



INNOVATIVE SELF-SHAPING TIMBER CONSTRUCTION: THE WANGEN TOWER

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ABSTRACT:

The Wangen Tower, designed for the Landesgartenschau 2024 in Wangen im Allgäu, Germany, exemplifies the innovative potential of advanced timber architecture and engineering. Rising to a height of 22.5 meters, it is the world's first publicly accessible structure to utilize self-shaped cross-laminated timber (CLT) components. This groundbreaking project harnesses wood's hygroscopic properties to achieve complex curved geometries through passive self-shaping during drying, offering the potential to reduce material waste and energy consumption compared to conventional construction methods. The hyperbolic timber shell structure achieves an exceptional height-to-wall thickness ratio of 173:1, efficiently bearing all significant loads, including wind forces. The project integrated material-aware computational design, digital fabrication, and expert craftsmanship within a co-design framework to foster interdisciplinary collaboration throughout its development. Tailored structural connections minimized visible metal fasteners, enhancing the seamless timber aesthetic of the interior. Additionally, prefabrication strategies streamlined on-site assembly while ensuring precision and efficiency. The tower's distinctive twisting geometry not only provides structural stability but also establishes a striking architectural landmark that creates a visual connection with its natural surroundings. By overcoming stringent engineering and regulatory challenges—including achieving structural certification—the Wangen Tower advances self-shaped timber technology from experimental prototypes to scalable applications. Ultimately, by combining scientific research with innovative design and construction methodologies, this project broadens the architectural applications of advanced timber technologies.

KEYWORDS: Self-shaping Timber, Curved CLT, Co-Design, Computational Design, Digital Fabrication, Sustainable Architecture

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1 – INTRODUCTION

The construction sector accounts for a substantial portion of global carbon emissions and resource depletion, underscoring the need for more sustainable building practices. As a renewable material, timber sequesters carbon and enhances resource efficiency compared to traditional concrete and steel. However, conventional timber fabrication primarily relies on straight, prefabricated elements, restricting architectural design freedom and limiting the potential of complex geometries for high-performance structural applications [1]. Curved timber elements typically require mechanical bending, lamination, or milling, all of which increase material waste, energy consumption, and fabrication complexity [2]. Self-shaped cross-laminated timber (CLT) presents an alternative by utilizing wood's hygroscopic properties to achieve controlled curvature passively during the drying process, significantly reducing material and energy demands.

This paper presents the design, engineering, and construction process of the Wangen Tower, emphasizing material programming, structural optimization, and the co-design framework that enabled a collaboration between disciplines. The outcomes contribute to advancing self-

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Figure 1: The Wangen Tower standing in the Allgäu landscape, illustrating its distinctive hyperbolic form and showcasing the possibilities of self-shaped timber construction.

shaping timber beyond experimental prototypes, paving the way for scalable, sustainable, and high-performance applications in architectural design and construction.

2 – BACKGROUND

Curvature offers an opportunity to achieve structural performance by leveraging geometry rather than additional material or reinforcement [3]. While surface-active curved building components are predominantly realized in concrete or brick construction [4, 5], the construction industry's significant carbon footprint underscores the need for more sustainable material alternatives, with timber increasingly regarded as a promising solution. Wood, a locally available resource in Central Europe, offers a low environmental footprint and sequesters carbon when harvested responsibly. [6]. However, contemporary timber construction relies largely on standardized rectilinear products and regular grids, limiting its geometric variability [7]. While traditional methods to produce curved timber elements rely heavily on external machinery and formwork, self-shaping technologies leverage wood's natural hygroscopic properties to achieve curvature passively. This principle, analogous to the opening and closing of conifer cone scales, exploits the moisture-induced swelling and shrinking of wood fibers [8]. Through an anisotropic bilayered buildup, where CLT sheets are assembled with a controlled difference in wood moisture content (WMC), a passive shape transformation into predefined curvatures can be induced. The resulting curvature emerges from differential shrinkage perpendicular to the grain in one of

the layers during drying [9]. By laminating multiple 2-ply panels (bilayers), a structurally stable, multi-layered curved CLT element can be achieved [10]. Recent research has demonstrated that self-shaping timber technology can significantly expand the design space of timber construction, enabling previously unattainable geometries and architectural expressions. This potential has been explored through a series of built prototypes, each advancing the method's scalability and applicability. The Urbach Tower [11], completed in 2019, was the first permanent building to incorporate self-shaped components. In 2023, the Hygroshell pavilion [12] focused on in situ self-shaped components. Building upon these precedents, the Wangen Tower represents the first multi-story, walkable structure utilizing self-shaped CLT, demonstrating the technology's viability for long-term applications with a projected durability exceeding 20 years.

3 – PROJECT DESCRIPTION

The Wangen Tower is located in Wangen im Allgäu, Germany, as a centerpiece of the Landesgartenschau 2024, a national horticultural exhibition showcasing innovations in landscape architecture and sustainable building construction. The tower interacts with its scenic surroundings, forming an architectural landmark visible from key approach roads and railway lines around the site. Its twisting geometry responds to the landscape's contours, creating a natural focal point (Figure 1). The tower's site selection was a critical process, balancing visibility and environmental considerations. It had to avoid interfering

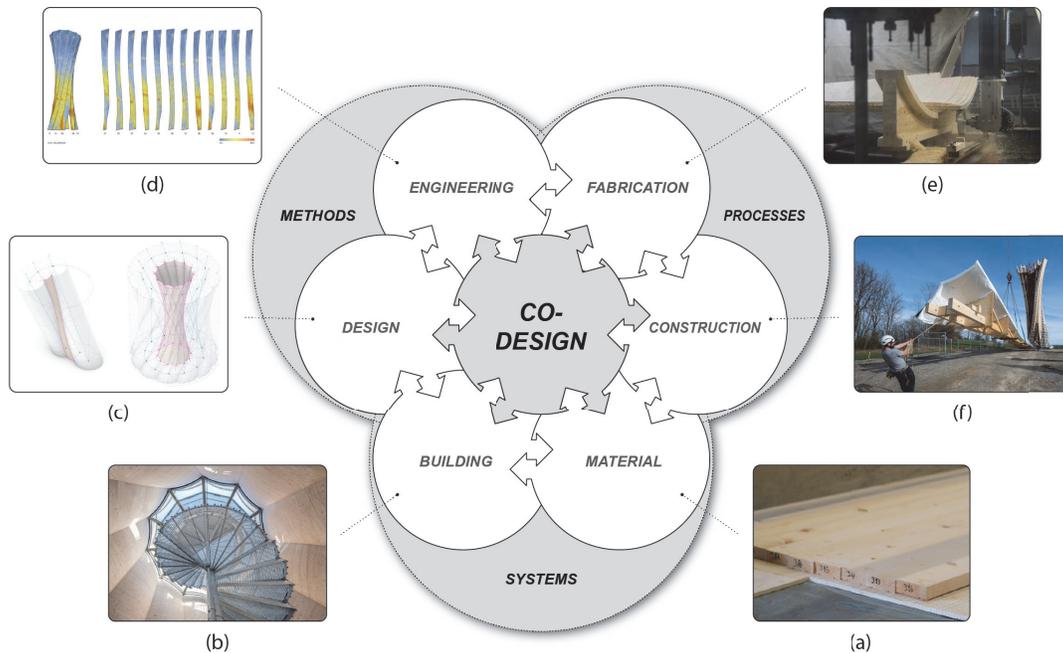


Figure 2: Co-Design process for the Tower design. (a) Material, (b) Building, (c) Design, (d) Engineering, (e) Fabrication, (f) Construction

with the geologically significant open drumlin landscape while maintaining distance from dense vegetation. This strategic placement was essential due to the tower's sensitivity to humidity, which could lead to structural issues, algae growth, and wood decay. Proper air circulation and controlled humidity were key factors in determining the tower's location to preserve its integrity and reduce maintenance costs.

The architectural concept effectively utilizes curvature as both a structural and spatial strategy, ensuring stability while creating a unique spatial experience. Although the twisted tower shell appears as a complex, free-form surface, it is designed using intersecting cylinders Figure (3). These cylinders, by definition, employ developable, single-curvature surfaces with zero Gaussian curvature. The use of intersecting cylinders offers a strategic design advantage: it leverages geometrically simple, single-curved shapes to achieve a visually striking form, balancing constructability with aesthetics spatial articulation. The twisted tower shell is built from timber, while a pre-fabricated metal staircase and observation platform enable public access to enjoy panoramic views of the surrounding landscape, and the snow-capped Alpine peaks. Meeting permanent building requirements posed unique challenges: the tower had to undergo Zustimmung im Einzelfall (Single Case Approval) (ZiE) approval, accommodate public accessibility, and transition self-shaped CLT fabrication from experimental setups to scalable industrial production.

4 – DESIGN PROCESS

Adopting a co-design methodology [13] was essential for developing solutions to construct an innovative timber building using a newly developed building system within

the required timeline. This approach, illustrated in Figure 2, involved iterative collaboration focusing on exchange across architectural design, material programming, structural engineering, fabrication, and construction planning. The co-design methodology, developed and explored in an Architecture, Engineering and Construction (AEC) context in the Cluster of Excellence 'Integrative Computational Design and Construction for Architecture (IntCDC)' at the University of Stuttgart, served as an overarching method for the project [13]. A focus on continuous refinement through detailing and execution, supported by feedback loops between disciplines, was critical to optimize integrative solutions for the project's specific challenges, which will be described further in this section. A close collaboration with the primary contractor, Blumer Lehmann, ensured practical technical solutions that ensured a swift construction while adhering to the project's architectural goals.

4.1 MATERIAL PROGRAMMING

The tower's cylindrical CLT components include self-shaped elements produced through a material programming process, embedding curvature into the material itself. This was achieved by bonding an 'active' layer (Figure 7 "a") with an elevated moisture content to a 'restrictive' layer (Figure 7 "b") that had already reached its final moisture level. By carefully controlling layer thickness, initial WMC, and the annual ring orientation of the boards, the target curvature was programmed. The suitable bilayer build-up in order to reach the target curvature was determined using a numerical approach based on Timoshenko's bimetal theory [9, 14] and further refined through physical testing. While alternative predictive methods have been developed and promise a higher accuracy [10, 15], they

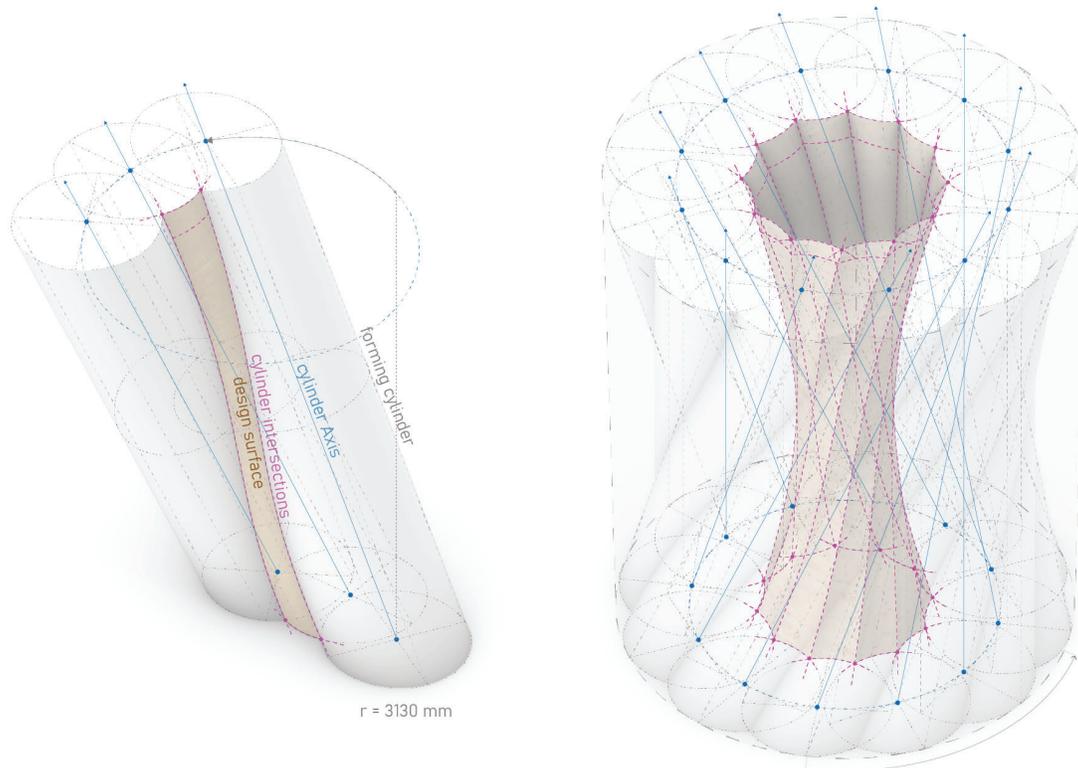


Figure 3: CLT Component modelling through cylinder intersection

also require significantly more data as input. Therefore, in this project the more accessible method was chosen - considering also that variations in curvature will be equaled out in the CLT lamination process.

An efficient and economically viable integration into industrial manufacturing processes was targeted throughout all steps of the self-shaped CLT production. The active layers were composed of 30-mm-thick locally sourced spruce with a year ring angle between 0 and 45° and only lightly air-dried before processing, maintaining a WMC above 20 percent. To streamline production, 10-mm-thick restrictive layers were obtained as edge-glued solid wood boards. These layers were bonded in a flat state using vacuum press application. Unlike conventional CLT manufacturing, where boards are kiln-dried prior to lamination, the spruce boards in this process underwent kiln drying only after being laminated into bilayers. The bilayers were dried in multiple batches over four to five days alongside standard industrial timber volumes, reaching a final WMC of 12 percent. During this process, the panels passively formed their programmed curvature on custom-designed drying racks, which ensured unrestricted deformation. To achieve the required wall thickness, three bilayers were laminated together and permanently fixed into the design shape with a 10 mm locking layer (Figure 7 "c"). This locking layer transforms the asymmetric setup of the CLT into a symmetric configuration, ensuring geometric stability under changing ambient moisture conditions.

4.2 BUILDING SYSTEM DESIGN

The Wangen Tower's timber shell consists of twelve curved CLT segments. The sectional view in Figure 5 shows the various structural and architectural elements composing the overall structure. These cylindrical CLT elements provide the tower with its signature spiraling form while bearing all significant loads, including wind, in a surface-active manner. Due to production constraints, each of the on average 23 m long CLT components is made up of three individual CLT elements. This means that the components are roughly divided into thirds along their longitudinal axis. The elements are connected with a newly developed, precision-milled, mono-material lap joint further described in section 4.3. These joints facilitate the seamless assembly of CLT components, maintaining both structural coherence and aesthetic purity. A two-part design of the steel feet enabled precise and efficient assembly on-site: the lower part was installed into the foundation, while the upper part was pre-mounted to the CLT panels at the factory. To further streamline construction, two CLT segments were pre-connected in the factory using cross-wise screwing, following a locally adapted pattern to ensure optimal structural performance (further described in section 4.3.2). This approach minimized on-site assembly time while maintaining a millimeter-precise fit for the 23 m long CLT components. On the exterior, 168 individually milled larch panels form a ventilated façade, augmenting durability and preserving material aesthetics. To reduce on-site construction time, most panels were pre-mounted

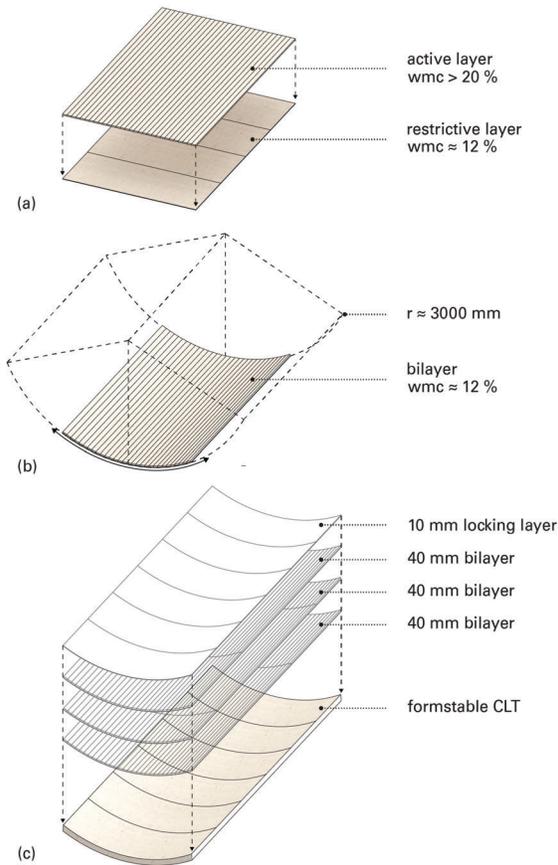


Figure 4: Self-shaping manufacturing of curved CLT. (a) Bilayer lamination in flat state. (b) Self-shaping during kiln drying. (c) CLT fabrication from three bilayers with one locking layer.

in the factory onto a batten- and counter-batten substructure. The individual panels for the facade were initially milled as planar elements and curved upon installation by being screwed onto a precisely fitted batten structure, layered over a facade membrane and the CLT components. Besides the structural CLT elements and the larch wood cladding, the Wangen Tower incorporates a metal viewing platform and a spiral staircase. The open-air platform at the top provides panoramic views while stiffening the CLT construction. Around the walkable area of the platform, a glass skylight introduces natural light into the interior, eliminating the need for artificial illumination (Figure 8). After the CLT structure was assembled, a prefabricated steel staircase was inserted vertically from above and establishes the connection between the platform and foundation, aligning with the tower's structural logic to ensure both stability and accessibility.

Together, these features reinforce the integration of architectural design and structural efficiency.

4.3 STRUCTURAL ENGINEERING

For an exposed tower structure of this height, the wind forces have the greatest influence on the structural design. The outer timber shell is designed to withstand all horizontal forces, in this case mainly wind, while also providing horizontal stabilization for the inner spiral staircase,,

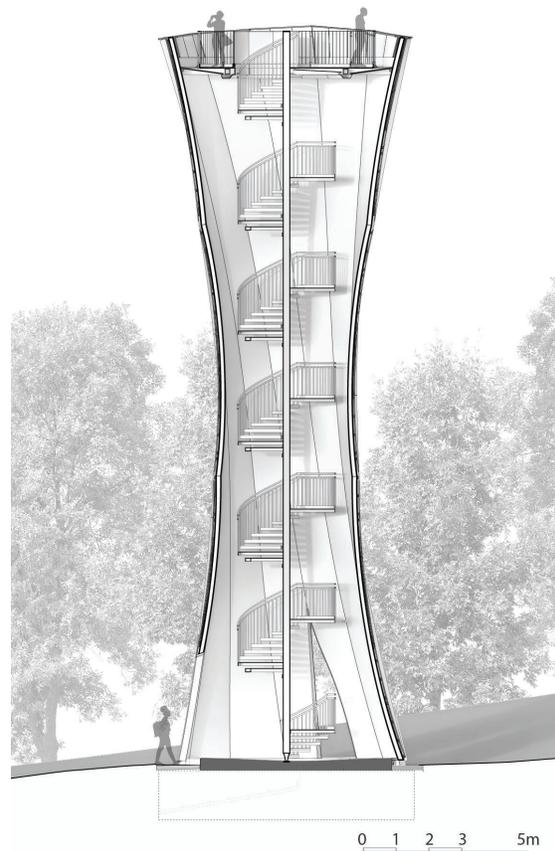


Figure 5: Section through the tower including the structural CLT skin, stair, and platform.

which transfers the majority of the vertical live-loads to the foundation. Due to these wind loads, the tower experiences bending and ovalization effects. The curvature of the elements provides the tower with additional stiffness, acting similarly to a corrugated sheet.

The “twist” of the elements gives the tower its unique appearance forming a hyperbolic shell structure. In addition to benefiting from surface-active load-bearing behavior, the wind attack surface is significantly reduced by the tapering in the middle of the structure to a minimum diameter of $D = 4.2$ m. Meanwhile, the hyperbolic shape allows for larger diameters at both the top and base, enabling a spacious observation platform with a diameter of $D = 7.8$ m, and providing more structural space for anchoring wind loads to the foundation.

To maximize the surface-active load-bearing capacity, the connections between the elements must provide high shear stiffness. The steel feet described in section 4.2 provide a particularly stiff connection between the tower and foundation by using glued-in steel rods in the CLT to limit deformations and ensure that the natural frequency remains above potential wind-induced resonance. The observation platform features a spoked-wheel layout composed of slender steel beams, functioning as a stiffening plate to prevent ovalization at the top of the tower caused by the acting wind loads.

As a unique structure incorporating self-shaped wooden

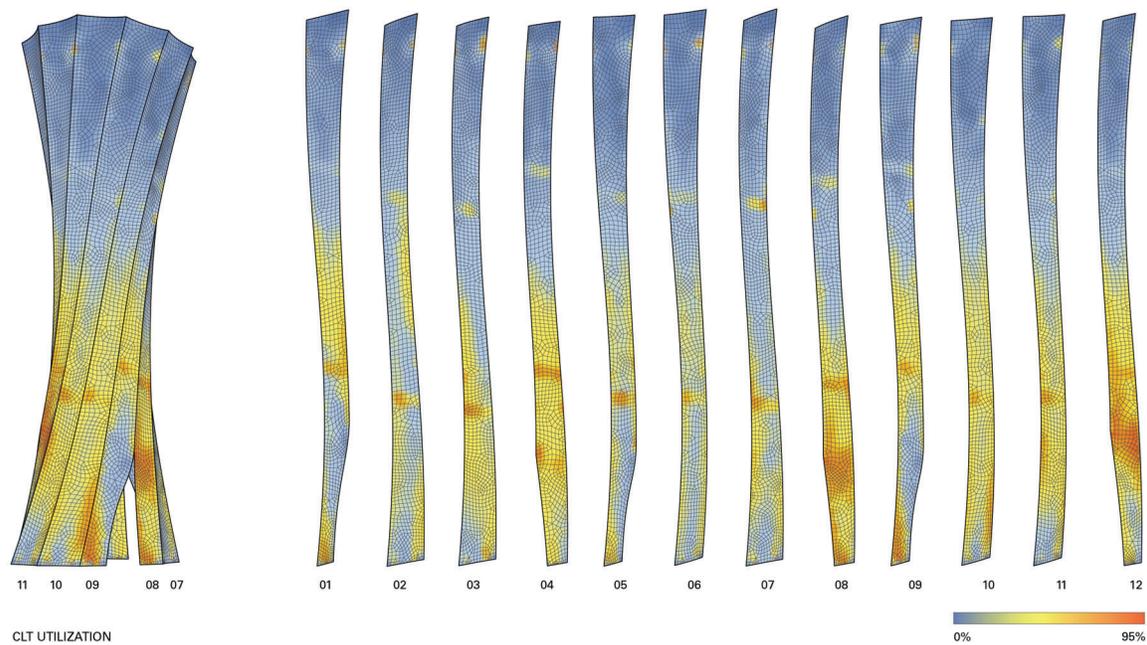


Figure 6: Finite element analysis: utilization of the CLT panels under maximum wind loads

components, which is publicly accessible, the used material and part of the designed connections required an assessment by the Materials Testing Institute (MPA).

4.3.1 Analysis and verification

The analysis of internal forces, deformations, and reaction forces was conducted using the finite element software SOFiSTiK 2023 under various ultimate limit state (ULS) and serviceability limit state (SLS) loading conditions, in accordance with DIN EN 1991 and its German national annex. Figure 6 shows the utilization of single CLT components in the tower. The timber elements were modeled using shell elements with stiffness properties derived from laminate theory, as specified in DIN EN 1995. Capacity verification was conducted using second-order theory, accounting for pre-deformations and imperfections derived from buckling mode shapes. The accuracy of the results is highly dependent on the stiffness properties of both the shell elements and the connections. To ensure realistic stiffness values, all connections were evaluated according to DIN EN 1995 or the corresponding technical approvals and modeled using spring elements. The complex geometry of the structure results in varying connection conditions, including different plate angles, fiber orientations, and screw-to-grain angles, necessitating a parametric approach for modeling the spring definitions.

4.3.2 Connections

To realize the hyperbolic shape, the twelve main timber components are connected to each other laterally where the seams form a crease. Given the complexity of the shape, these joints strongly influence the overall structural behavior. Connecting these slender, non-planar timber elements was not only geometrically challenging, but also required

keeping on-site assembly time-efficient. To perform this connection fully threaded screws arranged in a crosswise pattern have proven to be the most effective and adaptable solution in terms of geometrical flexibility, load-bearing capacity, assembly feasibility. Along the seams, the angle between two adjoining CLT elements varies between 118° and 138° along the tower's height. A uniform screw insertion angle of 70° between the crossing screw pairs, inserted from the outer surface, has been found to be practical and can be pre-drilled using a single template. With a screw diameter of $d = 6.5$ mm, this uniform 70° angle satisfies edge distance requirements along the entire tower height while ensuring maximum load-bearing capacity in shear strength and withdrawal resistance.

Due to the height of the tower and manufacturing constraints, the curved CLT elements had to be produced in three parts and connected in the factory using a rigid joint. A specially designed stepped laminated veneer lumber (LVL) lap joint was developed for this purpose, as displayed in Figure 7. The stepped LVL inlays were curved to match the CLT element radius and bonded using a gap-filling adhesive to compensate for any residual imperfections. The required pressing pressure was applied through screw press bonding. Based on computational and experimental investigations, the structural integrity was verified, and the necessary approval (ZiE) was granted.

For the interface between the wooden shell structure and the foundation or observation platform, custom-made steel connectors were designed and assembled using various joining strategies. The tower is connected to the foundation through an intermediate steel component, which is attached to the wooden shell using glued-in rods and anchored to the concrete foundation with embedded reinforcement bars. The beams of the observation platform rest on a steel connector embedded within the wooden



Figure 7: Assembly of the Stepped LVL lap joint at factory. (a) 'Active' layer; (b) 'Restrictive' layer; (c) locking layer.

shell cross-section, allowing for the direct transfer of vertical loads into the shell structure. Threaded steel bolts were chosen to connect the platform to the tower, enabling the transfer of both compression and tensile forces while ensuring the platform acts as a stiffening plate.

4.4 COMPUTATIONAL DESIGN

The interdisciplinary collaboration efforts were enhanced by a comprehensive computational framework. During conceptualization and design, advanced computational desing methods generated the tower's unique twisted geometry (Figure 3) while accounting for material behavior, fabrication constraints, and structural requirements. This framework streamlined information exchange across domains and facilitated iterative evaluations to align methods, systems, and processes (Figure 2).

As the project progressed to the detailing and execution phase, the framework evolved to handle high levels of detail. It coordinated stock-material distribution, fasteners, and material definitions, leveraging the precision of digital manufacturing at Blumer Lehmann's factory. This integration broadened the technical design space and therefore facilitated the solution of details.

Deploying these computational methods became instrumental to integrate input from different disciplines. The following subsections highlight two distinctive topics during the detailing phase: the positioning of the stepped LVL lap joint and the coordination of the skin substructure.

4.4.1 Stepped LVL lap joint positions

As discussed in Section 4.3.2, a stepped LVL lap joint was developed to connect the curved CLT components longitudinally, forming complete tower segments from three prefabricated parts. Regarding fabrication constraints, as illustrated in step "c" of Figure 4, 40 mm bilayers were lam-

inated to form raw bilayer components, which were subsequently milled into their final shapes. The placement of these raw components around the tower's design geometry determined the final position of the stepped LVL lap joint within the structure at the position where two raw components meet. This positioning influenced both the structural analysis and, similar to standard nesting processes, the amount of waste material generated.

To address these challenges and converge on a solution that balanced the fabrication constraints and structural performance, a computational model was employed to iterate through various design options. These iterations were mapped across three distinct fabrication states: the "Assembled Tower Space," the "Full Component Prefabricated Space," and the "Component-Part Lamination Space." Ultimately, the positioning of the raw bilayer components was adjusted to adhere to both manufacturing guidelines provided by the main contractor and structural engineering requirements. These engineering guidelines included constraints derived from finite element analysis, such as avoiding high-utilization zones under critical load cases and maintaining minimum distances from other connections and openings. Several iterations were needed, since the resulting arrangement always needed another loop of finite element analysis to confirm the adopted solution was viable.

4.4.2 Tower skin substructure

The facade was designed with a two-layer substructure, consisting of a first layer of battens that follows the component direction, and a second horizontal layer. The arrangement of the horizontal battens influenced three key aspects: assembly planning, the positioning of crosswise screws for on-site component connections, and the overall appearance of the facade.

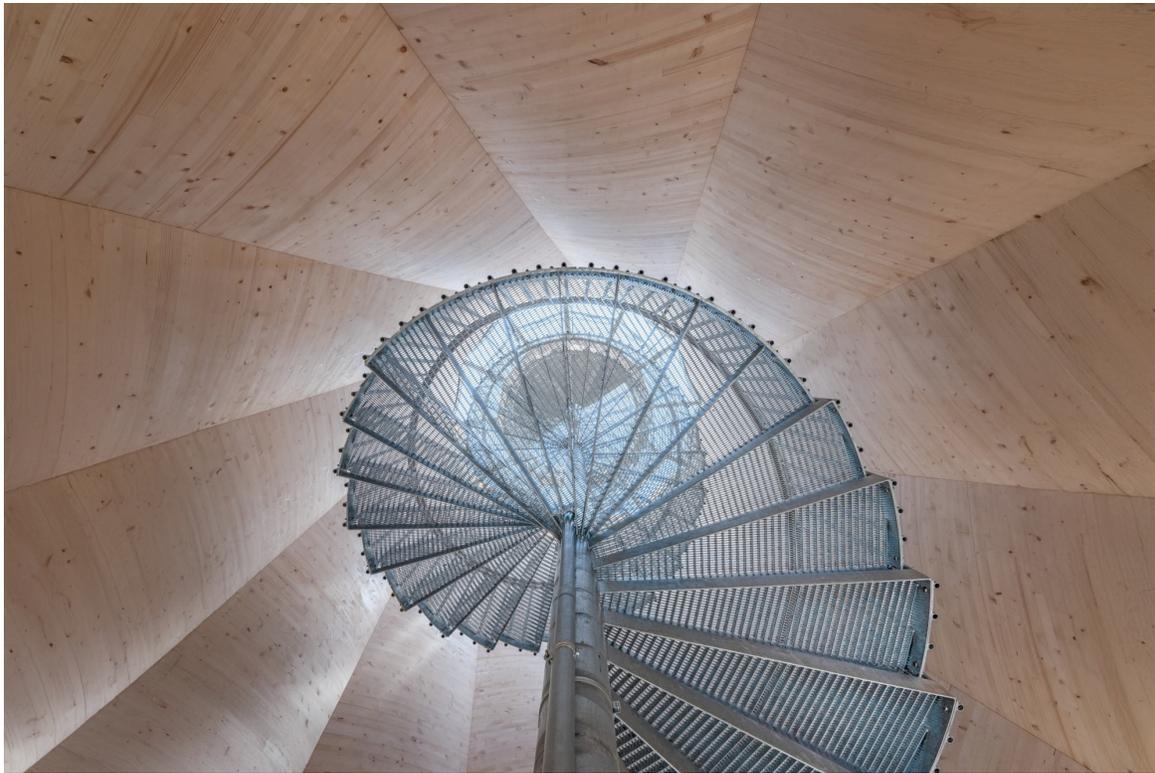


Figure 8: Interior view with distinctive curved timber structure, central spiral staircase, and glass skylights

From a construction planning perspective, the horizontal battens extended to the edges of the CLT components, which interfered with the installation of crosswise screws on-site. As a result, the substructure dictated the possible areas for screw placement.

Regarding the crosswise screw connections, varying screw densities were specified along the seams of the components to meet structural requirements, with minimal densities established for critical areas.

In terms of facade appearance, the position of the horizontal battens determined the lap joints of the facade elements, which demanded a coherent and visually appealing pattern.

To address these constraints holistically, all three rules were integrated into the computational design model, considering construction planning, structural requirements, and aesthetic alignment—into a feasible solution. This approach ensured compliance with fabrication constraints while achieving a satisfactory facade pattern.

5 – RESULTS

The Wangen Tower project demonstrates the successful integration of self-shaped CLT into a permanent, multi-story, walkable structure, advancing material programming, structural performance, and industrial feasibility. It demonstrates timber's capacity to redefine architectural possibilities, enabling geometries previously dominated by concrete construction.

A co-design demonstrator: with the successful deployment of co-design, the project becomes a demonstrator for the deployment of this overarching methodology in AEC.

Integrative Design Solutions: Overall, the project team meticulously developed solutions for various types of connections that successfully aligned with the design criteria. The minimal use and manifestation of metal components in the interior of the CLT structure enabled a seamless and uninterrupted timber experience.

Scaling of Self-Shaped CLT Fabrication: The project advanced from laboratory-scale prototypes to industrial production, enabling the manufacturing of self-shaped cylindrical elements with a 3 m radius.

Height-to-Wall Thickness Ratio: With a height of over 22.5 m and a wall thickness of 130 mm, the height-to-wall thickness ratio is approximately 173:1, demonstrating an exceptionally efficient lightweight structure with a mass of only 55 kg/m². This value surpasses the Urbach Tower's ratio of approximately 160:1, highlighting its exceptional lightweight structural efficiency.

Innovative Joint Design for Curved CLT: The integration of a multi-layered stepped veneer-laminated timber LVL lap joint allowed for longitudinally connected curved CLT components, ensuring structural coherence and minimizing deformations.

Structural Certification: The project received structural certification (ZiE approval), making it the first self-shaped CLT project legally recognized for permanent use in Germany.

Swift on-site installation: The project's effective pre-fabrication solutions resulted in a very short on-site assembly process. In terms of effective working days, excluding idle time, the tower shell was assembled in only four days, and the entire structure's completion, excluding landscape

finishing, took effective 19 working days.

6 – CONCLUSION AND RECOMMENDATIONS

This project, based on research conducted at the Cluster of Excellence 'Integrative Computational Design and Construction for Architecture (IntCDC)' at the University of Stuttgart, demonstrates the potential of advanced timber architecture and engineering in creating unique, sustainable structures.

The implementation of the co-design methodology facilitated a parallel yet synergistic development of construction planning, connection detailing, and structural design, paving the way for innovative architectural and engineering solutions tailored to the project's unique requirements and challenges. The success of these solutions highlights the potential of integrating scientific research, material-informed computational design, digital fabrication, and expert craftsmanship.

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