Kerf Canopy

Exploring the aesthetics and structural performance of kerf-bent timber structures

Renate Weissenböck[1], Timo Carl[2], Agnes Weilandt[3], Roger Loho[4]
[1,2,3,4]Frankfurt University of Applied Sciences
[1,2,3,4]{renate.weissenboeck|timo.carl|agnes.weilandt|roger.loho}@ fb1.fra-uas.de

The traditional craft technique of "wood kerfing" allows the bending of flat boards into 3D-geometry through a series of incisions ("kerfs"), thereby lending wooden structures a soft and pliable aesthetic. This method offers rich design potentials, driven by the interplay of material properties and geometric principles of the incisions. The incisions naturally weaken the wood, resulting in reduced material stiffness, which often poses a significant challenge to application kerf-bent timber structures at building element scale. This work addresses the dual challenge of achieving both soft aesthetics and load-bearing capacity. We explored design opportunities of kerfed wood in conjunction with a structural application through a 1:1 scale demonstrator with a footprint of 12 m². To enhance fabrication efficiency, traditional craftsmanship was combined with state-of-the-art CNC technology, significantly streamlining the complex manufacturing process. Additionally, we developed strategies to gain a better understanding of the structural behavior of "soft" wood materials through FEM simulation. This approach allowed us to correlate the precise digital design- and simulation-models with - sometimes unpredictable - physical outcomes, exploring the tension field between material agency, geometry and structural performance.

Keywords: *Design & Build Studio, Digital Fabrication, Digital Craft, Material-Driven Design, Structural Simulation, Kerf-Bending.*

INTRODUCTION

Several techniques are known for shaping wood, including cold-bending, steam-bending, and laminating. This work focuses on the traditional craft technique of "wood kerfing" (or "kerf-bending") that facilitates the bending of flat boards into 3D-geometry through linear incisions ("kerfs").

Typically, kerfs are created using a saw blade. This process imparts flexibility to an otherwise rigid material, a practice well-established in furniture design (Capone and Lanzara 2019). Kerf-bending allows for intriguing soft and sculptural characteristic, rarely found in wood structures. Consequently, designers and architects have shown increasing interest in wood kerfing. The advent of digital tools has sparked renewed enthusiasm within the architectural community (Schindler 2008).

Since around 2010, a series of demonstrators and pavilions involving kerf-bending have been investigated, primarily in an academic or research context. Notable examples include the University of Stuttgart's "Kerf-Based Complex Wood Systems" (2010), the MIT Department of Architecture's "Kerf Pavilion" (2012), and the AA/EmTech's "Re-Emerge" (2021). Most studies on kerf-bending have focused on geometric aspects, such as exploring patterns for double curvature (Capone et al. 2019), and on the aesthetic properties of bent wood, such as the composition of gradually changing curvatures (Gramazio Kohler Architects 2012).

However, fewer investigations have emphasized the structural performance of kerf-bent elements. This study addresses this gap by examining effective methods for dealing with the specific structural challenge posed by the kerf-bending technique, namely the significant material weakening resulting from the incisions applied.

The objective of this research is to correlate two primary issues: the design potential of kerf-bent wood and its structural performance at an architectural scale.

The design potential of wood kerfing emerges from the interplay between digital precision and material properties. This research is situated within a material-driven design project that combines digital fabrication with manual craftsmanship.

Traditional wood kerfing techniques are revisited using new technologies, such as parametric design, digital fabrication and FEM simulation, to create a modular wooden system suitable for building components. The modular system enables the adaptation to various dimensions and configurations.

BACKGROUND

By definition, a kerf is "a slit or notch made by a saw or cutting torch" ('Kerf' Merriam-Webster.com Dictionary, n.d.). Research on digital wood fabrication encompasses a range of techniques. These include laser-cutting (Kalama et al 2020), CNC-milling (Mitov et al 2019; 'An Exploration on Possibility of Double-Curved Wooden Panels Fabrication' 2019) and robotically-controlled milling or saw cutting (Gillkvist et al 2016).

Kerf-bending enables the creation of curved surfaces from flat, rigid materials without the need for additional molds, which are often single-use. The key challenge is maintaining the material in its bent state. This can be achieved through supplementary means, such as cables or screws, or by carefully engineering the joints.

Since kerf-bending starts with a flat material, complex and tightly fitting joints can be precisely fabricated by basic digital fabrication processes such as flatbed CNC-routing. However, for the fabrication of straightforward geometries, manual techniques are often more efficient, as digital methods (e.g. milling) can be time-consuming.

Figure 1
Kerf Canopy - Wood Demonstrator

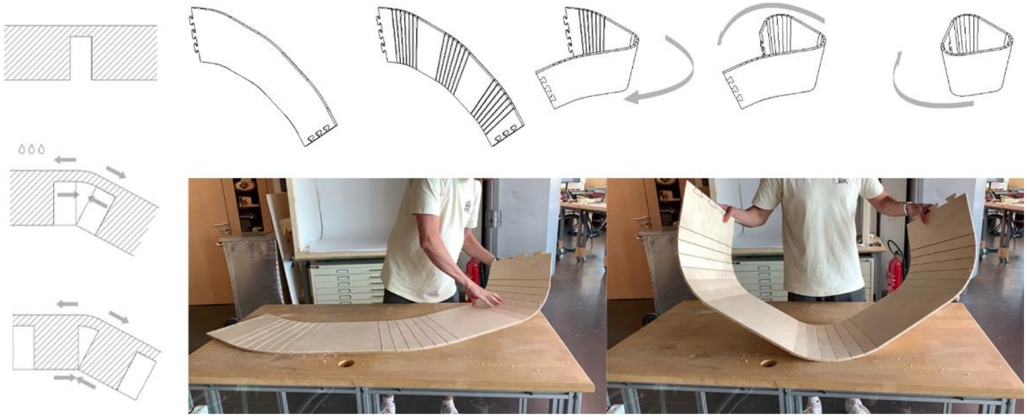

Figure 2
Kerfing technique and bending of the conic base module with interlocking puzzle joint

The choice of tools for kerfing is dependent on the material thickness. Laser cutting is the method of choice for thinner materials, while CNC-milling is the best option for thicker sheets (Mitov et al 2019).

The machines used determine the types of cut patterns and geometries that can be applied. These can be categorized into three types:

- cutting perforation slots continuously all the way through the material
- grooving continuous lines to a certain depth on one side of the material (approx. 3/4th of the wood thickness)
- grooving continuous lines to a certain depth on both sides of the material

Laser cutting is employed to perforate the material throughout its entire depth, thereby imparting a fabric-like quality to the wood. CNC- or robotically-controlled machines are used to score the wood in partial depth, thereby balancing the relationship between cuts and flexibility.

As the amount of material removed increases, the wood becomes progressively weaker. Therefore, for structural elements, incisions should be kept to a minimum in terms of both size and number.

Another crucial factor for structural applications is the orientation of the kerfs within the overall structure. Many of the aforementioned precedents explore vertical, wall-like structures (Kerf-Based Complex Wood Systems 2010; Kerf Pavilion 2012, Gillkvist et al 2016), where the flow of forces is aligned with the "weaker" direction of the kerfed structure (i.e. perpendicular to the incisions). This study investigates a horizontal, ceiling-like structure, aligning structural loads with the kerf direction.

METHODS AND CONTRIBUTION

In the framework of a research-oriented design & build studio, we conducted physical experiments to investigate the design potential of curved wood and the structural performance of kerf-bent elements. Over the course of a single semester, our team of two professors and six Bachelor students developed and constructed a modular roof structure, realized in 1:1 scale (Fig. 1).

The upscaling of material systems often leads to structural challenges, with kerf-bending posing additional difficulties due to the weakened material resulting from the necessary incisions. To address this issue, we employed "compression bending", optimizing the kerfs to a minimum, and developing tight-fitting puzzle joints. These joints act as locking mechanism, creating compression at the kerf incisions. Starting with flat wood sheets, we could fabricate the puzzle joints precisely enough by flatbed CNC-routing, allowing us to achieve the desired bending radii and to retain the cone-shaped surface geometry.

Thereby, the elements get relatively stiff in z-direction and can be aggregated into a lattice roof structure. The rigidity between the elements is crucial to create a self-supporting structure.

During our design explorations, we established a digital workflow for geometry generation and fabrication data. We also investigated the improvement of fabrication times by combining digital fabrication with manual craft techniques (Fig. 3). The 1:1 demonstrator displays the actual structural performance achieved by the well-thought-of geometries and joints, allowing the aggregation of the initially flexible elements to form a robust load-bearing structure.

Additional to the physical demonstrator, we conducted structural simulations to gain a better understanding of "soft" wood structures. Thereby we gained insights into the comparability between the demonstrator's structural performance and the FE model. The digital FEM workflow, described in detail in the section "Load Bearing Behavior", employs Rhinoceros, Grasshopper, Kangaroo and Karamba3D (Preisinger and Heimrath 2014).

PROJECT DEVELOPMENT, RESULTS AND REFLECTION

The project employs a bottom-up approach driven by the inherent properties of wood. It emphasizes life-cycle friendliness by using modular elements that can be aggregated into a structurally self-supporting ceiling and easily be disassembled.

The resulting demonstrator, "Kerf Canopy," is a lightweight wooden roof typology (approx. 150 kg) featuring geometrically varying cone modules. It epitomizes the fusion of craft and technology in fabrication, providing a proof-of-concept for the structural performance of kerfed wood modules.

Kerfing Experiments

This work adopts a surface-based approach for thin wood plates, in which ruled surfaces are precisely unrolled for 2D cutting and then assembled in 3D using compression-active bending joints.

When working with wood kerfing, pattern and geometry of the kerfs are crucial for achieving the desired bending radius, with material properties playing very a significant role. Therefore, the design process was informed by physical experimentation, exploring the interdependence of incision geometry, material properties and the achievable bending radii.

Findings indicate that to facilitate both smooth bending and structural integrity, the objective is to produce the smallest possible incisions placed closely together (Fig. 2).

Based on the experiences gained from the traditional craft technique of kerfing, we have established and formalized calculations for the most effective cut patterns using a parametric set-up. Given wood's anisotropic nature, calculations are only an approximation. Individual properties such as wood grain and humidity, unique to every piece of wood, influence the material behavior.

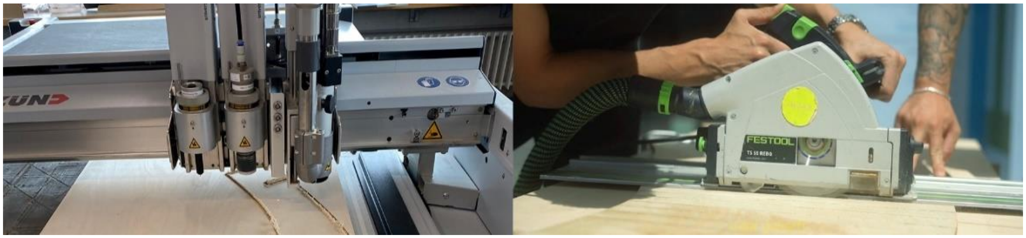

Figure 3
Combining different modes of digital fabrication and craft

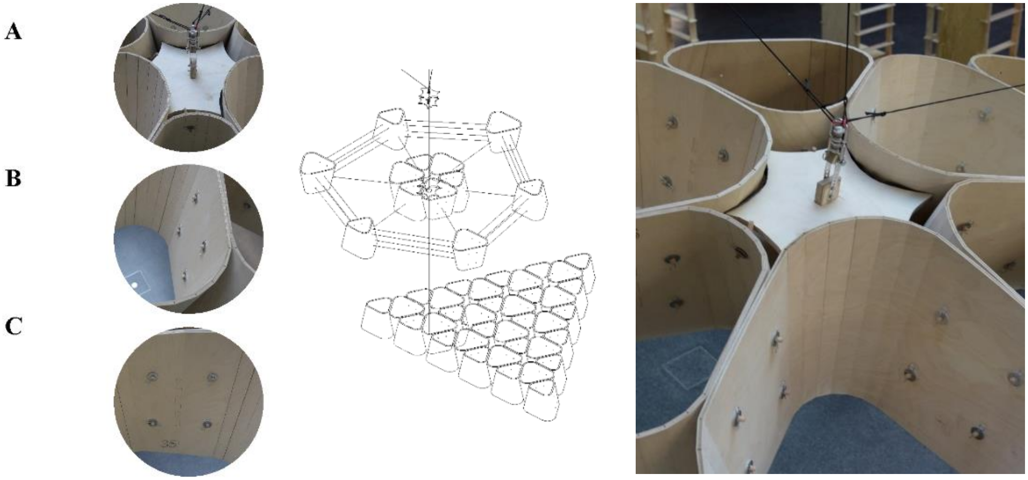

Figure 4 Aggregation principle and detailing of friction-based connection

A series of material tests were conducted to investigate the potential for deformation in specific wood materials. The tests involved the creation of incisions with different geometries and the subsequent examination of the resulting deformations. The focus was set on single-curved bending, with one-sided and two-sided kerf patterns being tested.

The objective of the material experiments was to assess both aesthetic and structural issues. One-sided kerf patterns enable the generation of two distinct bending types: expansion bending and compression bending. This is contingent upon the location of the incisions, with those on the exterior of a curved shape facilitating expansion bending and those on the interior enabling compression bending.

This research pursues compression bending, aiming to maintain the material's structural integrity. In bent state, incisions on the inner side of a curvature, the incisions are compressed to almost zero, thereby closing the material gap and maintaining the flow of compression forces.

To close the gaps completely across the entire thickness of the material, the incisions must be tapered. This requires either a conical milling cutter or multi-axis milling. In both cases, the width of the kerfs, when bending sheets in the range of 8 to 20 mm thickness, should not exceed 3-4 mm, which would require the use of very small cutting tools. When working on such small dimensions, it is irrelevant whether the incision is rectangular or conical. Consequently, we opted for the use of straight cutters to apply the kerfs, employing a low-tech manufacturing approach.

The cuts were achieved through 2D milling only, interlacing digital processes and handcraft. Digital fabrication tools are crucial for cutting the curved outlines and marking the exact positions of the kerf lines, while analog tools, particularly saw blades, are highly effective to achieve the full depth of the kerfs (Fig. 3).

Besides the cut pattern, the flexibility and humidity of different wood types are crucial. Beech wood is particularly suitable due to its flexibility and resilience. Plywood is easier to bend than solid wood because it consists of several thinner layers.

For our cutting and milling processes, we chose 8mm thick beech plywood as the optimal material. When using plywood, the grain direction is less significant. In our case, the wood grain of the top layer was oriented along the longer edge of the unrolled elements.

Aggregate Structure and Detailing

Building on previous experiments, a cone-shaped base module was selected and aggregated to a lattice structure. Using parametric 3D modelling, we developed connection methods, joint logic, overall composition, and fabrication data (unfolded panels with incisions). The Kerf Canopy is comprised of 36 laminated timber modules with varying geometries, collectively covering 12 m^2 and weighing 150 kg.

The 36 flat-cut panels were bent into conical modules using controlled watering, and secured with custom puzzle joints. These conical structures act as pre-stressed rings, as the bending of the grooves adds load transfer capacity (Fig. 2).

Subsequently, the modules were aggregated and interconnected with reversible friction joints to form a roof-like structure (Fig. 4). Each module is connected to its adjacent neighbors by four wooden pins, with rubber washers ensuring the necessary friction. Finally, a metal splint-pin is employed to secure the connection.

The overall roof structure is suspended by three supports and six ropes within a larger atrium. To determine the exact hanging position and cable lengths, the physics simulation Kangaroo in Grasshopper was used (Fig. 5). This simplified approach employed six springs, arranged in three spring pairs, which represent the suspension cables. The rigid wooden geometry is oriented in space to the springs' endpoints. By adjusting the individual cable length, the orientation and equilibrium of the structure in space are determined for the installation.

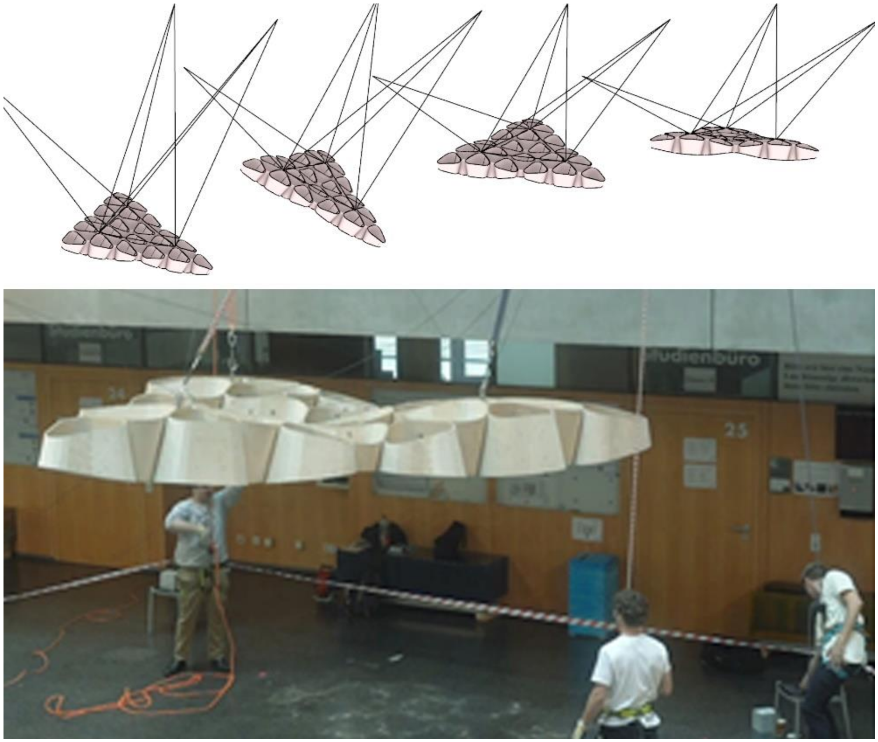

Figure 5
top: Kangaroo-simulation showing different states of equilibrium;
bottom: installation process

LOAD BEARING BEHAVIOR

The chosen structural typology of a modular beam grid performs well in the real-world demonstrator, even though the out-of-plane bending stiffness of the modules is already low due to the chosen small thickness, which is further reduced by the kerfs. This means that loads perpendicular to the element planes should be avoided to ensure a stable supporting structure (Fig. 6).

We observed that the membrane's load-bearing capacity and stiffness is maintained due to the pre-stressing caused by the shaping of the modules and the vertical layout of the kerf incisions. Therefore, the chosen geometry and connection type (i.e. precise interlocking puzzle joints and friction connections) allowed the development of a non-directional beam grid.

To gain a better understanding of the load bearing behavior of kerfed wood structures, two different parametric FE-models were set up in Karamba 3D. These models represent a partial section of the canopy, and correspond to a single-span-beam with two cantilevers and two support points. For simplification, the height of the modules was assumed to be constant.

For the first Karamba set-up ("truss model"), the elements were modelled as detailed truss structure (Fig. 7 left). The friction connections between the modules are mapped with spring elements in order to check the influence of the connection type on the overall model by varying their stiffness.

Four connecting springs are modelled at each connection between the modules, mimicking the bolt position of the real world assembly detail. By connecting the springs to the vertical members of the truss, these elements receive local bending, which in reality is dissipated by membrane forces in the modules.

To approximate a realistic load-bearing behavior, these cross-sections are represented as rectangular profiles with increased width in the module plane. Stiff connecting rods at the support points correspond to the aforementioned support detail. They allow the support structure to rotate around the suspension point and rigidly connect the modules at this point - just as in reality.

To explore the if the precision of the first simulation set-up is necessary, a second, simplified Karamba set-up ("beam model") was established, not considering the inclination of the conical module sidewalls. It consists of beam elements with no inclination, represented by straight curve extrusions (Fig. 7 right). To connect the modules, all springs lie in one plane, positioned in the middle of the cones. This leads to a reduction in the number of springs (in comparison to the first set-up, which used two planes), resulting in four connection springs for each sidewall.

A comparison of the results of the two different parametric FE-models shows that the inclination of the sidewalls plays only a subordinate role for the load-bearing behavior of the structures, due to the low overall curvature and the flexible support in the horizontal direction. Both models have a low stiffness perpendicular to the element plane due to their structure (cross-section or truss itself). This verifies the assumption that the connection details are significantly subjected to shear/hole friction or friction between the modules.

Both Karamba models show similar overall load-bearing behavior. The expected moment distribution for single-span beams with cantilever arms is shown along the main axis of the models between the support points (Fig. 8). In the truss model, this is represented by the normal forces in the upper/lower chord, also high forces occur in the diagonals in areas of high shear forces (near the supports). In the center of the span, it can also be observed that the structure allows a multi-axial load-bearing effect. The modules that are not directly connected to the main axis are activated by the connectors, and thus contribute to the load transfer.

If the structure is too soft or if larger spans need to be covered, the system could easily be reinforced by inserting additional straight elements between the supports. Furthermore, overlapping joints are easily conceivable, so that possible spans are not restricted by the available slab sizes.

Figure 6
Lateral and perpendicular bending stiffness performance

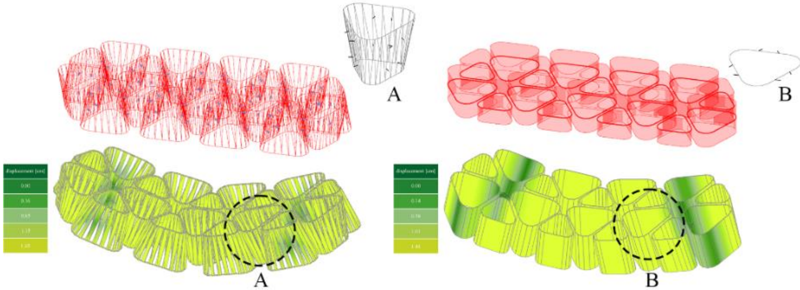

Figure 7
FE-model of a partial section of the canopy: comparison of (A) truss model and (B) beam model: top row: geometric setup; bottom row: displacement

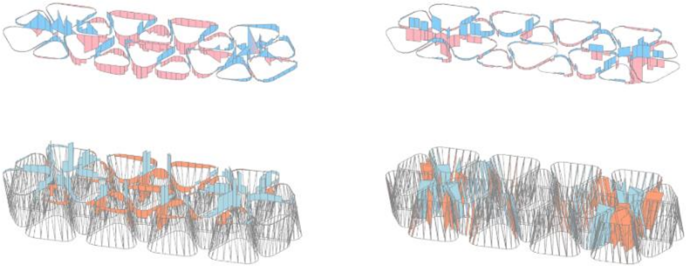

Figure 8
top row: distribution of bending moment My; bottom left: normal forces upper truss chord; bottom right: shear forces beam model

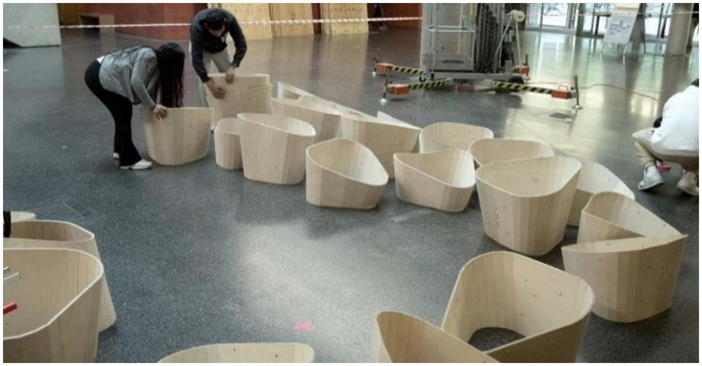

Figure 9
Assembly process of the cellular structure

Table 1
Comparison of load bearing behaviour of truss model and beam model

FE-model	Connection spring rigidity (Tx,Ty,Tz,Rx,Ry,Rz) in kN/cm and KNm	Max. displacement [cm]
Truss model		
a	100; 100;100; 100; 100; 100	4.77
b	100; 100;100; **0,01**; 100; 100	4.99
c	100; 100;100; **0,01; 0,01; 0,01**	5.14
d	**0.01;** 100;100; **0,01; 0,01; 0,01**	**7.67**
Beam model		
a	100; 100;100; 100; 100; 100	2.42
b	100; 100;100; **0.01**; 100; 100	2,69
c	100; 100;100; **0.01**; 100; **0.01**	2.96
d	100; 100;100; **0.01**; **0.01**; **0.01**	**94,3**
e	100; 100;100; 0.01; **1**; **0,01**	8.48
f	**0.01**; 100;100; **0.01; 1; 0,01**	**8.48**

To evaluate the load-bearing behavior, the two FE-models are compared with different spring stiffness for the connecting elements (Table 1). Due to the low stiffness of the modules in relation to out-of-plane bending, the rotational spring stiffnesses are first reduced (truss model b-c, see Table1).

The truss model shows that they hardly influence the overall stiffness of the system. Even a reduction of the spring stiffness in the direction of the connecting elements (normal force of the bolted connection, see Fig. 4B) leads to a slight increase in deformations (truss model d). To a certain extent, the friction bolt connections prevent the modules from gaping apart under bending loads perpendicular to the module face. This is less relevant in the real model due to the inclined position of the module faces of the connection area.

The interpretation of the truss model requires a detailed consideration at the connection level. Due to the lack of a second row of connecting elements in the beam model, the deformation increases significantly (beam model d), if all three rotational stiffnesses are reduced.

The second row of bolts significantly increases the rotational rigidity of the connection. This becomes apparent when comparing the two FE models.

The shear stiffness of the connection is decisive for the stiffness of the overall system. The parallel alignment of the modules in the connections leads to a mixture of frictional impact and shear connection via pre-tensioning of the connecting screws. This load bearing behavior is confirmed by both FE-models (Table 1).

As the shear stiffness of the connections prevents the connected surfaces from moving and rotating against each other, and thus ensures the load-bearing capacity of the overall system, the connections should be optimized in this respect. Therefore, frictional connections and large bolt spacings in the sidewalls are crucial to reduce the bearing stresses in the modules.

CONCLUSION

This research demonstrates the successful integration of aesthetic and structural considerations for kerf-bent structures at an architectural scale by revisiting the traditional craft technique of wood kerfing enhanced with parametric design, digital simulation, and digital fabrication.

This study illustrates a strategy to investigate and analyze the structural performance of a timber roof composed of curved modules, validated through both a 1:1 scale structure (Fig. 9) and digital simulation. This approach allowed us to correlate digital design and FE simulation with physical outcomes, revealing that our structure's load-bearing behavior can be adequately assessed using simplified FE simulations.

Our findings indicate when digital manufacturing is appropriate and when manual craftsmanship is more effective, ensuring a time-efficient and nuanced approach to fabrication. This combination of relatively low-tech fabrication and well-thought-out computational workflow enables the creation of intricate and complex wooden designs. Given the aggregation of relatively small modules with high structural "softness," identifying the appropriate architectural typology of the beam grate was crucial.

The structural simulations provide valuable insights for further improving the performance of "soft" materials. The rigidity between elements was essential for the creation of a self-supporting structure, necessitating the development of effective friction joint details for the 1:1 scale demonstrator. To optimize structural performance, friction between the modules should be further analyzed and enhanced, potentially through surface roughening or intermediate layers.

Overall, the insights gained from developing these design- and fabrication-methods for kerf-bent timber at a building component scale - both on an aesthetic and material level - can inform future research into the reuse of wooden sheet materials at the end of their first lifecycle.

ACKNOWLEDGEMENTS

We would like to thank Prof. Holger Techen for his invaluable support, as well as all participating students.

REFERENCES

'An Exploration on Possibility of Double-Curved Wooden Panels Fabrication' (2019). *IAAC Blog.* Available at: https://www.iaacblog.com/programs/exploration-possibility-double-curved-wooden-panels-fabrication/ (Accessed: 12 January 2024).

Capone, M. and Lanzara, E. (2019). 'Parametric Kerf Bending: Manufacturing Double Curvature Surfaces for Wooden Furniture Design', in F. Bianconi and M. Filippucci (eds*) Digital Wood Design: Innovative Techniques of Representation in Architectural Design*. Cham: Springer International Publishing (Lecture Notes in Civil Engineering), pp. 415–439.

Gillkvist, O., Henriksson, V. and Poulsen, E. (2016). 'Digital Wood - Design & fabrication of a full-scale exhibition structure in plywood', *Master thesis in Architecture*, Chalmers University of Technology.

Gramazio Kohler Architects (2012). Spannungsreihe, Installation im Gewerbemuseum Winterthur für die Ausstellung Wood Loop, Gramazio Kohler Architects, Zürich, in Zusammenarbeit mit: dukta gmbh. Available at: https://www.gramaziokohler.com/web/d/installationen/227.html (Accessed: 12 January 2024).

Kalama, A., Tzoni, D. and Symeonidou I. (2020). 'Kerf Bending: A Genealogy Of Cutting Patterns For Single And Double Curvature' in *Proceedings of the 7th International Conference on Geometry and Graphics MONGEOMETRIJA 2020*, At: Faculty of Mechanical Engineering in Belgrade, Serbia.

'Kerf' Merriam-Webster.com Dictionary, *Merriam-Webster*, https://www.merriam-webster.com/dictionary/kerf. (Accessed 1 Apr. 2024).

'Kerf-Based Complex Wood Systems | achimmenges.net' (2010). Available at: http://www.achimmenges.net/?p=5006 (Accessed: 12 January 2024).

'Kerf Pavilion | MIT Department of Architecture' (2012). Available at: https://www.arch2o.com/kerf-pavilion-mit/ (Accessed: 12 January 2024).

Mitov, D., Tepavčević, B., Stojaković, V. and Bajšanski, I. (2019). 'Kerf Bending Strategy for Thick Planar Sheet Materials' in *Nexus Network Journal 21*, pp. 149–160.

Preisinger, C. and Heimrath M. (2014). 'Karamba—A Toolkit for Parametric Structural De-sign' in *Structural Engineering International 24:2*, pp. 217-221.

Re- Emerge pavilion by EmTech/AA and Hassell (2021). Available at: https://www.metalocus.es/en/news/using-only-reclaimed-wood-re-emerge-pavilion-emtechaa-and-hassell (Accessed: 12 January 2024).

Schindler, C. (2008). 'A Computer-Aided Fabrication Method for Bending Panels without Molds'. Available at: https://www.semanticscholar.org/paper/A-Computer-Aided-Fabrication-Method-for-Bending-Schindler/73b1392cbaa0dd168826eb52f4c73c9fd475af77 (Accessed: 12 January 2024).