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PARAMETRIC IMPLEMENTATION OF STRUCTURAL ANALYSIS DATA IN THE CONSTRUCTION OF A COMPLEX CURVED TIMBER STAIRCASE

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ABSTRACT: This paper presents the use of advanced computational techniques to generate and integrate structural analysis data for the Atrium staircase at the new Blumer-Lehmann head office in Gossau, Switzerland. The project, realised through a collaborative effort among architects, structural engineers, and digital fabrication experts, exemplifies the application of parametric tools in enhancing structural integrity and material efficiency. Parametric modelling tools, such as Grasshopper; a visual programming language and environment for the Rhinoceros 3D design software, and Python scripting, were used to create detailed 3D and structural design models to perform iterative design adjustments. This project highlights the practical benefits these computational techniques bring for developing efficient and precise CNC manufacturing for complex curved timber structures.

KEYWORDS: parametric, scripting, curved CLT, structural design, digital timber design

1 – INTRODUCTION

The objective of the Atrium project was to design and construct a complex free-form timber staircase that serves as the main vertical communication and connecting element within the building. This collaborative project involved key stakeholders, including architects, structural engineers, and digital fabrication experts. The geometrical and architectural design was generated by the Institute for Computational Design and Construction (ICD), (Prof. Achim Menges), University of Stuttgart. Further development, timber engineering and detailed modelling for fabrication were undertaken by the timber design teams of SJB Kempter Fitze AG (SJB), and Blumer-Lehmann AG. This paper demonstrates the innovative use of advanced computational tools in the timber design and engineering of the above-mentioned Atrium staircase. Furthermore, it explains the necessary workflows and highlights the potential of digitally designed timber construction for such complex geometries and functions.

This project continues the collaboration between the University of Stuttgart and Blumer-Lehmann on the development of curved cross-laminated timber (CCLT), this being the third project working together on this material. The first project was the Urbach Tower in Baden-Württemberg, Germany, serving as the first example of the use of 'self-shaping' CLT material [1]. The second application came with the Wangen Tower [2], constructed for the Landesgartenschau 2024, hosted in Wangen im Allgäu, Germany. And thirdly, the Atrium staircase at Blumer Lehmann followed soon after in mid-2024. It constitutes the first application of CCLT in a load-bearing role. In contrast to previous projects such as the Wangen Tower where CCLT did not serve a primary structural function, or only as self-supporting cladding, this development represents a significant advancement in both the structural performance requirements and the design complexity associated with the material.

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Figure 1. Image of the staircase under construction showing the entrance from the first floor, Bertie Hipkin.

2 – BACKGROUND

The integration of computational tools, CNC manufacturing, and adhesive technologies has significantly advanced timber construction, enabling the realization of large-scale free-form structures through digital design-to-fabrication workflows [3][4]. These structures typically consist of numerous CNC-milled components, joined by connectors whose number and type are determined through structural analysis. Depending on the design complexity, the number of connectors can reach tens of thousands, and may change throughout the development process [5].

In conventional timber construction, the distribution and placement of connectors can be effectively managed using timber modelling software like Cadwork [6]. However, in free-form construction, the complexity becomes almost unmanageable with conventional design and modelling tools which are best suited to orthogonal modelling. Therefore, it is essential to develop efficient planning workflows that facilitate the implementation of structural analysis data and effective connector placement [7].

2.1 STRUCTURALLY AESTHETIC

A key challenge in the Atrium staircase was reconciling structural performance with architectural finish. As both a primary load-bearing element and a visually exposed centerpiece, the staircase had to meet high demands for precision and appearance—requiring minimal panel gaps and no visible fixings.

Unlike conventional buildings where structural and aesthetic layers are separated, allowing generous tolerances during heavy assembly and refined finishes through cladding, the Atrium staircase integrated both in a single construction layer. This dual role imposed strict constraints on detailing, as structural fixings could not compromise the visual quality of the timber surfaces. To meet these requirements, connector positions and details were fully developed in the digital 3D model. The model functioned as a digital twin, enabling early detection and resolution of potential clashes and ensuring clean, concealed connections that could be reliably assembled on-site.

3 – PROJECT DESCRIPTION

The Atrium timber staircase serves as the main vertical circulation across five floors and carries a load-bearing function for the adjacent floor slabs. The structure is 19.5 meter tall, featuring a curved form with a radius that varies by storey, with heights ranging from 3.8 meters at the ground floor to 2.6 meters on the upper levels. Its main components include curved walls, stairs, and landings.

The outer structural wall is constructed from 7-layer, 130mm thick cross-laminated timber, while the inner pocket wall is made from 5-layer, 90mm thick CLT. The curvature of the panels was achieved using CNC-milled templates and a large-scale vacuum press. The walls are segmented for handling and transport, with the largest panel measuring 5.4 x 6.05 meters and the smallest 0.74 x 3 meters. The outer wall also supports adjacent 7-layer, 240 mm-thick CLT floor slabs, which

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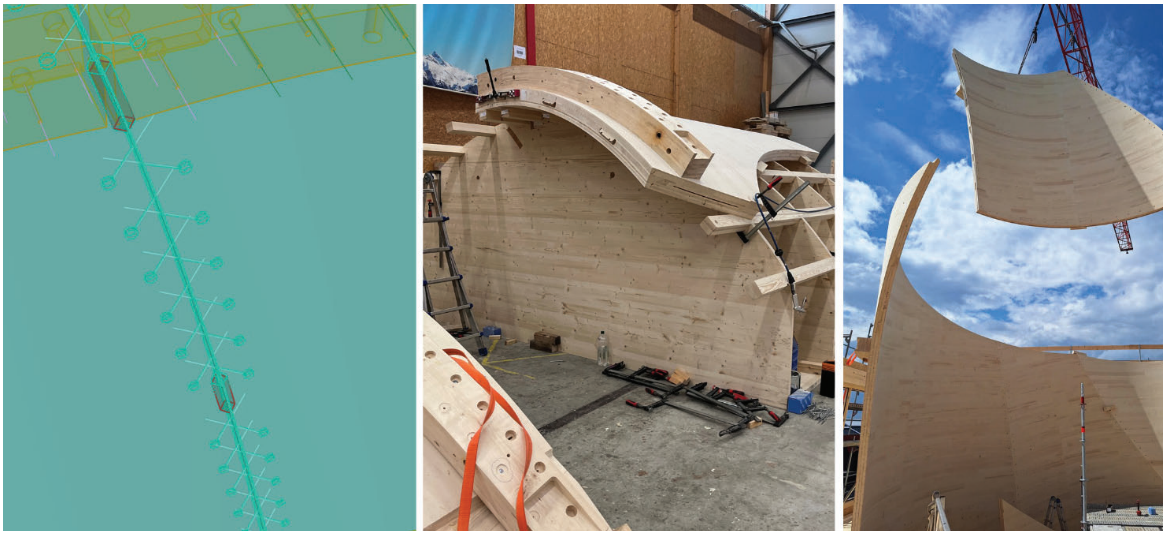


Figure 2. Image of the staircase modelling, pre-assembly of segments in factory hall, and on-site erection. Bertie Hipkin

are anchored via integrated ring beams for structural continuity. The stairs are made of 5-layer, 60 mm-thick CLT boards finished with a 40 mm ash wood top layer. The fabrication method for curved CLT used in this project represents a further development from earlier experimental strategies. The previous method involved gluing together lamellas with varying moisture contents and allowing differential shrinkage during controlled drying to generate curvature. While innovative [8], this method proved impractical for large-scale production due to its dependence on extensive drying areas and precise humidity control.

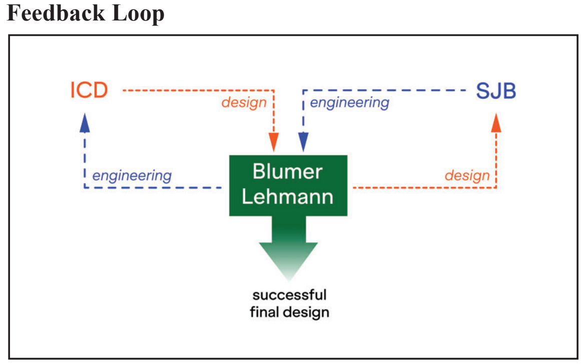
As an alternative, a more production-friendly method was implemented. Multiple layers of lamellas were glued and compressed over formwork using a vacuum press. The press applied uniform pressure across the panel, conforming it to the curved formwork. Once the glue cured, the panel retained its shape, offering a scalable and efficient manufacturing process for producing CCLT elements [9].

4 – DESIGN PROCESS (MAIN TEXT)

The design process began with the use of parametric tools to create and refine the 3D model of the staircase. Iterative adjustments were made based on parametric feedback, incorporating digital fabrication constraints from the outset. Early design checks included verification of usable width and clear height to ensure compliance with Swiss building codes for staircases [10], as well as ergonomic evaluations of step length, riser height, and intended walking line to optimise comfort for users [11].

These feedback loops, as illustrated in Graphic 1, occasionally resulted in design changes significant enough to require renewed structural evaluation by the partner engineers, SJB. Simplified models were extracted and analysed using DLUBAL RFEM 5, in combination with Rhinoceros 3D and Grasshopper. Connection forces were extracted by establishing links between surfaces in the structural model, with the staircase's complex geometry resulting in unique connection requirements at nearly every location.

Feedback Loop



Graphic 1: Diagram of the feedback loop between ICD, Blumer-Lehmann AG, and SJB. Bertie Hipkin.

The feedback loop between structural analysis and parametric modelling enabled precise and responsive updates to the design, ensuring that all load-bearing and safety requirements were met. Several connection types were developed to address varied structural conditions, including partially and fully threaded screws, and glued-in threaded rods bonded with a two-component adhesive [12]. To preserve the clean visual expression of the timber surfaces, different connector details were devised

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Figure 3. Images of the finished staircase situated in the new head office of Blumer Lehmann, Switzerland . Blumer Lehmann AG.

to remain hidden and compatible with single-sided machining strategies, avoiding the need to flip panels or rely on complex indexing.

Given the curved and non-repetitive geometry of the panels, manual placement of connectors was impractical. Instead, all connector positions and drill paths were defined within the 3D model and directly embedded in the CNC machine data. Connector placement was automated through Grasshopper and Python scripting, allowing precise definition of drill angles and depths. This scripting also helped detect collisions with other elements and prevented screws from penetrating through visible surfaces, while adhering to structural performance criteria. Where full-depth drilling was not feasible due to tool limitations, pre-drilled guide holes instead provided critical reference points for manual finishing on-site.

The staircase was divided into transportable modules and pre-assembled in a controlled workshop environment, minimising the need for complex on-site operations. Throughout this stage, Design for Manufacture and Assembly (DfMA) principles were prioritised to ensure the feasibility of production and erection processes [13][14].

By developing this model with all connectors included and precisely placed, it was possible to use it as a digital twin, becoming a valuable tool for further analsysis. For example, special attention was given to assembly sequencing and logistics. Due to the staircase's non-uniform helical geometry, component movement and insertion angles were difficult to generalise. Therefore, each element was virtually tested through motion simulation to confirm that it could be inserted without obstruction or conflict with previously placed components. All of which highlights the importance of digital workflow integrated planning.

5 – RESULTS

The final result of the workflow is the built staircase with no visible connectors and with a fully integrated structural function. The external curved CLT walls support the steps and internal stair walls, as well as part of the horizontal floor slabs. The basis was the digital twin generated with the process described above, which included all the connectors required for structural stability. The integration into the 3D model of all those connecting elements was very efficient and time-saving. The resulting highly detailed 3D model served for digital fabrication, pre-assembly, and assembly on the construction site.

6 – CONCLUSION

This paper discusses a real-life industry application of advancements in parametric modelling and engineering. It shows an efficient workflow to perform calculations and provide feedback on connector position and density. This workflow establishes an effective feedback loop, ensuring precise and efficient design iterations, and professional disciplines. Future research should explore improving the digital chain between partners in the construction industry and automation to enhance efficiency in this design process, e.g. do current AEC digital collaboration tools provide a useful software agnostic means to achieve a fully digital design chain?

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