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Timber Gridshells: Challenges and strategies in fabrication and assembly

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Abstract

Timber gridshells offer structural efficiency, use of renewable materials, and freeform, lightweight construction. However, their potential for sustainable building solutions is often hampered by the complexity of design, fabrication, and assembly. Various strategies have been developed and tested in research and practice to create the curved geometry of individual elements and grids. These strategies include the individual bending and coupling of lamellas, complete robotic prefabrication of curved elements, and elastic deformation of the entire grid. Recently, a new strategy utilizing architectural geometry has emerged, allowing the combination of straight and flat planks into a so-called geodesic-asymptotic hybrid gridshell. This paper examines four innovative large-scale timber gridshells, focusing on their fabrication and assembly techniques. The four methods are critically analyzed in terms of planning, component bending, prefabrication versus on-site construction, construction complexity, and future viability. Finally, these methods are compared with the novel geodesic-asymptotic hybrid approach to assess the potential and challenges of this new method for large-scale applications.

Keywords: timber gridshell, free-form structures, timber construction, asymptotic paths, geodesic paths, construction-aware-design, lightweight structures, parametric design, active bending, architectural geometry

1. Introduction

Lattice shells are highly efficient structures that offer sustainable construction methods from rigid or bent timber elements. Due to their complex, double-curved geometries, grid shells have always been challenging to plan and construct, limiting their applications to unique structures rather than finding widespread use. The paper uses the method of differential geometry to analyze and innovate gridshell construction. We here give a short overview of the relevant parameters and relationships of geometry and construction.

1.1 Geometric background

There is a close link between differential geometry and construction, which can be used to analyze and control the curvature of individual components, thus simplifying construction. *Architectural geometry* has introduced diverse methods to rationalize the network geometry and generate repetitive parts and parameters [1]. The linear elements that compose a gridshell are represented as curves on a design surface. When analyzing the curve, the information on the direction and the orientation on the surface are combined to construct the *Darboux frame* at any point on the curve [Fig. 1]. This frame consists of the normal vector n, the tangent vector t and its cross-product u. The curvature around these three axes can be measured and is described around u as normal curvature κ_n, around n as geodesic curvature κ_g and around t as geodesic torsion τ_g. There are two special cases [Fig. 1]: if a curve follows a path of constant normal curvature $\kappa_n = 0$, it is asymptotic. These can only exist on flat or negatively curved surfaces. If the paths are constrained by $\kappa_g = 0$, the curves are geodesic curves. With $\kappa_n = 0$ or $\kappa_g = 0$, a grid shell can be constructed from straight planks that are oriented either tangent (geodesic) or perpendicular (asymptotic) to the design surface. To fabricate elastic gridshells, following these curves, the choice of cross-section and the bending stiffness in the according axes (EI_T, EI_y, EI_z) is decisive for controlling the deformation of the elements and is well described in *compliant grids* [2]. Triaxial-compliant cross-sections have the same bending strength around both axes and can bend around κ_n and κ_g [Fig. 1]. Cross-sections with biaxial compliancy (flat cross sections) have less bending strength around one axis [Fig.1]. The bending can be easily restricted to this side. Profiles that range between these two extremes behave proportionally. Elements with no compliancy are rigid.

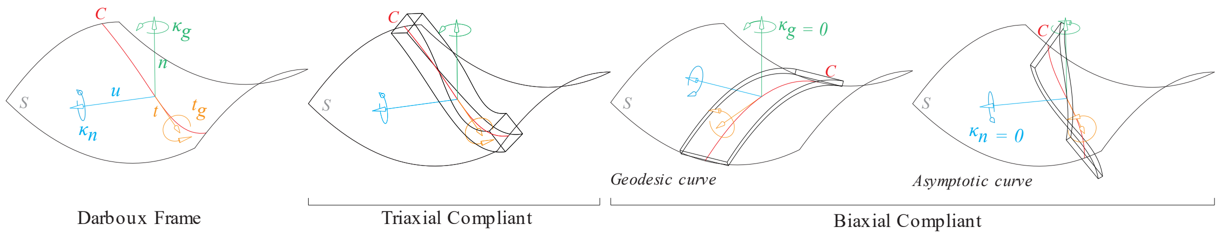

Figure 1: The *Darboux* frame depicting the three curvatures τ_g, κ_n, κ_g of a curve on a surface. Triaxial-compliant cross section. Biaxial compliant cross-section as Geodesic and Asymptotic curve.

Over time, various methods have been developed to simplify and facilitate the construction of timber grid shells ranging from elastically deformed to the assembly of rigid components.

1.2 Elastic Gridshells

This approach uses material elasticity to deform initially straight cross sections into the design shape. Based on the deformation properties described above, the following categorizations are introduced.

Triaxial compliant gridshells such as the well-known Multihalle Mannheim [3] by Frei Otto, a grid of 5x5 cm timber laths was laid out flat and pushed into shape. For later examples, such as the Weald and Downland Gridshell [2] or the Savill-Garden Gridshell [3], a flat grid was lowered into shape. For these methods, it was important that the laths could deform freely. Therefore, more uniform cross-sections were chosen.

Biaxial compliant gridshells refine this strategy by bending and twisting, curved or straight, flat cross-sections around their weak axis. An example of a curved flat cross-section bent into shape is the recently built Wisdome [4]. Initially straight planks thus follow either (pseudo-) geodesic or asymptotic paths on the design surfaces. The principle of *geodesic gridshells* is used in the many *ribbed timber shells* mainly developed by Julius Natterer, such as the Polydôme [5]. *Asymptotic grid shells* are built from lamellas orientated perpendicularly on the design surface. The first timber construction built using this method was the Asymptotic Timber Prototype in 2016.[6] Recently, an approach was developed to combine asymptotic and geodesic lamellae (AAG) in a hybrid gridshell shell [7], tested in the Asymptotic Geodesic Timber Vault (AGTV) in 2022 [8] [9]. The paper aims to distill the potential of this new AAG construction by comparing it with common timber construction approaches for gridshells.

1.3 Rigid Gridshells

Most of the techniques named above involve constructing and deforming the entire structure on-site. Today, the prefabrication of components and even whole modular units, easily assembled on-site, is becoming increasingly prevalent and integral to *Construction 4.0* [10]. The *design for assembly* [11] method is based on a high degree of prefabrication and has been used for Gridshells such as Shigeru Ban's Centre Pompidou Metz [12]. The complexity of the overall geometry is broken down into highly complex components using modern parametric software, while modern CNC milling enables the fabrication of these. However, this also leads to a high amount of waste, which weakens the potential material efficiency of grid shell structures.

This paper examines four large-scale Gridshells representative of the named categories. We systematically analyze the entire construction workflow and distill advantages and disadvantages, which will be compared with the novel AAG gridshell system. In section 2, we provide a brief overview of four references addressing network design, material selection, and construction specifics. Subsequently, we systematically analyze fabrication and assembly methods, tracing the process from raw material to the final curved shape. Additionally, we introduce the experimental prototype of the Asymptotic Geodesic Timber Vault. In Section 3, we compare our findings with the innovative construction strategy of AAG gridshells, highlighting both challenges and opportunities. We conclude in section 4 with potential developments and research gaps for timber gridshell construction.

2. Analysis of selected reference projects

2.1 Elastic, Biaxial Compliant Gridshell: Polydôme Lausanne

The Polydôme in Lausanne (1991) is one of many timber gridshells built with the *ribbed timber shell* approach, mainly developed by the engineer Julius Natterer [5]. Together with the architect Dan Badic, the shell geometry was designed as a calotte. Natterer's approach follows the constructive idea of stacking and deforming straight planks of wood on top of each other along the weak axis. They follow geodesic lines on the shell surface. The spacing between the curves was partially densified to ensure equal utilization for all members [Fig. 2]. [5]

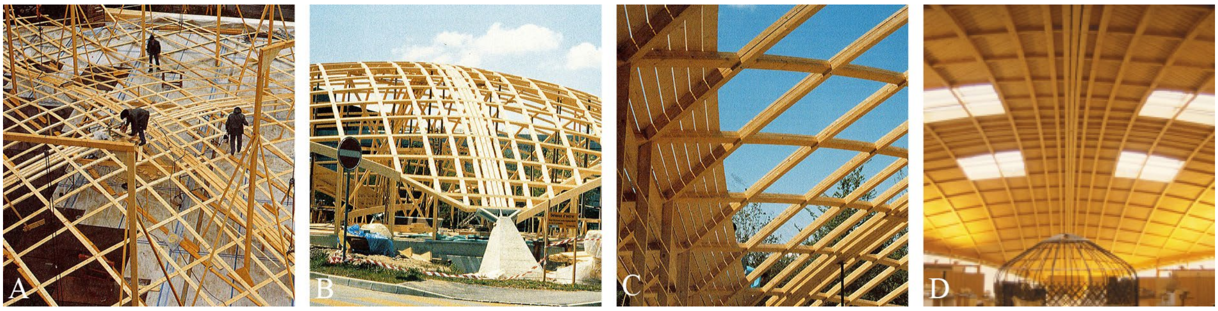

Figure 2: (A) Flat assembly of the planks, bending the grid by gradually adding layers and lifting [13]. (B) The deformed grid, with scaffolding/measures inside to determine the shape [13]. (C) Installing the cladding from the edge inwards [13]. (D) Interior view of the completed Polydôme [5].

Spruce cross-sections of 27 x 120 mm were used for the structure. The timber was finger-jointed to a maximum length of 19 m and transported to the construction site. The planks were scribed, drilled, and assembled on-site. To achieve this, the boards were stacked as a flat grid. The elements were joined at the corresponding intersections starting from the center, gradually inducing the designated curvature into the elements [Fig. 2]. Simultaneously, the filler boards in between were installed from the inside out. Gradually, the curvature formed, and the entire structure was slowly lifted into the desired shape, and the layers of planks were screwed together to maintain the shape. Finally, the edge beams were installed [Fig. 2]. Planks running diagonally to the grid were mounted on top of the structure, bracing the structure and providing a sublayer for insulation and cladding [Fig.2].[13] The erection process has been further developed over time. The deformation through lifting caused the shape to be manually controlled on-site. To gain more accuracy, later ribbed shells were fabricated on a falsework [5].

Benefits and challenges

Ribbed lattice shells have already proven their potential in numerous built examples. One advantage is that the entire system can be made from simple board cross-sections. By stacking the flat cross-sections, inhomogeneities and defects, like knots, are compensated. Furthermore, no complex processing of the components is necessary. The fabrication is limited to cutting, drilling and screwing. This means that constructors without a large machine park can build this type of construction. However, one disadvantage of the system is that the deformation of the structure can only be carried out on the construction site or in the immediate vicinity. This can lead to inaccuracies, which can affect the deformation process. Furthermore, construction and deformation can take several weeks. During this time, the timber must be protected from environmental influences by covering it or using a temporary roof. During the deformation process, additional measures are required to control the form. Alternatively, a falsework is used to bend the elements directly into the correct shape, which is a significant effort. However, in the case of serial production, such as for the Expo roof [5], this approach can provide an efficient and accurate solution. Although the approach was often built until the early 2000s, the built projects have declined significantly. This may be due to the high amount of manual labor involved. However, this construction approach still has great potential for sustainable timber production, especially with advancements in modern timber construction and prefabrication techniques.

2.2 Elastic, Triaxial Compliant Gridshell: Savill Garden

An illustrative case that aligns with the developmental trajectory of the Multihalle Mannheim [3] and the Weald and Downland Gridshell [14] is the Savill Garden Gridshell, completed in 2005. Glenn Howells Architects and HRW engineers developed a gridshell-roof, covering an area of 1.800 m [15]. The shape can be described as a sinusoidal doubly curved surface with three dome-like rises. The curve network was designed as a regular grid with the same edge length. Fabrication parameters, like bending around both axes of the cross sections, were evaluated during the design process. [16]

Figure 3 (A) Scarf-jointing the laths on site [16]. (B) Flat assembly of the grid on a scaffold and adding shear blocks [16]. (C) Lowering the scaffold and grid [17]. (D) Interior view of the finished Savill Gridshell [16].

The architects decided to use regional Larch from the Crown Estate's woodlands. After cutting, the Timber was sorted visually, defects and knots were cut out, and the pieces with an average length of 0,6 m were then finger jointed to laths of 80 x 50 mm cross-section and 6 m length. The parts were then brought to the construction site and divided into two categories regarding their quality. The higher-grade timber was used for the grid and scarf jointed to laths up to 36 m [Fig. 3], while the lower-grade timber was used for the shear joints. The scarf-jointing of the laths, together with all drillings and the erection process, was done manually on-site. The constructors used a temporary polytunnel to work in a controlled environment for jointing.[18]

The Savill gridshell was deformed by only assembling the bottom grid flat on a scaffold and adding the shear joints [Fig. 3]. By precisely lowering the grid, it was bent into shape [Fig. 3]. The roof was checked at 200 Points across the construction to ensure the shape was close to the design. Finally, the two upper laths forming the top grid were bent onto them. The bottom and top grids are two families of continuous laths crossing on top of each other. The vertical connection with separate shear blocks strengthens the out-of-plane stiffness, so the two separate layers act as one larger cross-section. A simple bolt joint connects the bottom and the top grid. The shear blocks were fixed with screws.[16]

Benefits and challenges

The construction method employed in the Savill Garden Gridshell exemplifies the feasibility of realizing large free-form surfaces through the comprehensive deformation of the grid. Nevertheless, the preparation process is highly intricate. The tasks involve cutting out the weak points, resulting in substantial waste production and labor-intensive preparation. Additionally, the design necessitates manual extension of the wooden elements on-site using scarf joints. Assembly of the structure can only be done on-site, followed by the deformation process. A scaffolding system capable of facilitating the lowering mechanism is needed. Manual deformation and the subsequent adding of various layers may introduce inaccuracies, mandating constant manual measuring of the shape during the lowering process. Like the construction challenges encountered with the Polydôme in Lausanne, the elements were exposed to the environment throughout construction. However, the controlled deformation and the implementation of a rigid steel ring have proven effective in ensuring the shape and enabling precise integration of other elements, such as glass facades. Consequently, the construction method underscores the contemporary applicability of the system. Nonetheless, the needed construction effort likely limits its application to primarily unique structures.

2.3 Rigid Gridshell: Centre Pompidou Metz

Individually curved rigid components have been utilized in several timber grid shells, many of which were designed by architect Shigeru Ban. One notable example is the Centre Pompidou in Metz, developed in collaboration with Arup and Hermann Blumer. The parametric design concept was primarily developed by designtoproduction GmbH [19]. Built in 2010, the museum spans 8.500 m² and is one of the most renowned examples of this innovative construction technique.

The initial form was found to be a minimal surface. A regular flat tri-hex grid was projected on the design surface to create a curved network. [20] This approach was not geometrically optimized, resulting in highly diverse curvature radii of all three categories: geodesic-, normal curvature, and torsion.

Figure 4: (A) Pre-bent, milled, double-curved beams [21]. (B) The entire construction process necessitated scaffolding for measurement and assembly [22]. (C) The prefabricated curved elements are gradually assembled on the construction site [18]. (D) Interior view of the Centre Pompidou Metz [21].

The design posed a difficult challenge for fabrication. The timber constructor suggested the solution to mainly mill oversized timber cross-sections into the double curvature using modern CNC technology [Fig. 4]. Although this meant that the shape could be produced very precisely, it also weakened the parts due to cutting the grain of the timber. For highly curved components, the parts were pre-bent before milling so that the timber grain remained within a defined of the beam axis. [21]. This method was chosen because it was the cheapest, fastest, and most accurate approach [18].

The fabrication concept envisaged an elementisation of the construction and maximum prefabrication of the components at the timber constructor. The bottleneck for the prefabricated components was the transportation from the production hall to the construction site [11]. This limited the double-curved elements to a maximum length of 14 m and correspondingly shorter for higher curved elements, as they took up more space in width/height during transportation. The 45.000 double-curved parts were brought to the construction site and assembled on a falsework [Fig. 4].[18]

The gridshell consists of four layers of curved beams with a dimension of 140x440 mm connected at the intersection points and in between with shear connectors. The grid and the edge beams are made of glued laminated timber (spruce). At points where the structure reaches the ground, the material switches to larch due to its better resistance to environmental conditions. The components require rigid connections for assembly. This was achieved using two planar slotted plates and steel dowels, which are intricately milled into the double-curved beams to ensure a secure fit. Hexagonal LVL (Laminated Veneer Lumber) dowels at the intersection points provide a robust connection, secured by a 24 mm bolt. The shear connectors, made of CLT, connect the layers between the crossing points.[21]

Benefits and challenges

The precision inherent in the construction approach of the Centre Pompidou in Metz is notably high. Standardized glulam serves as a homogeneous building material, allowing the integration of curvature into individual components, which then require assembly on-site. This facilitates the production of nearly any free-form grid. However, complexity is shifted to the planning phase, demanding intensive cooperation and extensive skills from planners. Moreover, only constructors equipped with state-of-the-art machines can manufacture this construction. The approach also presents other limitations. Firstly, it results in significant material loss due to component milling. Secondly, the transport of curved components is inefficient and may necessitate numerous truck transports depending on the design. Despite offering a wide range of potential applications, the disadvantages of the manufacturing method regarding material consumption and transport should not be overlooked. Incorporating the geometric deformation properties of cross-sections in future endeavors could lead to a reduction in material consumption.

2.4 Rigid / Elastic, Biaxial Compliant Gridshell: Wisdome Stockholm

A recently built example was opened in Stockholm in 2023 as an extension for a museum, the Wisdome. The initial shape was designed by the architect Elding Oscarson and DIFK engineers. An orthogonal planar grid is projected onto the design surface, forming the initial gridshell net. Then, an iterative optimization process was done to match the base grid and maximum normal curvature κ_n and geodesic torsion t_g for the intended lamellas cross-section. Subsequently, five offset geometries were generated from the reference geometry, representing every layer of beams. All beams are made from five layers of 31 mm LVL (laminated veneer lumber), with widths of 380 – 500 mm. Only the bottom layer was fabricated rigidly and served as falsework. The other layers were bent elastically onto the first layer on-site. Two newly developed dowel joints were created to connect the layers. The cross-dowel joint connects the lamella layers at the intersection points. The shear-dowel joint connects lamellas running above each other. [23] [4]

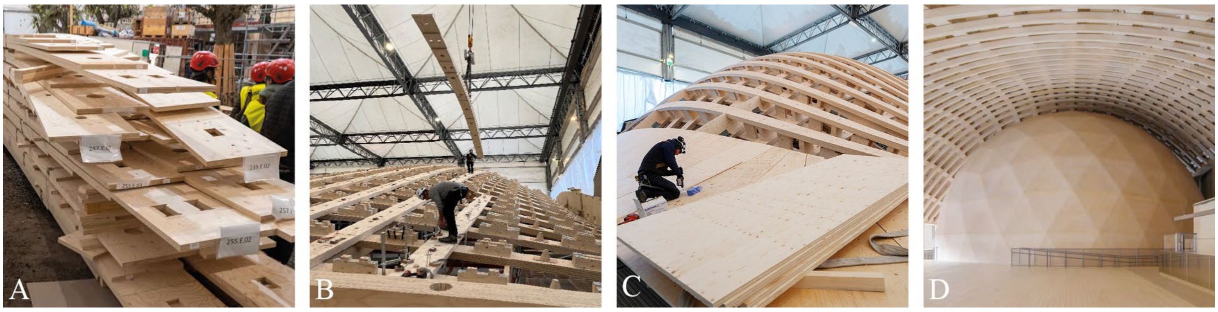

Figure 5: (A) On-site, prefabricated panels are cut, milled, and labeled with their respective cross-sections.[24]. (B) The pre-bent bottom layer is mounted with cross-/shear-dowels, and the next layer of lamella is bent on top of the bottom layer [23]. (C) Panels for the cladding are installed [25]. (D) Interior view of the Wisdome [24].

Due to the grid being projected onto the curved surface, the curves exhibit geodesic torsion, geodesic and normal curvature. The geodesic curvature in the components was fabricated by cutting curved planks from LVL boards. Afterward, these curved members were bent around their weak axis, normal curvature, and geodesic torsion to form the desired shape.

The components were mainly prefabricated. Specifically, the slats' cutting, the bottom layer's pre-bending, and all millings for dowels, plates and washers [Fig. 5]. The assembly was carried out on-site. Therefore, the entire construction site was covered with a temporary tent, including a gantry crane, to operate independently of environmental influences [Fig. 5]. The precise positioning of the bottom layer was ensured by using a template on a scaffold. The slats of the other four layers were then gradually bent in shape by using self-weight, manual pushing, and screw clamps [Fig. 5]. The elements were transported by truck from the production hall to the construction site. Due to its geometry, the double-curved beams of the lowest layer required a significant amount of space for transportation and, as a result, had to be delivered to the construction site in multiple shipments. The other parts were limited to a maximum length of 13 m due to the maximum transport length of the trucks. [23]

Benefits and challenges

The construction method employed for the Wisdome bridges the methods of the Polydôme and the Centre Pompidou Metz. The goal was to achieve an optimal mix of prefabrication and on-site construction while maintaining high precision. The rigid bottom layer determined the form for the elastically bent layers on top. No additional falsework was needed. However, the on-site construction process also has the disadvantage of exposing elements to environmental conditions. Here, a tent was erected over the construction site to provide protection, enabling working anytime. Like the Centre Pompidou in Metz, complexity primarily lies in the planning and pre-production phases, requiring highly qualified planners and constructors. As the planks do not follow geodesic lines, they had to be cut curved from LVL boards, resulting in material waste despite optimization efforts. This could potentially be mitigated through a geometrical approach to network design. Nevertheless, the project represents a promising method for combining prefabrication with an active deformation of the lamellas on-site.

2.5. Elastic, Biaxial Compliant Gridshell: Asymptotic Geodesic Timber Vault

The Asymptotic-Geodesic-Timber-Vault (AGTV) utilizes controllable deformation of biaxial-compliant cross-sections. The experimental prototype combines horizontal and vertical planks in a negatively curved gridshell. It was designed as a triple-symmetric dome consisting of three negatively curved shell modules [Fig. 6]. The gridshell network was geometrically optimized to be an AAG grid with a constant intersection angle (60°), and geodesic boundaries at the bottom and sides. The design is based on a triangular web consisting of two families of asymptotic curves and one triangulating family of geodesic curves. The geodesic curves were shifted to the middle of the grid, resulting in a tri-hex pattern, allowing decentralized joints and halving the length between each joint to prevent buckling. [8] The lattice shell consists of 25 x 100 mm ash planks, which have been split again to obtain thinner (12x100 mm) and more deformable cross-sections. The 60° intersection angle between the asymptotic families allowed a standardized 24 cm hexagonal pin joint connecting the upper and lower asymptotic lamellas. The geodesic lamellas were joined to the asymptotic grid with simple rectangular timber blocks between the asymptotic twin-lamellas. [8]

Figure 6: (A) Pre-bent asymptotic twin-lamellas. (B) Flat assembly and lifting/pushing the grid into the desired shape, the geodesic lamellas slide smoothly through the AA-Grid. (C) The modules were transported to the construction site and assembled with the other modules. (D) Interior view of the finished vault

The slats were cut to the correct length and the holes were drilled. Two parallel lamellas were bent and coupled for each asymptotic beam, embedding their geodesic curvature [Fig. 6]. Following this step, the grid was assembled flat from two families of curved asymptotic beams and geodesic slats placed loosely in between. The grid was then elastically deformed into the spatial geometry by hoisting and pressing [Fig. 6]. Finally, the geodesic and edge lamellas were bolted, and the form was fixed. The modules were brought to the construction site, installed onto precast concrete supports, and connected at the ridge [Fig. 6]. To form a triple symmetric dome (10 m outer diameter and 6 m internal span). The construction was covered with polycarbonate sheets, fixed with aluminum strips running along geodesic lines.[8] The modules were built in a workshop close to the construction site and moved manually onto the site using trolleys. After six months, the AGTV was deconstructed and moved to the premises of Holzbau Amann GmbH to aid in future research development. For this purpose, the facade was disassembled, and each shell was divided into three segments (a total of 9), which could be transported in one truckload. In the following chapter, we will compare the benefits and challenges of the AGTV with the other references.

3. Analysis and comparison of the reference projects with the AAG method

In contrast to the examples previously shown, where component deformation has to be guided by scaffolding, the AAG approach primarily represents innovation. The directed kinetic behavior facilitates construction, allowing the flat grid to be shaped without falsework. The asymptotic lamella pattern and scissor rotation at the joints determine the kinetic transformation. This approach can be scaled up to accommodate large-spanning roof structures. However, this kinetic deformation also necessitates maintaining a delicate balance between tolerances and industry construction standards. Furthermore, the active deformation of the lamellae results in prestressing, which limits the curvature radius and creates additional residual stresses. Due to the relaxation effect, these stresses gradually diminish over time.[9]

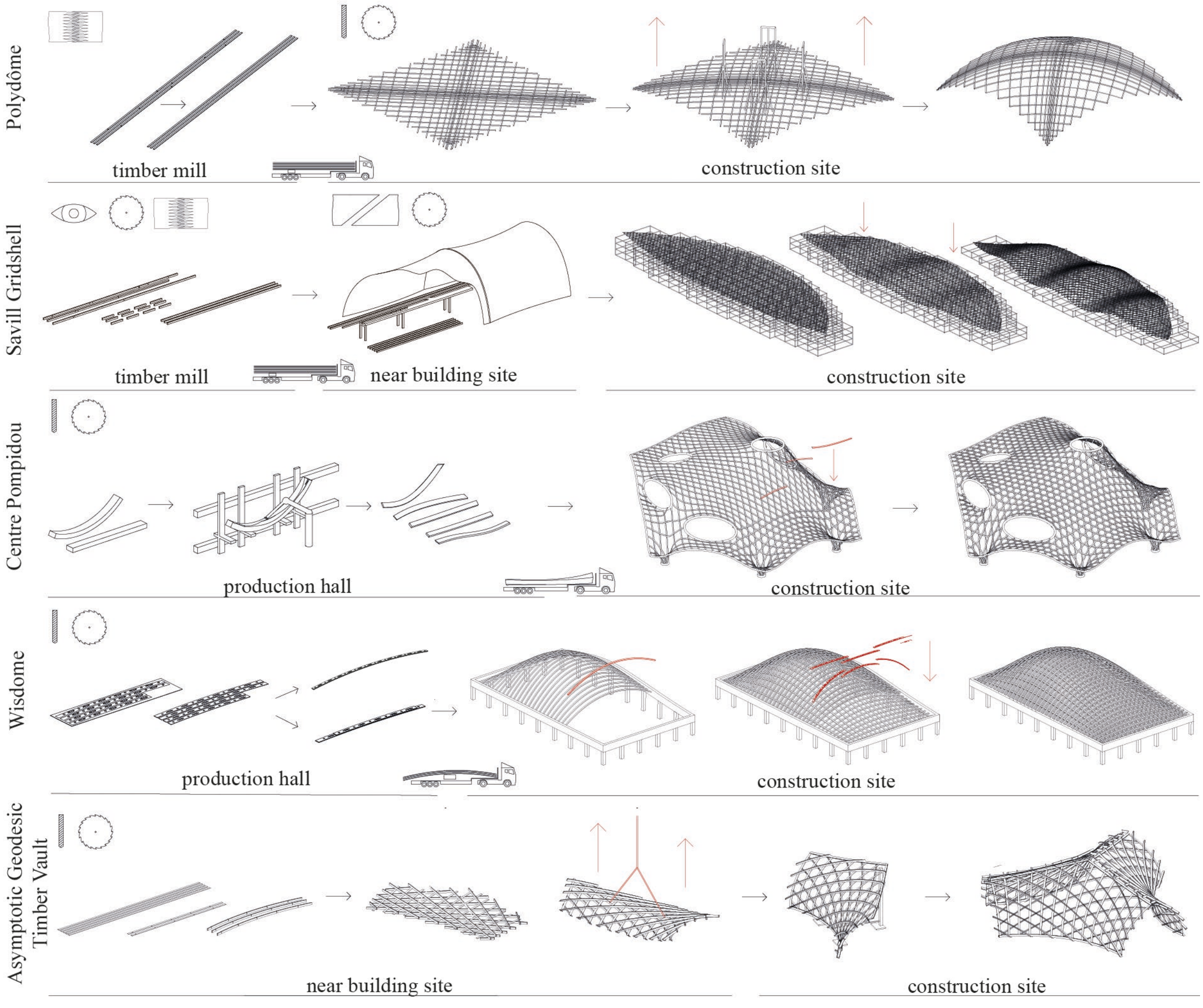

Figure 7: Fabrication and construction methods of the analyzed gridshells

Like in the Polydôme in Lausanne or the Savill Gridshell, originally straight cross-sections can be used for production [Fig. 7]. The elasticity of the lamellae is crucial for the overall deformation. More material homogeneity results in a higher predictability of deformation. For the AGTV, knot-free ash wood was used. However, a larger-scale application poses the challenge of dealing with wood material defects. Strategies like doubling the planks, as in the Polydôme, could be pursued, or more homogenous plywood, such as in the Wisdome project, could be used. The Savill Gridshell approach of cutting defects and knots out of the timber is less suitable due to the great effort involved and the resulting waste.

The AAG approach is not limited to in-situ production, as entire pre-curved modules could be prefabricated. However, as with the Centre Pompidou Metz or the Wisdome, transportation becomes a bottleneck for module size. Similarly, the length of the slats is also limited by the transport [Fig. 7]. Strategies for joining or lengthening the cross-sections must be considered for larger applications.

A hybrid approach like the Wisdome in Stockholm could be more promising, emphasizing maximum pre-production of elements to expedite assembly and molding on the construction site.

Constructively, the AAG method is more challenging. Whereas previous examples dealt with horizontal or broad cross-sections that could be easily connected vertically, the combination of horizontal and vertical slats running on top of each other requires the joints to mediate between these two extremes. This complexity necessitates precise planning and investigation of the deformation process and collisions. However, the type of connection can then be realized with simple drill holes and screws.

Overall, the AAG approach shows potential for prefabricated modular timber shells in terms of its efficient use of timber planks, utilizing their strong axis to create stiffness, and its unique deformation behavior to simplify the erection process. However, further research is necessary on the detailing and testing of the use of other timber species, improving detailing and approval processes, and minimizing tolerance in the deformation process. These challenges are currently addressed in collaboration with the industrial timber manufacturer Holzbau Amann GmbH, aiming to create an industrial fabrication process for curved timber gridshells.

Conclusion

This paper analyzed five different strategies for the production and fabrication of four large-scale timber grid shells and the novel AAG method. The *timber ribbed shells* by Julius Natterer already demonstrated that an approach to building double-curved timber structures can have broader applications. Since then, however, there has been an increasing trend towards more precise planning and manufacturing, constantly attempting to simplify the molding process and reduce manual production. The current possibilities in parametric CAD planning allow for accurate design. The modern timber construction industry can realize this precision. The combination of asymptotic and geodesic lamellas simplifies the forming of negatively curved grids. However, strategies must be developed to balance deformation and tolerance, appropriate prefabrication and construction on site, a suitable choice of materials, and easier joining to apply this method on a larger scale.

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References

[1] H. Pottmann, A. Asperl, M. Hofer, and A. Kilian, *Architectural Geometry*. Bentley Institute Press, 2007.

[2] J. Schikore, "Compliant Grids Theory, Design and Realization," Technical University of Munich, Munich, 2023.

[3] E. Happold and W. I. Liddell, "Timber Lattice Roof for the Mannheim Bundesgartenschau," *The Structural Engineer*, vol. 53, no. 3, pp. 99–135, Apr. 1975.

[4] M. Niebler, S. Usai, M. Antemann, F. Scheurer, and E. Slabbinck, "Bent-on-site flat-pack delivery of a timber shell," in *Advances in Architectural Geometry 2023*, De Gruyter, 2023, pp. 69–82. doi: 10.1515/9783111162683-006.

[5] J. Natterer, N. Burger, A. Müller, and J. Natterer, "Timber rib shells made of stacked planks," *Bautechnik*, vol. 77, no. 11, pp. 783–792, 2000, doi: 10.1002/bate.200006410.

[6] E. Schling, "Eike Schling Repetitive Structures. Design and construction of curved support structures with repetitive parameters," Technical University Munich, Munich, 2018.

[7] E. Schling, H. Wang, S. Hoyer, and H. Pottmann, “Designing Asymptotic Geodesic Hybrid Gridshells,” *CAD Computer Aided Design*, vol. 152, Nov. 2022, doi: 10.1016/j.cad.2022.103378.

[8] E. Schling, Z. Wan, H. Wang, and P. D’Acunto, “Asymptotic geodesic hybrid timber gridshell,” in *Advances in Architectural Geometry 2023*, De Gruyter, 2023, pp. 97–110. doi: 10.1515/9783111162683-008.

[9] Z. Wan, P. D’Acunto, and E. Schling, “Structural behaviour of asymptotic geodesic hybrid timber gridshells,” *Eng Struct*, vol. 308, Jun. 2024, doi: 10.1016/j.engstruct.2024.117918.

[10] H. Rhomberg, “Construction 4.0: The LifeCycle Tower and Digitalised Timber Construction,” 2018, pp. 373–384. doi: 10.1007/978-3-319-50079-9_26.

[11] F. Scheurer, H. Stehling, F. Tschümperlin, and M. Antemann, “Design for Assembly-Digital Prefabrication of Complex Timber Structures,” in *IASS Symposium*, 2013.

[12] Shigeru Ban Architects, “Centre Pompidou Metz.” Accessed: Apr. 05, 2024. [Online]. Available: https://shigerubanarchitects.com/works/cultural/centre-pompidou-metz/

[13] M. Hoeft and J.-F. Kaelin, “Ausstellungspavillon in Brettstapelbauweise,” *Fachbeilage zum Schweizer Baublatt Nr. 2*, 1992.

[14] R. Harris, J. Romer, O. Kelly, and S. Johnson, “Design and construction of the Downland Gridshell,” *Building Research & Information*, vol. 31, no. 6, pp. 427–454, Nov. 2003, doi: 10.1080/0961321032000088007.

[15] G. Tang, J. Chilton, and P. Beccarelli, “Progressive Development of Timber Gridshell Design,” in *Proceedings of the IASS Symposium*, Wroclaw, 2013.

[16] R. Harris, J. Roynon, and H. Bath, “The Savill Garden Gridshell Design and Construction,” in *10th World Conference of Timber Engineering*, Jun. 2008.

[17] “Savill Gardens,” *Building For A Future*, Jul. 2006. Accessed: Apr. 12, 2024. [Online]. Available: https://www.fourthdoor.org/annular/annular-archive/britain/17-2/

[18] J. Chilton and G. Tang, *Timber Gridshells: Architecture, Structure and Craft*. New York: Routledge, 2017.

[19] designtoproduction GmbH, “Centre Pompidou Metz.” Accessed: Apr. 05, 2024. [Online]. Available: https://www.designtoproduction.com/

[20] B. Lewis, “Centre Pompidou-Metz: engineering the roof,” *The Structural Engineer*, vol. 89, no. 18, pp. 20–26, 2011.

[21] “Centre Pompidou-Metz,” in *DETAIL*, vol. 10, 2010, pp. 1040–1045.

[22] M. Golini, “PHOTOS. La construction du Centre Pompidou-Metz ,” Le Republican Lorrain. Accessed: Apr. 12, 2024. [Online]. Available: https://www.republicain-lorrain.fr/edition-de-metz-ville/2017/07/17/photos-la-construction-du-centre-pompidou-metz

[23] E. L. Slabbinck, H. Blumer, S. Rick, D. Riggenbach, M. Antemann, and F. Scheurer, “Integrative approach to a timber gridshell formed on-site,” in *Proceedings of the IASS Annual Symposium*, Melbourne, 2023.

[24] P. Ayres, M. R. Thomsen, B. Sheil, and M. Skavara, *Fabricate 2024*. UCL Press, 2024. doi: 10.14324/111.9781800086340.

[25] A. Wennberg, “Nu avtäcks Stockholms nya landmärke i trä,” Stockholms BYGGNYHETER. Accessed: Apr. 12, 2024. [Online]. Available: https://www.stockholmsbyggnyheter.se/20230508/5679/nu-avtacks-stockholms-nya-landmarke-i-tra