Mono-Material Wood Wall

Digital Fabrication of Performative Wood Envelopes

Oliver Bucklin[1*], Prof. Achim Menges[1], Felix Amtsberg[1], Oliver Krieg[1], Hans Drexler[2], Angela Rohr[2]

* Corresponding author
1 University of Stuttgart, Institute for Computational Design and Construction, Stuttgart, Germany.
oliver.bucklin@icd.uni-stuttgart.de
2 Jade University of Applied Sciences, Department of Architecture, Oldenburg Germany

Abstract

The project seeks to create a building envelope that functions as structure, enclosure, and insulation, which is assembled from one solid timber construction element type. Wood has clear environmental benefits when compared to other standard construction materials such as steel and concrete, a good strength-to-weight ratio, relatively high thermal insulation, and low production costs. This research seeks to leverage these characteristics to simultaneously reduce the number of material layers in timber building envelopes while improving the building physics performance. Thus, the environmental impact of buildings can be reduced during planning, construction, operation, and disposal. The project proposes a system that reduces material layers and improves envelope performance by combining contemporary fabrication technologies with traditional woodworking techniques. Design tools should allow for compelling formal opportunities and facilitate fabrication and construction. The system manifests as a free-form, curvilinear log-cabin. Solid timber beams are used to minimise binders and fillers found in composite wood products, and the entire primary construction is achieved with pure wood joinery. CNC machining allows for the precise joining of members to achieve robust, easy-to-assemble, structural and airtight façades. By sawing deep slits into solid timber beams, the resulting air chambers improve thermal insulation values up to 30% compared to comparable solid wood assemblies while also relieving naturally occurring internal stresses. Computational design algorithms generate toolpaths and construction data directly from simple input curves, enabling direct coordination of architects, engineers, and contractors. To evaluate the system, multiple prototypes are fabricated to test constructability, thermal conductance, and airtightness, including a demonstrator building to test full-scale implementation. Laboratory tests and the successful completion of the IBA: Timber Prototype House demonstrate the potential for this renewable material to fulfil the requirements of contemporary building envelopes and open the door for the development of all-wood multi-storey façades.

Keywords

Computational design, timber, digital fabrication, layer-reduced construction, wood, façade, envelope

10.7480/jfde.2021.1.5398

1 INTRODUCTION

1.1 ENVIRONMENTAL BENEFITS OF WOOD

Widespread awareness of anthropogenic global warming has led to the adoption of stricter building energy codes by government regulation agencies as well as increasing consumer demand for sustainable construction solutions. This increasing pressure for environmentally friendly buildings has led to the development of new high-performance materials and pushed architects and contractors to reconsider traditional material solutions such as strawbales, rammed-earth, and log construction. Wood is a strong candidate for wider adoption in contemporary construction due to its environmental merits, good energy performance, low cost, and versatility. Wood is a renewable resource with low energy processing compared to steel and concrete. (Ximenes & Grant, 2013; Skullestad, Bohne, & Lohne, 2016). When the ability of trees to store atmospheric carbon dioxide is considered, solid timber can be tabulated to have a negative carbon footprint (Hill & Dibdiakova, 2016; Rosa, Pizzol, & Schmidt, 2018; González-García, Krowas, Becker, Feijoo, & Moreira, 2013). Tectonic strategies such as beams, trusses, and slabs are translated from standard steel and concrete construction into wood components for structural systems (Skullestad, Bohne, & Lohne, 2016). Wood also has lower thermal conductivity than steel and concrete (ISO 10456), which potentially reduces energy usage for heating and cooling buildings, and a high strength-to-weight ratio that allows for efficient use in structural applications.

With these benefits in mind, this research seeks to develop a building envelope system that achieves modern structural and energy performance requirements with a minimum of non-wood materials.

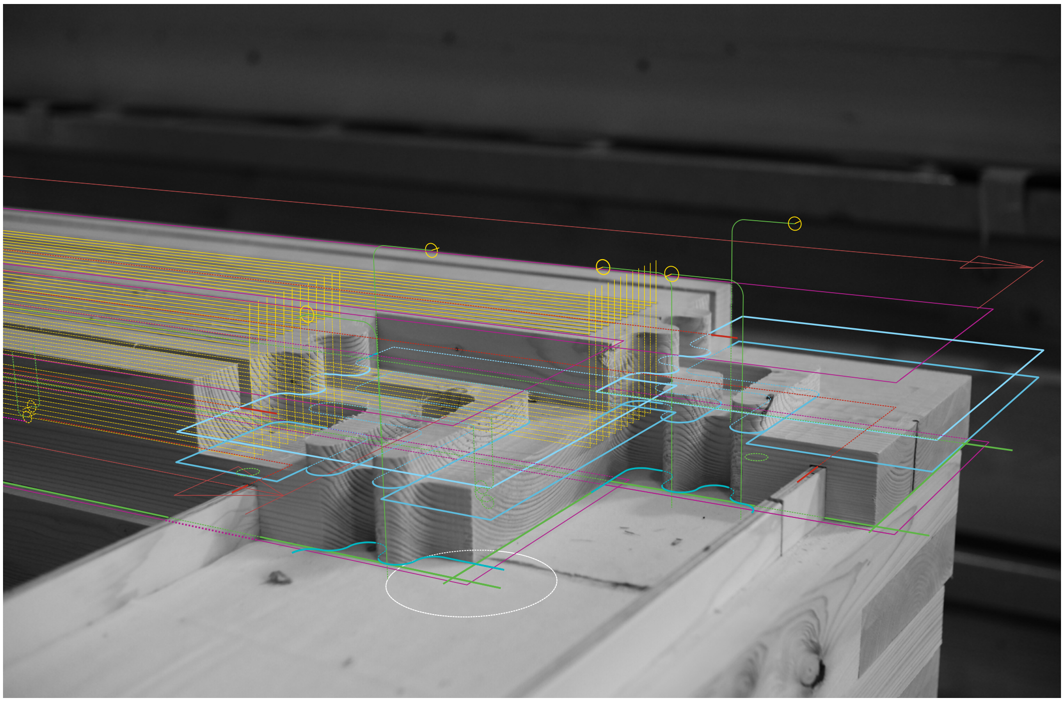

FIG. 1 Solid wood, insulating, airtight, moment frame connection detail with CNC toolpath overlay

1.2 MONO-MATERIAL CONSTRUCTION

Contemporary construction has normalised the continuous addition of subsequent material layers to strive for ever-better energy performance. Adhesives, foams, tapes, and membranes made from synthetic polymers are frequently employed to increase insulation values and reduce air permeation. However, these products require proper installation to function as intended, and performance often suffers from lack of training or discipline from construction workers (Korpi, Vinha, & Kurnitski, 2004; Kalamees, Alev, & Pärnalaas, 2017). Composite wood products require extra energy inputs for binding adhesives, with 8-28% of total energy consumption going to resin production (Puettmann & Wilson, 2005). When dismantling structures for disposal, extraneous materials complicate material separation, impeding recycling. This extends to timber product types, as solid timber has a much higher post-consumer value than composite wood products due to its usefulness in subsequent construction projects and furniture making, and produces less damaging pollution when it is incinerated for energy production (Erlandsson & Sundqvist, 2014).

Mono-material construction offers a strategy for simplifying building assemblies by using a single material that can be functionally graded and geometrically manipulated to achieve performance that is on par with composite systems. Einfach Bauen is a research project being undertaken at the Technical University of Munich, which explores mono-material construction strategies in both concrete and wood, where material density is varied to achieve different thermal and structural performance characteristics; for example, aerated concrete is used to improve insulation values. To similar ends, their wood system embeds air chambers into the construction to reduce density and increase thermal resistance. However, it relies on glued and pressed layers of planks, essentially creating composite panels (Nagler, Jarmer, Niemann, & Cruel, 2018).

The traditional precedent for solid timber construction is the Log House. Log construction uses minimally processed tree trunks, often left round or milled only on one side, which are notched at the ends and stacked to create solid wall sections. They suffer several shortcomings: the wood grain is perpendicular to principal loading creating an inefficient structure (Ross & USDA Forest Service, 2010); the joints are often cut by hand and suffer air leakage (Alev, Uus, Teder, Miljan, & Kalamees, 2014; Alev, Uus, & Kalamees, 2017); and they don't usually have added insulation layers, meaning thermal insulation relies on a thick wall section to achieve comfortable interior temperatures (Roos, Eklund, & Baylon, 1993). Log construction demonstrates a strategy for building architectural envelopes with a linear material by using a system of wood joinery and is the starting point for the development presented in this paper.

1.3 CAD/CAM INTEGRATION

Automation has entered nearly every industry to increase production speed and reduce labour costs. The timber construction industry developed automation strategies to fabricate standard components and joinery details precisely and quickly but expanded to include differentiated components for free-form architectural geometries (Schwinn, 2016). These developments have been enabled by advancements in Computer Aided Design (CAD) and Computer Aided Machining (CAM). The integration of these tools allows a holistic approach to design and construction that involves all project partners.

2 METHODOLOGY

The research follows a project at the Münster School of Applied Science called Timber Prototype I. That project used a system of horizontally oriented stacked beams, sawn longitudinally with deep slits (Fig. 2) to create air chambers within the wall section that improve thermal insulation. This research seeks to improve the energy performance of TimberPrototype I while reducing extraneous material layers, expanding the formal capabilities of the system, and creating an integrated design and fabrication system.

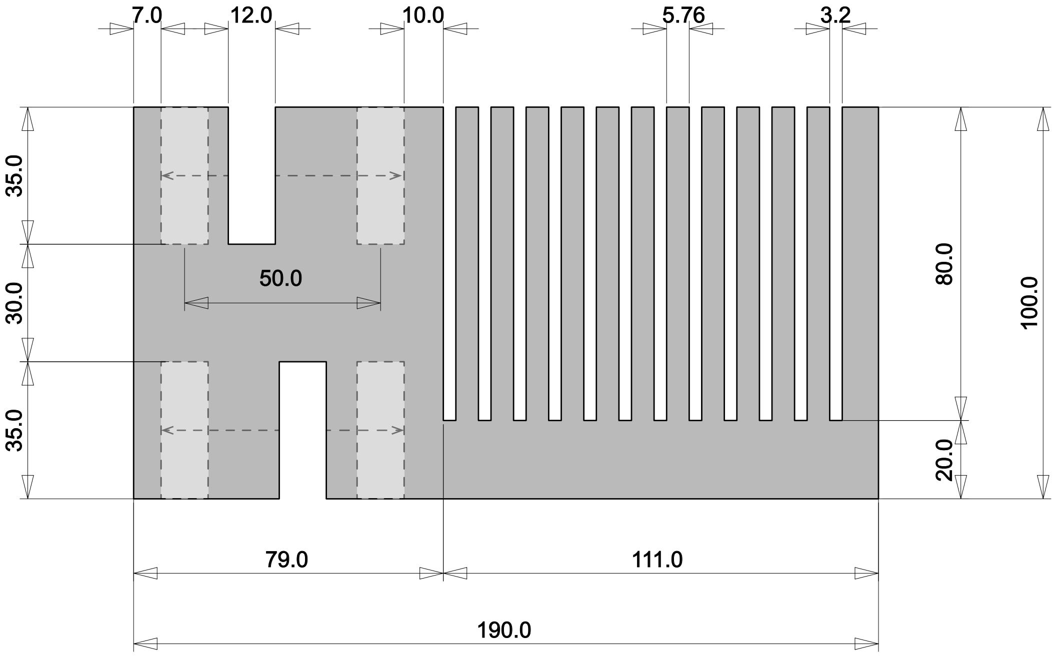

FIG. 2 Timber profile dimensions

2.1 TIMBER ELEMENT PROFILE

The research uses a 100 × 200mm spruce beam as the base material. The cross-section profile is subdivided into three distinct functional sections: insulation, structure, and enclosure (Fig. 3). The deep slits sawn into the construction elements of Timber Prototype I are utilised to generate a section of lower thermal conductivity and alleviate internal stresses that cause large-dimension timbers to crack and warp over time. These slits consist of 80mm deep slits sawn with a 3.2mm wide circular saw blade. The remaining 20mm of section profile acts as a structural member, allowing efficient bearing of axial and horizontally spanning loads. Finally, a section milled with longitudinal slits provides material required for airtight enclosure and geometrical variation.

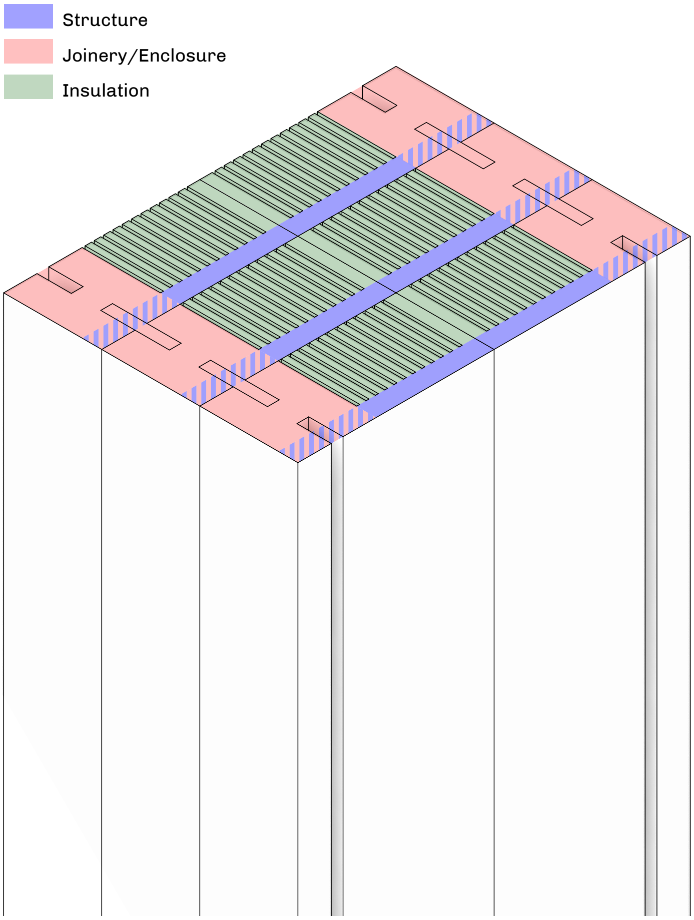

FIG. 3 Timber profile functional zones

2.2 ELEMENT CONNECTIONS

The construction elements connect using three different joinery techniques (Fig. 4). To create a thick wall section with adequate rigidity and thermal resistance, two construction elements are joined with a dovetail key to create a two-layer, 400mm deep wall section. At each end, the elements are finished with a lap joint with interlocking milled features that stiffen the joint to create a rigid moment frame and are oriented perpendicular to airflow through the envelope to reduce air permeation. Eight elements are joined into a single, rigid, trapezoidal frame. In contrast to the vertical stacking of horizontal elements found in traditional log construction and Timber Prototype I, these frames are vertically oriented in order to align the wood fibre with the principal structural forces for optimal use of the material. The frames are joined with a spline joint that uses a plywood plank to generate an airtight barrier, and which is pinned with beechwood dowels to bind the frames and minimise movement.

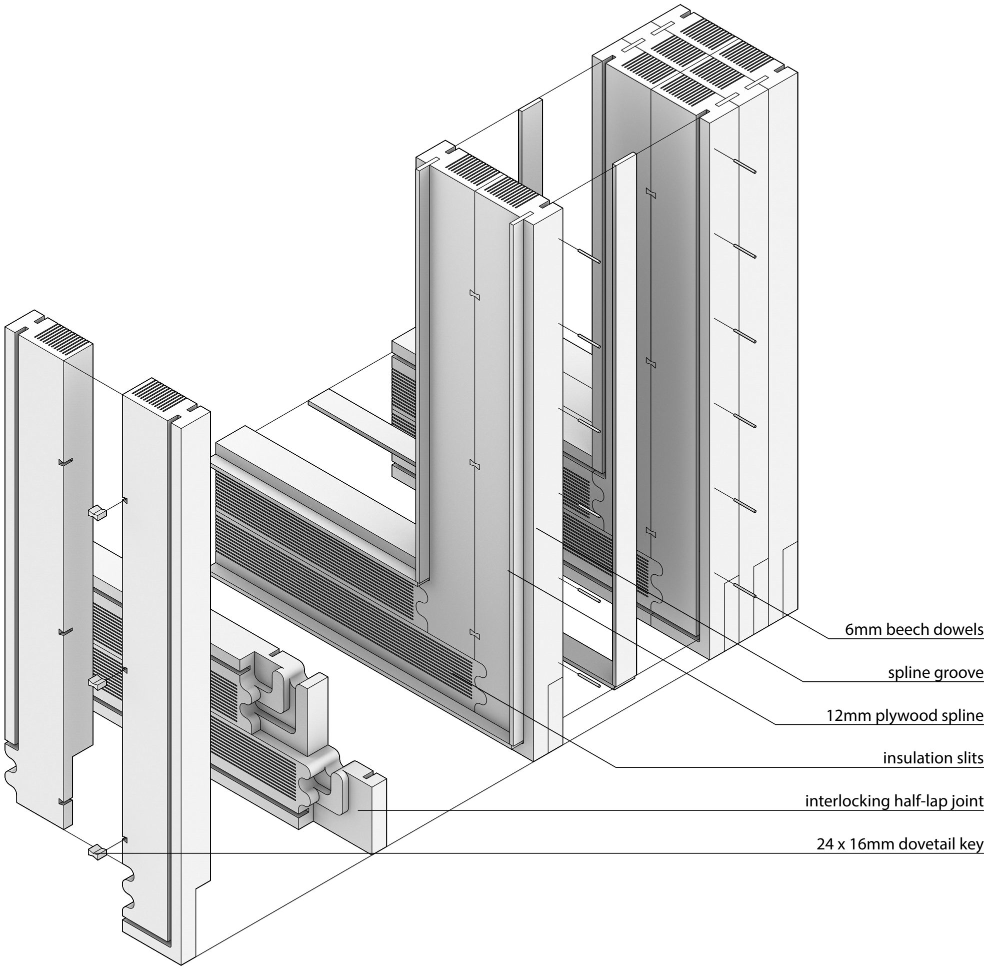

FIG. 4 Wood joinery assembly details

2.3 CONSTRUCTION SYSTEM

The construction system is developed to comprise factory prefabricated modules that are transported to site and assembled by crane. Individual modules are assembled flat and then tipped up to their final vertical orientation. They are then wrapped with a waterproof membrane to protect against rain and then a façade of wood planks is screwed onto the exterior. The modules are dimensioned for highway transport and assembly by crane. Assembly of modules is intended to utilise the same spline connection that joins the preassembled frames. Doors and windows are also aligned and mounted using the same spline joint.

2.4 CAD/CAM INTEGRATION

In traditional log construction, each layer bears upon the layer below, necessitating a near-vertical wall. However, orienting the trapezoidal frames vertically presents an interesting design opportunity. Each frame supports the spanning beams of the roof with efficient, vertical wood grain. This allows the subtle offset of subsequent frames to generate non-orthogonal and curving walls.

By changing the lengths of timber beams and the angles of joints that connect them, the walls can form three-dimensional curved surfaces.

This research develops a method for creating freeform building envelopes by systematising this formal flexibility through custom computational scripts that automatically produce detail variations based on simple user input. CAD software allows architects to rapidly design and evaluate buildings. To design with the system, a user manipulates curves in the three-dimensional CAD software Rhinceros3D. Custom C# scripts for the plugin Grasshopper were developed by the researchers which convert these curves into a complex model with layers of building information (Fig. 5). The script begins by creating intersection points at regular intervals along the curves. By connecting these points, lines are generated that correlate to the timber beams of the envelope. The scripts generate a broad array of model geometry and data relating to the building and the fabrication thereof:

- Solid geometries are generated to rapidly evaluate the quality of proposed forms and spaces.
- Frame geometry is evaluated to ensure that structural capacity will not be exceeded.
- Connection details are evaluated to ensure that the components can be assembled.
- Building metrics such as floor space, internal volume, and material quantities are output for cost analysis.
- Construction sequences can be tested virtually to ensure fit and feasibility.
- Machine Code instructions are generated to drive CAM milling.

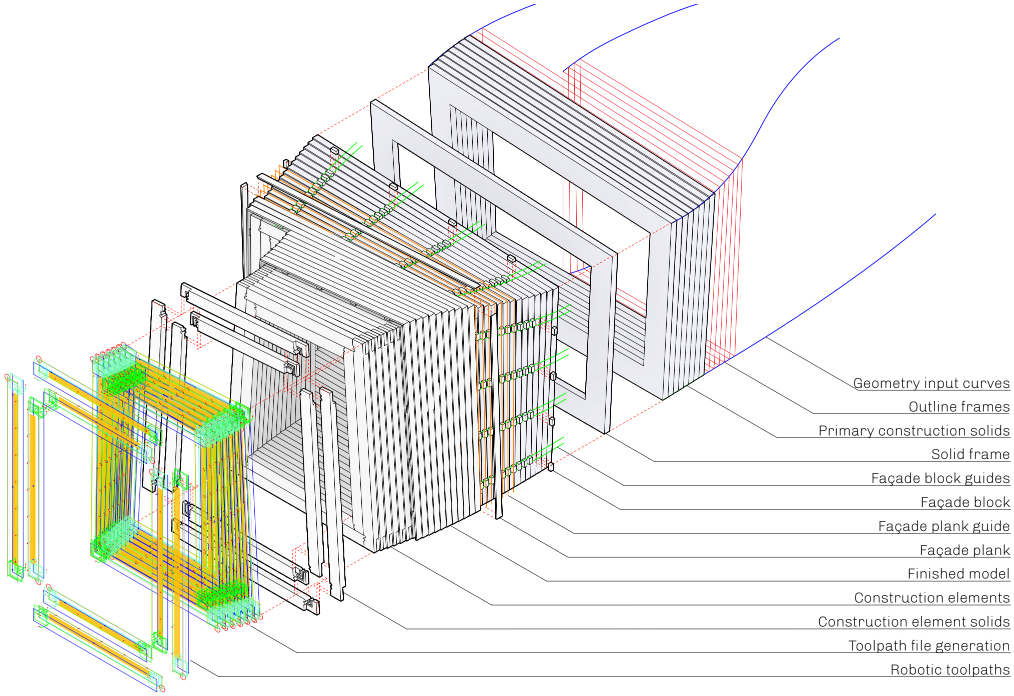

FIG. 5 CAD/CAM integrated digital model

The various outputs are accessible to project partners including building physicists, structural engineers, and contractors. Structural analyses were an important aspect of early system development. Building codes informed wood connections to ensure proposed parametric joints would remain within acceptable dimensions. Strength values for these joints were inserted into bending moment analyses of the trapezoidal frames. These yielded structural capacities of individual frames which were integrated into the CAD/CAM model as geometric limits. Thus, the model would avoid design options where walls or roof exceeded certain angles or span lengths. By ensuring that each individual frame could bear its own weight, the designer was given free rein to design within that range without worrying about the building's global structural system. The custom software that integrates CAD and CAM processes permits the subtle yet precise variation in detail planning and fabrication that allows the high-fidelity realisation of the complex, global design geometry. The submillimetre precision of modern Computer Numeric Control (CNC) milling machines gives the added benefits of accurate planar surfaces and tight-fitting joints, which are necessary to improve airtightness by minimising gaps between construction elements and to generate stiff moment connections for the trapezoidal frames.

3 EXPERIMENT/RESEARCH

To verify all aspects of the Mono-Material Wood Wall system, small- and large-scale tests were constructed. Small test panels were used in laboratory building physics measurements. A large-scale construction mock-up was fabricated to test the CAD/CAM workflow and assembly processes, and a full-scale demonstrator building was constructed to test industrial implementation.

Test panels and the construction mock-up were fabricated using a 8kW milling spindle end effector on a KUKA KR125-2 6-Axis industrial robotic arm. The demonstrator components were produced in a factory on a Homag BOF 311_5 5-axis CNC mill with 9kW spindle and automatic tool changer. Insulation slits were sawn with a 250mm circular saw blade resulting in 3.2mm wide air chambers. Dovetail connections were milled with a 30°, 16mm wide dovetail endmill. Spline grooves were milled with a 12mm end mill and lap joints with a 20mm end mill. Additionally, demonstrator components used a variety of surfacing tools for planing.

3.1 TEST PANELS

Approximately 32 linear metres of timber beam were milled for laboratory tests. These each had twelve, 80mm deep insulation slits and one spline groove on each of the larger faces. Some of the beams were milled with dovetail grooves to bind interior and exterior layers. These elements were assembled into two test panels for thermal and airtightness measurements.

3.2 THERMAL CONDUCTION

The research seeks to measure the reduction of thermal conduction across the building envelope. This is initially done through the tabulations outlined in ISO 6946. Those values are compared to a wall section of solid wood and to the wall section of Timber Prototype I. Then, a 200mm thick test panel consisting of nine, 900mm long construction element profiles was tested for thermal conductivity in a Hot-Box test per DIN EN 12664:2001-05 (Fig. 6).

3.3 AIRTIGHTNESS

A 900×1200mm double layer airtightness test panel was tested in a blower-door test in a laboratory setting to estimate the airtightness of the envelope and to identify problem areas that should be addressed. This measurement gave a value in cubic metres per square metre of façade per hour, which could be applied to a proposed building design to determine Air Changes per Hour (ACH), the typical airtightness unit for evaluating entire structures. This panel consisted of beam elements whose exterior profiles were not milled to precise dimensions and arrived from the lumber supplier with up to 5mm of dimensional variation.

Once constructed, the research demonstrator was also fitted with a blower-door device and tested for air tightness (Fig. 7). This value was given in ACH and is extrapolated to leakage per surface area and leakage per linear metre of joint for comparison to other systems. All demonstrator elements were fully milled on each side to achieve submillimetre dimensional tolerances.

FIG. 6 Hot Box thermal conductivity test

FIG. 7 IBA: Timber Prototype House blower-door test

3.4 CONSTRUCTION MOCK-UP

24 complete elements including end joint details were fabricated on the KUKA robot to test fabrication and assembly. This was an early version of the corner joint detail which relied on an inserted block in the corners and a series of wooden dowels which pinned the lap joints to create rigidity. These joints lacked the interlocking channels of the final corner lap joint. From those elements, a 3.2×2.5×0.3m (H×W×D) section consisting of three layers of frames was assembled. This process highlighted issues in the production and assembly of components and informed changes that were implemented in the final version of the system.

3.5 DEMONSTRATOR

A full-scale demonstrator, called the IBA: Timber Prototype House, was designed and built to test industrial implementation. The primary construction of the 6×5×3.5m(L×W×H) structure consists of 464 milled elements. The elements were assembled into six modules that were clad with a waterproof membrane and rain screen façade before being transported to a site in Apolda, Germany, where they were assembled into the final structure. The design is meant to show the expressive flexibility of the system and is capped with two large picture windows and custom operable glazed doors. The demonstrator was designed as a micro-house, and can be fitted with a prefabricated utility box that contains the essential systems for a residential unit (Fig 8).

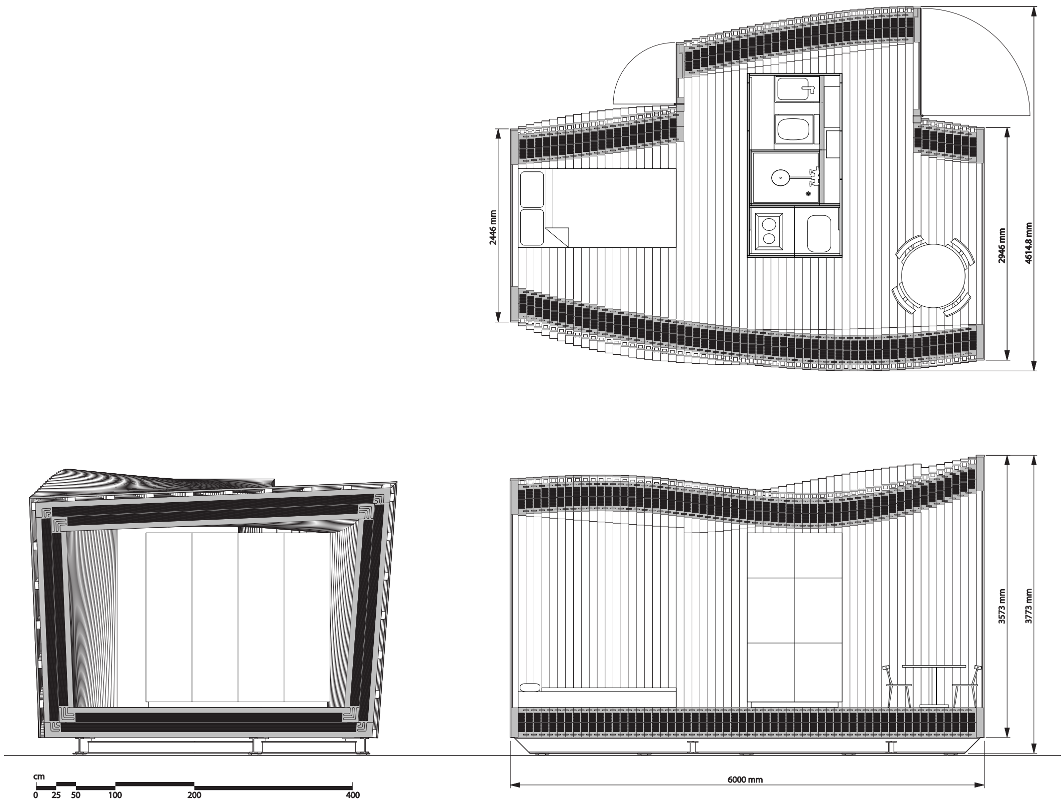

FIG. 8 Plan and Sections of IBA: Timber Prototype House

4 RESULTS

4.1 THERMAL CONDUCTANCE

Calculations of thermal conductance demonstrated a significant improvement in thermal insulation due to sawn air chambers. Compared to a solid timber wall section of the same thickness, which would have a thermal conductance of 0.285 $W/ m^2{\cdot}K$, the Mono-Material Wood Wall would have a conductance of 0.230 $W/ m^2{\cdot}K$, a nearly 24% improvement. Hot-Box tests demonstrated even better performance, with a conductivity of λ =0.0846 $W/m{\cdot}K$ at 10°C. At a wall thickness of 400mm, that would result in conductance value of 0.20$W/ m^2{\cdot}K$ per (ISO 6946).

4.2 AIRTIGHTNESS

The initial laboratory test of airtightness test had very high permeability of $q50 = 13.3\ m^3/m^2h$. By taping off the ends of the insulation slits, this value was brought down to a reasonable $q50 = 2.1\ m^3/m^2h$. This result demonstrated the need to fully enclose the insulations slits, and in subsequent component configurations, the slits ended short of the corner, leaving a solid section of wood for the corner joint. This elucidated the need to minimise gaps between components and led to the decision to fully plane all sides of the components.

These improvements seem to have been effective as demonstrated in the IBA: Timber Prototype House. The Blower-Door test of the finished structure demonstrated an average permeability of 2.7 ACH. From this value, the performance of the Mono-Material Wood Wall itself can be estimated to be $1.22m^3/m^2{\cdot}h$. However, anemometer tests identified areas of significant leakage at the gaps between modules and where windows and doors were installed, so the permeability of the preassembled envelope would be lower.

4.3 CONSTRUCTION MOCK-UP

The construction mock-up informed refinements to the system. It proved the basic functionality of the CAD/CAM integration script which could directly output machine-readable code. It demonstrated assembly feasibility and a strong formal expression. The fabrication of the 24 components took approximately one hour each, as mounting the material and changing milling tools was done manually. Beams were mounted on a rotating external axis to extend the KUKA industrial robot's reach to mill 3.5m components, allowing milling on 3 sides of the beam without manually flipping it (Fig. 9).

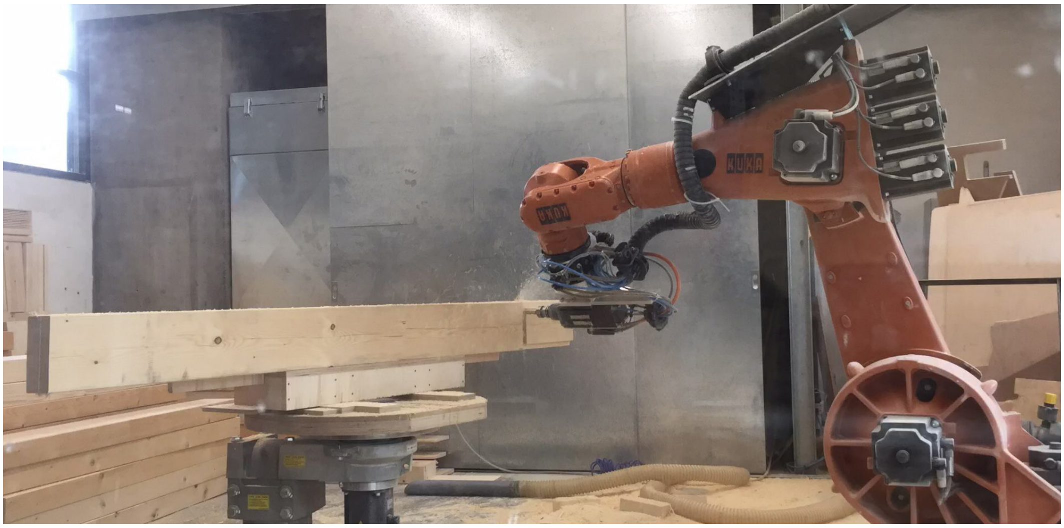
FIG. 9 Robotic milling of construction mock-up component

The external axis, loose tolerances in the robotic arm, and varying material quality led to the imprecise fit of components. The tolerances aggregated to create gaps of up to 10mm, which would have a detrimental effect on airtightness and led to the decision to fully plane all sides of the components in the demonstrator.

4.4 DEMONSTRATOR

Despite being kiln-dried and factory planed, the timber beams had up to 5mm of variation from their nominal dimensions and displayed significant warping and twisting. Therefore, oversized lumber was ordered and milled to precise final dimensions. Each face of the element had to be fully surfaced during milling and each component was flipped twice during milling.

Due to the depth of the insulation chambers, each was sawn in two passes of 40mm deep to reduce torque CNC mill's spindle and linear axis. Thus, most of the machining time was spent sawing the insulation slits. Milling times ranged from 20-30 minutes, depending on component length and, including loading and unloading material, production lasted 30-40 minutes per element.

Each component was milled with a numeric code that allowed rapid identification and straightforward assembly sequencing (Figs. 10-11). A single worker could assemble a frame of eight construction elements in 30-40 minutes. Other processes, such as wrapping the finished modules in waterproof membrane and installing the rainscreen façade planks, took a significant amount of time, but the main bottleneck was still the CNC milling. Accounting for this, one work shift per day assembling modules could keep up with two shifts per day of mill operation.


FIG. 10 CNC milled corner lap joint detail

FIG. 11 Assembled corner lap joint detail

The demonstrator was assembled in the factory into six finished modules averaging 1m deep (Fig. 12). The modules were loaded onto deep-bed trailers and transported to site (Fig. 13). In two days, the modules were placed on a lightweight steel foundation frame and mated together (Fig. 14). The spline connection used for component assembly was the planned method for connecting finished modules, but due to their weight and resulting friction, it was not possible to generate enough force to press the splines into the grooves between modules. Ultimately, short sections of planks were used to align modules during mating. This led to visible gaps between modules, which were areas of higher leakage during the airtightness test of the finished demonstrator. The same intended connection between the primary construction and the window frames and door jambs were not feasible and installers had to rely on smaller blocking for alignment and large screws and adhesives for structural mounting.


FIG. 12 completed modules in factory


FIG. 13 transport of modules


FIG. 14 onsite assembly

5 CONCLUSIONS

The validity of the integrated design and fabrication process was demonstrated by the successful completion of the IBA: Timber Prototype House (Fig. 15). The simple design, assembly, and construction processes resulted in a fully enclosed mini house that showcases the formal flexibility and building physics performance in a full-scale, inhabitable structure.

FIG. 15 Completed IBA: Timber Prototype House Demonstrator

5.1 CAD/CAM INTEGRATION

The custom computational scripts developed for the Mono-Material Wood Wall proved to be instrumental in the successful realization of the demonstrator. Dozens of designs were proposed and evaluated to suit the needs of the client, with a variety of proposed spatial configurations and formal expressions. The digital model was used to plan every stage of fabrication and assembly, including element production, module assembly, transport, and façade installation. Subcontractors were able to use the model to plan fabrication and installation of windows and doors using the spline connections for alignment.

If the Mono-Material Wood Wall is to be adopted as a method for widespread implementation, the scripts would need to be expanded into more robust programs with a simpler user interface, better error detection, and broader utilisation cases. More rigorous integration with structural engineering software, coupled with thorough benchmarking of joint strengths could expand the range of potential forms the envelope could take. Adding more joint types could allow for new architectural spaces, including internal spatial subdivision or changing the orientation of the frames. Similarly, new milling steps could be introduced that would create voids for plumbing, electrical and HVAC installations within the envelope. Functionalities could be added that facilitate fabrication on a wider range of machines.

5.2 FABRICATION AND ASSEMBLY

The very intensive milling process is the greatest hurdle to overcome in the wider adoption of the Mono-Material Wood Wall. There are several proposals to address this issue. The most time intensive machining step, sawing the insulation slits, could be shortened by mounting multiple circular saw blades on a single axle with a much more powerful spindle and material feed. This could be done on a standalone machine, such as an adapted planer with material feeder, or integrated into an industrial wood joinery centre. The latter would have the additional benefit of integrated material handling, which would nearly eliminate both time and physical labour required for loading and unloading material onto the CNC milling bed. Because fully planed beams are then milled again to achieve the necessary precision for the system's joints, overall material savings could be found by sourcing rough sawn timber or even round logs.

5.3 BUILDING PHYSICS

The performance of the Mono-Material Wood Wall was shown to be an improvement over previous solid-timber systems. To continue to make improvements, more in-depth tests should be undertaken to isolate variables and identify specific details that can be further improved. Assembly of completed modules will also require thorough investigation. Joint details between frames were out of scope of the research. However, an effective method for mating the 2-3 tonne pieces that results in an airtight seal will be crucial.

5.4 OUTLOOK

The research is currently in further development to expand the system to a multi-storey façade system. This inherently presents new challenges to create different self-supporting structural systems, to plan the logistics of transport and installation, and to generate new details to attach to other novel and pre-existing building systems. While these new challenges must be addressed, researchers are also returning to the initial aims of the project by continuing to reduce the extraneous material layers in the envelope to achieve a true Mono-Material envelope.

Acknowledgements

The authors acknowledge the support of the Forschungsinitiative Zukunft Bau, Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) as part of the project "Baukonstruktionen aus Massiv-Holz (SWD-10.08.18.7-15.59)" lead by ICD University of Stuttgart in collaboration with Jade Hochschule and IBA Thüringen. In addition, Oliver Bucklin and Achim Menges acknowledge the partial support of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2120/1 – 390831618.

Special thanks to Tobias Haag, Dr. Martina Doehler-Behzadi, and Elisa Wrobel of IBA Thüringen, Victor Rodriguez of the University of Stuttgart: ICD, Geronimo Bunjy, Ganna Bulavintseva, Marie Deilmann of Jade Hochschule: Oldenburg, Manfred Weid of Ackermann GmbH, and our industrial partners: Thüringer Forst, Rettenmeier Holz, Ackermann GmbH, Uni-Holzbau, Serge Ferarri GmBh, Wider Holz, MFPA

References

Alev, Ü., Uus., A, Teder, M., Miljan, M-J., & Kalamees, T. (2014). Air leakage and hygrothermal performance of an internally insulated log house. In J. Arfvidsson, L-E. Harderup, A. Kumlin, and B. Rosencrantz (Eds.). *NSB 2014-10th Nordic Symposium on Building Physics - Full Papers*. Lund: Building Physics, LTH, Lund University, pp. 55–62.

Alev, Ü., Uus, A., & Kalamees, T. (2017). Airtightness improvement solutions for log wall joints. *Energy Procedia 132*, pp. 861–866. doi: 10.1016/j.egypro.2017.09.678.

ISO 6946: 2017. *Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods* (ISO 6946:2017).

ISO 10456, 2007 + Cor. 1:2009. *Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values* (ISO 10456:2007 + Cor. 1:2009).

Erlandsson, M., Sundqvist, J-O. (2014). *Environmental consequences of different recycling alternatives for wood waste.* Retrieved from https://www.ivl.se/download/18.343dc99d14e8bb0f58b76a7/1445517707516/B2182.pdf, checked on 11/18/2019.

González-García, S., Krowas, I., Becker, G., Feijoo, G., & Moreira, M. T. (2013). Cradle-to-gate life cycle inventory and environmental performance of Douglas-fir roundwood production in Germany. *Journal of Cleaner Production* 54, pp. 244–252. doi: 10.1016/j.jclepro.2013.05.012.

Hill, C. A. S., & Dibdiakova, J. (2016): The environmental impact of wood compared to other building materials. In International Wood Products Journal 7 (4), pp. 215–219. doi: 10.1080/20426445.2016.1190166.

Kalamees, T., Alev, Ü., & Pärnalaas, M. (2017): Air leakage levels in timber frame building envelope joints. *Building and Environment,* 116, pp. 121–129. doi: 10.1016/j.buildenv.2017.02.011.

Korpi, M., Vinha, J., & Kurnitski, J. (Eds.) (2004). Airtightness of Timber-Framed Houses with Different Structural Solutions. *Buildings Conference*, December. Oak Ridge National Laboratory: Building Technologies Program. Retrieved from https://web.ornl.gov/sci/buildings/conf-archive/2004%20B9%20papers/070_Korpi.pdf.

Nagler, F., Jarmer, T., Niemann, A., & Cruel, A. (2018). *Einfach Bauen. Ganzheitliche Strategien für energieeffizientes, einfaches Bauen – Untersuchung der Wechselwirkung von Raum, Technik, Material und Konstruktion. Endbericht für das Forschungsvorhaben [Simply Building. Holistic strategies for energy-efficient, simple building - investigating the interaction of space, technology, materials and construction. Final report for the research project].* With the assistance of Thomas Auer, Laura Franke, Hermann Kaufmann, Stefan Winter, Stephan Ott, Marco Krechel, Christoph Gehlen, , Charlotte Thiel. Technische Universität München: Lehrstuhl für Entwerfen und Konstruieren. Munich, Germany. Retrieved from https://www.einfach-bauen.net/wp-content/uploads/2019/04/einfach-bauen-schlussbericht.pdf.

Puettmann, M. & Wilson, J. (2005). Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. *Wood and Fiber Science Journal, 37*, pp. 18–29.

Roos, C., Eklund, K., & Baylon, D. (1993). *The Thermal Performance and Air Leakage Characteristics of Six Log Homes in Idaho.*. US Bonneville Power Administration. United States. doi: 10.2172/10103110

de Rosa, M, Pizzol, M., Schmidt, J. (2018). How methodological choices affect LCA climate impact results: the case of structural timber. *International Journal of Life Cycle Assessment,* 23 (1), pp. 147–158. doi: 10.1007/s11367-017-1312-0.

Ross RJ (ed) (2010) Wood Handbook: Wood as an Engineering Material. General Technical Report FPL-GTR-190. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory,

Madison, W.I, & Schwinn, T. (2016). Manufacturing Perspectives. Tobias Schwinn in conversation with Holzbau Amann and Müllerblaustein. In A. Menges, T. Schwinn, and O. D. Krieg (Eds.). *Advancing wood architecture. A computational approach*. London: Routledge.

Skullestad, J.L., Bohne, R.A., & Lohne, J. (2016). High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives. *Energy Procedia 96,* pp. 112–123. doi: 10.1016/j.egypro.2016.09.112.

Ximenes, F.A. & Grant, T. (2013). Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. *International Journal of Life Cycle Assessment,* 18 (4), pp. 891–908. doi: 10.1007/s11367-012-0533-5.