the same language is key. The use of dowels to mechanically laminate timber has been a focus point of research in the last decades. Mechanical lamination of timber was already documented in the 19th century by Amand-Rose Emy, where he illustrates the bending of timber elements in a jig and held in place by the help of bolts and clamps (Emy 1837). More recent research shows ribbed shells with doweled planks, keyed beams where shear keys are used between timber layers to improve the overall beam stiffness and efficiency, and dowel laminated timber (DLT) (Miller and Bulleit 2011; Gliniorz et al. 2002; Sotayo et al. 2020; O'Ceallaigh et al. 2022).

3 Digital process and methodology

Off-site prefabrication has been around for centuries within the timber construction industry, allowing builders to shift complexity from the construction site to a controlled workshop environment. Nowadays, so called free-form project forces builders to shift part of the complexity once again from the workshop onto the digital drafting board (Scheurer et al. 2013). These projects make full use of digital tools both during planning (CAD) and fabrication (CAM). However, to fully bear the fruits of the digital revolution on the production side, the entire process chain, from procurement to fabrication and assembly, needs to be coordinated by "pulling" from the back-end (Scheurer and Stehling 2020). The objectives for digital modelling are defined by the final step: a level of detail that contains every screw-hole to be drilled by digital machinery, and a level of accuracy that matches that of digital fabrication. Multi-scalar parametric models, a stack of models with different resolutions as defined by Scheurer and Stehling (2020), containing minimal but accurate information is a mean toward both these ends. Each model embeds the learnings and results of a design stage and is used as input to parametrically detail the model of the next stage (see Fig. 3) (Scheurer and Stehling 2020).

Dependencies and limitations must be identified upfront to make the process viable and a high degree of systematization and clear interfaces between trades and building parts are required to achieve quality and consistency.

Entering the Wisdome project pre-tender allowed for an early consideration of logistics, material constraints, assembly feasibility and fabrication limitations. These dependencies were woven into the process during the revision of the Reference Geometry[1]

1 The Reference Geometry defines basic geometric properties of the project, including Reference surfaces and axes (in production quality), Main components (beams and panels) as continuous axes and surfaces and undetailed 3D volumes and Nodes positions.

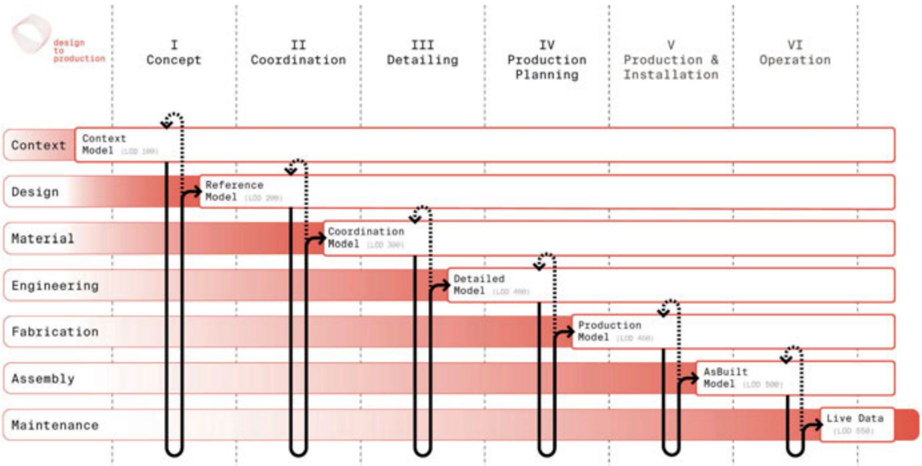

Fig. 3: Agile Design-to-Production process.

optimization. Additionally, lessons learned from three early built demonstrators involving all stakeholders and subcontractors proved an invaluable basis for decision-making.

A building element catalogue describes all existing element types in the building. It can be used to derive a detail matrix, describing the interfaces and dependencies between these element types. Such a building catalogue was created from an early stage and maintained during the entire project, allowing for a clear understanding of the dependencies between elements. The detail matrix was paramount to reach systematization of the Joint Catalogue, leading to the control and reduction of the amount of detail types, complexity, cost and time (see Fig. 4).

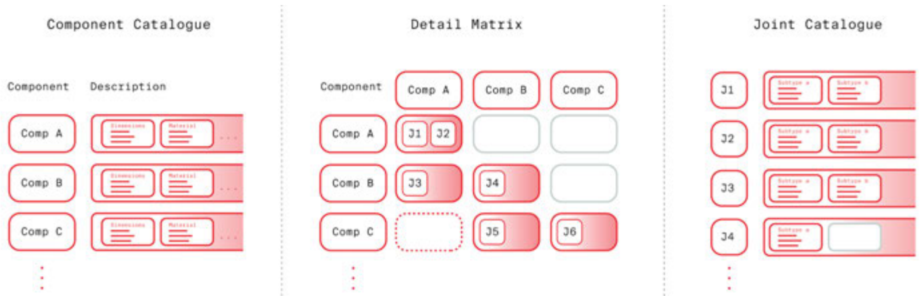

Fig. 4: Schematic catalogues concept overview.

4 Demonstrators

The construction system imagined for the roof was beyond the team's experience. Additionally, the forces required to bend the lamellae (which was to be performed repeatedly by the montage team on-site), the internal stresses and the behavior of the beams and dowels under bending and torsion were unknown. The beams with the highest torsion (8.4°/m) and the one with the smallest radius of curvature (10 m) were isolated and fully detailed for production in order to test bending and recoil. The lamellae were unrolled, CNC milled, positioned in a formwork jig made of milled-out beam profiles and fixed with LVL oblong dowels measuring 300 × 160 × 60 mm.

Fig. 5: Left: Torsion demonstrator; Right: Four crossing segments.

The demonstrators proved that bending lamellae was physically possible. Nonetheless, recoil out of the formwork exceeded 1 m for the bent demonstrator (see Fig. 5 left). Even if the spring back would have remained in check, the number of dowels and the manual labor required to insert them all could not be justified. In parallel, four crossing segments were also detailed and assembled to test and validate the aesthetic of the stacked lamellae and dowels (see Fig. 5 right).

The construction system was subsequently reworked and further tested with a second demonstrator. The beams on the lower layer were glued and shaped off-site and serve as stay-in-place falsework for the rest of the timber layers. This means that less dowels were required and recoil is limited because dowels were fastened to a stiff base. Additionally, the dowel shape was changed to allow for an easier assembly (see chapter 3D Detailing). This demonstrator consisted of 5 beam crossings in a high torsion area. It involved the entire team of subcontractors and served as a dry run for the actual building production and assembly. Effectively, most special details present in the building had to be solved for the mockup in a 2-week period. This demonstrator satisfied tolerance and precision expectation and the feedback from the montage team was highly positive, it remained so during the entire project assembly (see Fig. 6).

Fig. 6: Second demonstrator.

5 Definition and optimization of reference geometry

The reference surface is the basic geometric definition for all subsequent parametric modeling of beams and their connection details. The 3D-model provided by the architect as input for Wisdome, while transporting design ideas and concepts did not meet the requirements for execution and needed to be revised and rebuilt. An optimization of the reference geometry was carried out as part of the pre-project in close collaboration with the architect, structural timber engineer and the timber contractor. The entire stakeholder involvement allowed to cover and inform the optimization process with all aspects from architectural design intent, site boundary condition, material, and fabrication constraints.

The optimization problem revolved around the architectural design intent by extending the strict orthogonal grid basis into the roof construction. A key requirement was to establish a clean and matching interface between the base grid and the member axes of the roof structure, addressing both architectural and engineering considerations. This involved ensuring that the offset of the surface symmetry axes, and the beam axes grid align with the axes system of the columns. Additionally, material constraints related to maximum feasible bending and twisting need to be taken into account.

To address these challenges, an optimization workflow comprising multiple iterations was employed to determine the most suitable and producible surface and beam grid geometry. Given the manifold boundary conditions and the need for coordination with various parties, a manual approach was chosen to optimize and inform the geometry generation and formulation. Each iteration involved surface and beam grid optimization. The initial design surface was rebuilt from the architectural MESH input. And the beam grid on the surface was based on a strict orthogonal planar grid projected to the surface. Throughout the process, the resulting normal curvature and geodesic torsion were constantly monitored to ensure they remained within the range of the material properties.

The asymmetrical position of columns between North and South (long edge of the building, see Fig. 1 right) meant that the optimal on one side did not reflect on the other. Minor adjustments on both the surface, beam grid and column position were therefore necessary. Resulting in a slight deformed planar curve network.

Ultimately, five reference surfaces were created, one for each beam layer. The three lower surfaces (layer B-D) are strict offsets of the main surface, the last one (layer E) is only partially following the main surface on the center and deviates as it gets close to the border to define the outer roof and meet the horizontal eave lines (see Fig. 7, left). To reduce the number of individual dowels while reducing torsion and bending in the beams and maintaining geometric surface continuity, the offset between A and E was maintained as much as possible (see Fig. 7, right).

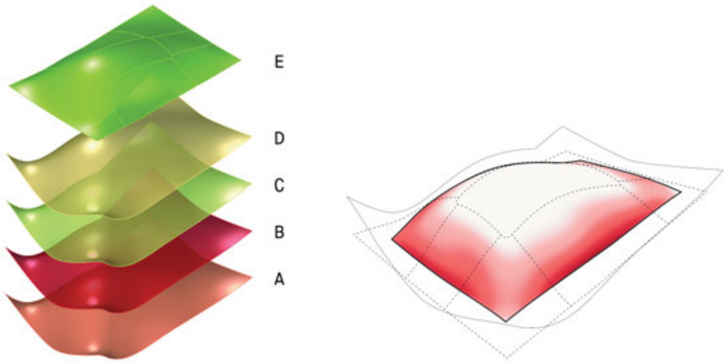

Fig. 7: Left: Master surface overview; Right: Master surface E offset deviation compared to A.

6 Segmentation

The beam length ranges from 25 to 53 m long while the maximum length of the standard panel from which beams are produced is 13.5 m. This meant that beams had to be produced in smaller segmented elements. In addition to raw material requirements, the segmentation strategy of a timber gridshell must comply with transport regulation and sizing, structural requirements, logistic, and engagement directions.

In an effort to minimize kinks in a lamella stack after on-site bending, the segmentation position is staggered within all the lamellae of the same beam. These segmentation joints are located between shear and cross dowel and span four consecutive dowels. Within one segment, these staggered joints can span between 2.9 and 4.2 m.

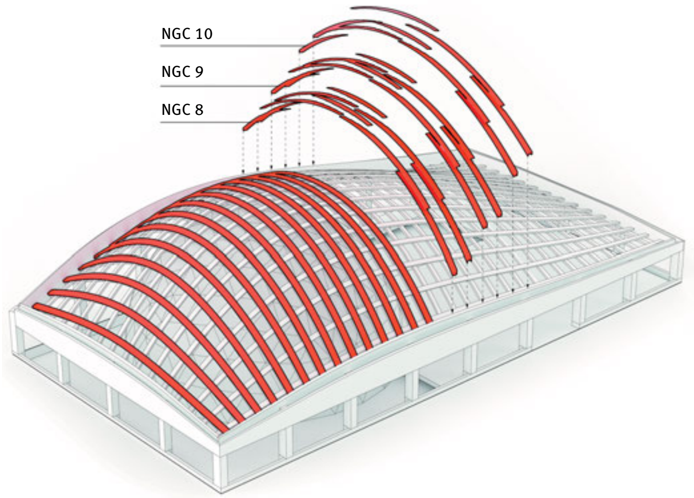

Fig. 8: Layer C assembly sequence.

To identify segmentation positions, a script ran from each opposite end of the beam, collecting cross and shear joints normal directions until the cumulative angle deviation exceeded 5° or 15° depending on the area of the roof. These threshold values relate to the slope of the dowel faces: once the angle value exceeds the threshold, it means that the lamella can't be inserted on the dowel, a segmentation joint is created, and the process is iterated further. This ensures that all joints on one segment share a common assembly direction. It is worth noting that this process simulates the translation of a rigid curved segment (all joints inserted at the same time) and ignores the bending motion (joints inserted one after the other), giving a comfortable margin for the team on-site.

If the angle value is still in range after 13 m, segmentation is triggered in order to fit in the 13,5-meter-long raw standard panels. The optimal solution was then adapted by the assembly team, favoring length homogeneity (see Fig. 8).

7 Nesting of 2651 components

Once segmented, all lamellae received a reasonable oversize (to compensate for the fact that most details were still undefined at this stage) and were nested into raw LVL panels and translated into a bill of quantity (BoQ). Available raw panel length ranged from 8 to 13 m with 200 mm increments, such variety of sizes increased the utilization rate of the raw material. This early BoQ was motivated by material order, production and shipping lead times. In a glulam free-form project, the 3D part is used as a basis for both the blank generation and the machining data. In Wisdome, the 3D geometry will only be “revealed” once bent into shape on-site. Therefore, all lamellae were unrolled into a “flat twin” model containing the parts as they are produced and shipped.

Within each beam layer, nesting panels are grouped into sectors according to the assembly sequence. The use of two different sheet materials LVL-S and LVL-X as well as two different visual qualities prompted further subdivisions within one sector. This resulted in 96 nesting batches for 2651 lamellae with a total of ca. 12,000 m^2 of sheet material (more than 10 times the footprint of the building). Taking the assembly sequence into account during the nesting allowed for lean production, keeping logistics and part sorting to a minimum on the workshop floor and simplifying the flat-packing of the lamellae into segments for a swift on-site handling and assembly. The resulting nesting has been kept untouched from the early undetailed stage until the final production export and proved to be a crucial part for the success of the project (see Fig. 9). Ultimately, every panel was exported individually as a Cadwork file containing named and detailed volumes for each nested lamellae and every relevant cutting operation.

Fig. 9: Flat-packed beam segments.

8 3D Detailing

Joints are created at every crossing between two elements (cross joints) or within one element itself (continuous joint). Each joint is typed according to the elements it connects and subtyped according to structural requirements. Every joint defines their own coordinate system, used to parametrically build the details. Dependencies between neighboring joints are important to consider during detail development as moiré effect can appear when two details are instantiated on different coordinate systems close to each other. The joint between the column, edge panel and beam is a good example (see

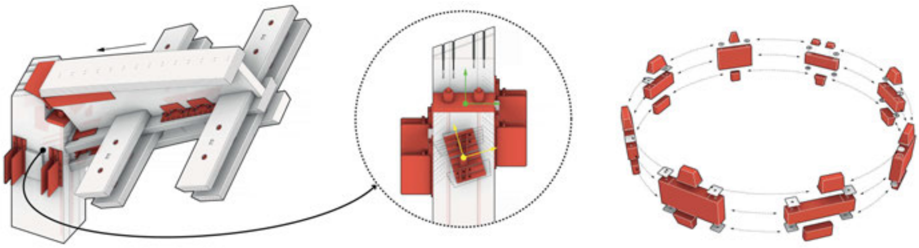

Fig. 10: Left: Column, edge panel, beam detail; Right: Shear-Dowel Configuration..

Fig. 10 left). Vertical tensioning rode (instantiated on the green plane) meets screws from the beam foot detail (instantiated on the yellow plane) and screws from the steel socket on the side of the column.

All details within layer B-E are instantiated in 3D and subsequently unrolled onto the lamella. The Flat twin model is synchronized after every change on the 3D models. Layer A did not require unrolling of details as the raw blanks were glued in shape and details were 5-axis milled out of the blank.

The entire gridshell contains 1820 cross dowels and 1756 shear dowels. Cross dowels are instantiated at every crossing and are made of truncated conical tenons, they are holding the lamellae into position. Shear dowel span between parallel horizontal beams (AC, BD, CE) and have 4 sided pyramidal tenons on the top and bottom face to shape the lamellae into form. Even though layers B, C, D are strict offsets from the reference A surface, local curvature and torsion configuration meant that the dowel height would have to be unique for every joint. For each subtype, the smallest existing dowel height configuration was identified and used as the baseline height. The remaining height difference was compensated by steel washers partially sunk in the lamella. This reduced the amount of different dowel types from 2859 to 9, simplifying dowel production, logistics, assembly time and reducing cost significantly (see Fig. 10 right). Working with repeating geometries also allowed the planning team/process to make full use of modeling "blocks": the coordinate system of each block is parametrically defined within one connection and the block geometry is simply oriented to its final position, rather than parametrically encoding the base, plug, washer, bolts, drilling, cutters, etc. Additionally, these repeating dowels are made symmetrical so it would be impossible to assemble them "flipped". For the individual dowels, positioning drillings facing toward the building edges are introduced to inform the montage team of the dowel orientation.

The E surface is following its own rules and is not an offset of the reference A surface around the edges (see Sec. 5), therefore, the cross dowels between layers DE and shear dowels between layers CE had to be unique anyway.

9 Flat part detailing

Once instantiated in 3D, all detail operations are unrolled with the flat lamellae. Two different unrolling strategies were developed consecutively for the unrolling of detail operations. For the demonstrator, operations were intersected with the top and bottom face of the lamella and pulled (normal projection) onto the middle surface of the lamella before being unrolled. After unrolling, the top intersection curves were moved up and the bottom intersection curves were moved down by half the lamella thickness. Cutters were then rebuilt in 3D by interpolating these curves. This process allowed to account for the cutter deformation induced by curvature and torsion during the unrolling, but it was discarded by the fabricator after the mockup as it significantly increased the complexity of milling operation for a marginal gain in precision. The alternative solution was to individually unroll the detail planes onto the flat lamella to map cutting operations from 3D plane to flat plane: the cutters for the dowel tenons can then be milled as a straight contour instead of a twisted one.

Unrolling detail planes instead of single operations allows to apply the same unrolling routine to any drillings, saw-cuts, pockets and block instances. This implies that every operation must use one of these detail planes as its local coordinate system. The unrolling of detail planes follows a three step process. They are serialized into a set of unrollable geometries with attributes, unrolled and deserialized back into a plane (see Fig. 11).

To serialize a plane in reference to the lamella mid surface, three points are projected normally to the lamella: the plane origin, origin + plane unit X and origin + plane unit Y. Distances from the point and its projected counterpart, as well as additional information regarding the operation type, where embedded as a dataset on a Text-Dot object. Text dots store an operation type string and a concatenation of height distance, Global Unique Identifier (GUID) and additional operation specific information. The GUID is common for all texts dots defining the same plane (origin, X and Y) and is later used to retrieve and group them together as dozens of planes get unrolled simultaneously. After unrolling, dots are sorted by GUIDs and deserialized to a local unrolled plane. To check deviations between the 3D and flat detail plane the angle between the lamella normal at origin and plane normal are compared. Keeping the initial detail plane as close as possible to the surface helps reducing deviation. Unrolling was considered successful as long as the normal deviation between flat and 3D did not exceed fabrication tolerances (5/10 mm). For critical detail planes close to an edge of the surface, additional points in negative plane space are added to the process. All operations then simply follow a plane-to-plane transformation to be mapped onto the flat lamella. Detailed volumes were generated for both 3D and unrolled parts. Quality control involved visual checking of overlayed 3D and flat sibling parts to ensure that they were correctly oriented, and all cutting operations were properly transferred between the 3D and flat version.

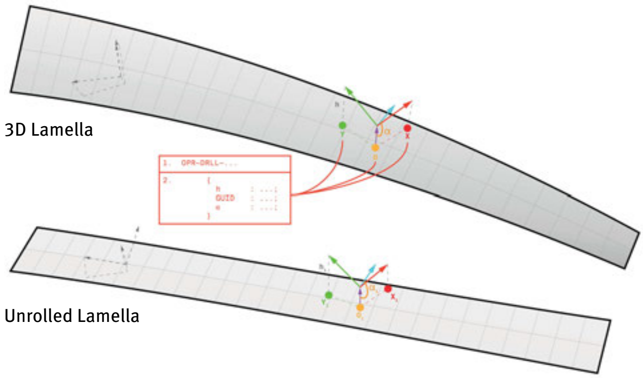

Fig. 11: Schematic unroll of detail planes.

As shown with the third demonstrator and by extension the final project, both approaches of unrolling operations proved to be valid solutions in terms of geometric representation. Although the second more pragmatic method is more relevant at an architectural scale in terms of fabrication and part size.

10 Conclusion

Fabrication and assembly optimization concerns were central during The Wisdome gridshell conception. The precise milling of unrolled lamellae out of flat LVL panels proved to be a viable (time and cost-wise) alternative to the glulam blanks approach with notable upside regarding fabrication (milling from a flat panel is easier than milling from a 3D blank) and shipping (transporting bundled flat lamellae is easier than formed 3D segments). On-site assembly was more labor intensive than a glulam gridshell but this was alleviated by precise and unambiguous pre-fabricated details, comprehensive naming system and assembly strategy. The entire project execution was immensely facilitated by the extensive digital methodology: front-loading the Material, Engineering, Fabrication, Assembly and Maintenance constraints allowed to keep potential issues in-check and pro-actively find solutions and plan for fabrication in a lean and efficient way, allowing the gridshell to be planned and ultimately assembled in time and on budget.

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