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Research article

Digital Fabrication for Circular Timber Construction: A Case Study

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Abstract

The European timber industry has successfully implemented the cascading utilization of wood for several decades, downcycling material resources at the end of each product cycle by turning them into new industrial commodities through additional manufacturing procedures. In its current implementation, this approach is effective in keeping wooden materials in circulation. However, a significant amount of material still reaches the end-of-life stage through incineration prematurely, constituting a considerable waste of valuable resources. Therefore, we propose repurposing low-quality, low-engineered waste wood for architectural applications to avoid unnecessary downcycling processes. Specifically, we suggest a digital design and fabrication method to build tectonic structures using repurposed timber offcuts. As a case study, we present a pavilion structure built at a 1:1 scale, demonstrating the potential of digital technologies for circular timber construction. Based on this case study, we discuss how digital fabrication and material grading can foster a transition towards a circular built environment.

Keywords: Circular Economy, Circular Construction, Cascading Utilization, Waste Wood, Repurposing, Upcycling, Timber Manufacturing, Strength Testing, Digital Fabrication, Computational Design

1. INTRODUCTION

With his 1713 treatise, Hans Carl von Carlowitz heavily influenced our current understanding of sustainable forest management (Warde & Carlowitz, 2017). Indeed, the European timber industry has implemented a concept known as cascading utilization of wood products to a certain extent since at least the 1990s (Höglmeier et al., 2015). This approach involves downcycling material at the end of a product's life cycle to create another product or component. However, as Höglmeier et al. (2015) pointed out, this method currently applies to only a fifth of the timber, with the remaining material being prematurely incinerated. Nevertheless, the concept of cascading utilization holds great potential for conserving valuable resources while promoting contemporary circular economy principles (Mair & Stern, 2017).

Although there are numerous definitions of the circular economy in circulation, Kirchherr et al. (2017) and van Buren et al. (2016) provide tangible frameworks where circular economy aims to create ecological, social, and economic value. Despite the debatable argument that a circular economy may not be entirely feasible (Skene, 2018)—also in the context of wood manufacturing and forestry—an increased use of timber in construction could foster a sustainable building culture, with buildings potentially serving as global carbon sinks (Churkina et al., 2020). To achieve this, it is crucial not only to reuse construction materials currently stored in buildings but also to repurpose production waste from timber manufacturers, thereby prolonging the product cycle and tapping into a valuable resource for

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architectural applications. In this context, digital fabrication, recognized as one of several enabling digital technologies that promote a circular digital built environment (Çetin et al., 2021), may have a significant impact: It enables the alteration of non-standard waste wood with low value through bespoke manufacturing processes, transforming these materials into components with higher value (Dubor et al., 2019).

In this paper, we discuss how technological advancements in digital design and fabrication enable innovative practices in circular timber construction, encompassing both the reuse of components and the upcycling of waste materials. We delve into the range of advanced technologies employed, spanning from computational design methods to digital fabrication processes that utilize a wide array of tools. Subsequently, we present our own work, which serves as a case study involving the transformation of timber offcuts into a full-scale tectonic structure through digital design and fabrication. As such, we discuss the key potentials and challenges associated with digital fabrication in the context of circular timber construction. Furthermore, we outline future research directions aimed at expanding the applicability of this approach to larger scenarios and applications.

1.1 State of the Art

The timber industry began adopting digital fabrication processes in the 1980s, employing CNC machinery to manufacture precise parts and building components. More recent developments have utilized industrial robotic actuators with customized end-effectors, equipped with a range of tools such as chisels, circular saws, chainsaws, and bandsaws, to subtractively remove material as needed (Johns & Foley, 2014; Takabayashi et al., 2019; Vercruysse et al., 2019). Simultaneously, robotic fabrication has opened up new possibilities for additively placing standard timber elements, enabling the construction of large, complex structures like the Sequential Roof of the Arch_Tec_Lab at ETH Zurich (Willmann et al., 2016). Collaborative robotic fabrication methods have even enabled the potential dis- and reassembly of building components made of standardized, discrete timber elements, such as beams (Kunic, Kramberger, et al., 2021; Kunic, Naboni, et al., 2021; Naboni et al., 2021) and balloon frame structures for future reuse cases (Bruun et al., 2022).

These technological advancements have transformed the way reclaimed timber is utilized, sparking renewed interest in recent years. An example is the architecture firm Lendager, which incorporates reclaimed wood as both interior and exterior cladding materials in their projects (Lendager & Pedersen, 2020). However, despite the potential benefits of digital technologies, much of the labor involved remains manual. A primary obstacle of timber reuse is material grading, a significant and labor-intensive challenge exacerbated by the absence of certification systems (Bergsagel & Heisel, 2023; Browne et al., 2022).

Despite the challenges encountered, digital technologies, including digital fabrication and computational design methods, hold tremendous potential for repurposing waste wood (Finch & Marriage, 2019). These technologies enhance the efficiency of material reuse, making the approach more accessible. The concept of Form Follows Availability, suggesting that design should adapt to the available material, is particularly relevant in this context. Linear matching algorithms serve as a computational implementation of this concept, as demonstrated by various projects (Brütting et al., 2019; Luczkowski et al., 2023; Warmuth et al., 2021). This computational method, when combined with multi-objective optimization algorithms, has been employed to design and fabricate diverse structures using reclaimed timber beams. Examples include domes (B. Byers & De Wolf, 2023; B. S. Byers et al., 2022; Huang et al., 2021) and reciprocal frame systems with reversible joints (Browne et al., 2021; Castriotto et al., 2022).

In addition to reusing discarded wood from buildings, several research projects are exploring the repurposing of waste wood from all stages of timber manufacturing, including small diameter raw logs and tree forks (Bukauskas et al., 2019). The natural shape of these materials is leveraged through 3D scanning, extensively applied in the construction of aggregated structures through combinatorial processes (Allner et al., 2020; Kerezov et al., 2022), mass timber wall prototypes (Wójcik & Strumiłło, 2014), nexorades (Vestartas et al., 2021), as well as free-form gridshells (Aagaard & Larsen, 2020; Larsen et al., 2022; Larsen & Aagaard, 2020), facilitated by augmented-reality assisted assembly (Cousin et al., 2023; Lok et al., 2021; Lok & Bae, 2022). The exploitation of the material's natural shape has proven to be structurally advantageous even in the construction of large-scale pavilion structures

(Self & Vercruysse, 2017). Furthermore, tree forks have shown promise as load-bearing joints (Amtsberg et al., 2020).

Repurposing production waste from cross-laminated timber (CLT) production has been a subject of investigation as well. The range of applications is again divers and includes mass timber walls (Poteschkin et al., 2019), shell structures (Robeller & Von Haaren, 2020), as well as interlocking systems for reciprocal structures (Augustynowicz & Aigner, 2023) and reconfigurable structures (Hudert & Mangliár, 2023; Mangliár & Hudert, 2022b, 2022a).

Despite its potential, short pieces of reclaimed timber have received comparatively less attention. This could be attributed to their dimensionality and the inherent diversity of the material available. For instance, Cousin constructed shingle envelopes using reclaimed pallet wood (Cousin, 2022), whereas Sunshine employed short logs to construct beams and vaults (Sunshine, 2022). This nowadays untapped potential was already exploited in the 16th century when de l'Orme utilized short timber offcuts for constructing free-form structures (Tutsch, 2020). The only feasible method for building such curved shapes was through discretization until the emergence of curved laminated beams, rendering the labor-intensive process of using short timber redundant (Müller, 2000). Yet, the construction of complex free-form timber structures on a large scale only became feasible with the advancements in computational design and digital fabrication technologies (Stehling, Scheurer, & Roulier, 2017). These developments have proven successful in constructing numerous buildings with free-form gridshells employing glulams (Chai & Yuan, 2019; Stehling et al., 2020; Stehling, Scheurer, Roulier, et al., 2017; Stehling & Scheurer, 2017; Yuan et al., 2016; Yuan & Chai, 2017). Svilans et al. further advanced the design-to-fabrication workflows related to such free-form glulam structures, leading to more informed design decisions, optimized building components, and novel timber morphologies (Svilans et al., 2019).

1.2 Problem Statement and Contribution

As discussed in Section 2, digital fabrication processes in timber manufacturing have reached a high level of sophistication, enabling both additive and subtractive manipulation of materials with a wide range of tools. When combined with computational design methods, these processes have made it feasible to reuse and repurpose non-standard reclaimed timber sourced from demolition, harvesting, and production waste. However, none of the previous projects explored how short, brick-like offcuts from structural timber production can be employed to construct free-form shapes. Furthermore, the challenge of grading and assessing the reclaimed timber is often left unaddressed.

Within the context of these developments, we propose a new methodology, addressing two issues: First, we harness tailored computational design methods and digital fabrication processes to repurpose timber offcuts generated during the production of solid structural timber beams. These beams are composed of five-meter-long timber elements extended with glued finger joints. Manufacturers typically cut out any imperfections occurring in these immaculate products, thereby producing offcuts that they then incinerate due to the materials short, non-standard size. Our approach involves rescuing, grading, and subjecting this material to critical assessment through destructive strength testing, leveraging digital technologies to efficiently process the vast quantity of unique elements available. Second, we employ this material to design, fabricate, and construct low-engineered free-form timber structures. This approach avoids the complex task of laminating double-curved beams by capitalizing on the shorter length of these offcuts, allowing for the discretization of timber assemblies. While acknowledging the rough shapes resulting from this process, we emphasize the practicality and sustainability of this approach. Ultimately, identifying a suitable structural application for these offcuts might extend their product cycle, fostering a discussion of how we treat natural resources.

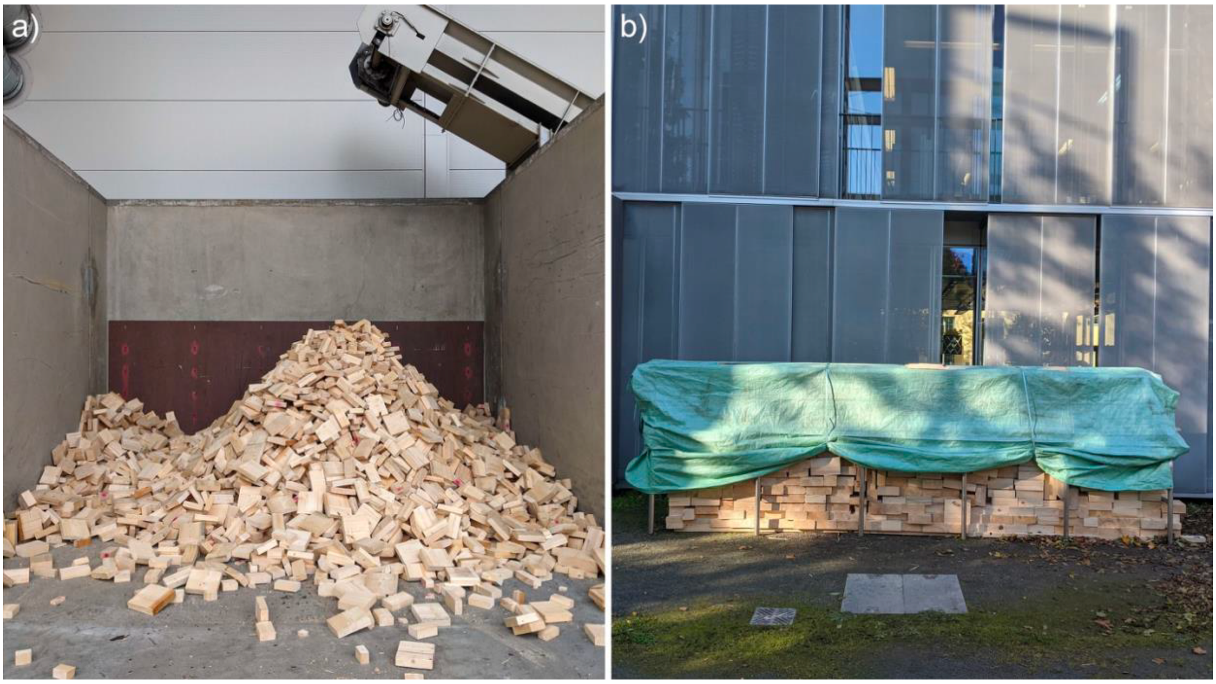

Figure 1. The Complexity of Repurposing Vast Amounts of Irregular Waste Timber Offcuts: a) Offcut Storage Space at a Timber Manufacturing Company, Producing up to 12,000 M3 of Offcuts per Year. b) Temporary Physical Storage Space of Approximately 400 Offcuts, Which Were Used in This Research Project. 2021.

2. METHODS

2.1 Computational Design

In our study, we employ an experimental-empirical approach (Aydemir & Jacoby, 2022), utilizing iterative physical and digital prototyping to develop a design-to-fabrication workflow suitable for repurposing timber offcuts. In particular, this involves the development of appropriate computational methods, as outlined in a previous publication (Reisach et al., 2023). Essentially, we created an algorithm that generates timber offcuts from a database and places them on lines or curves using numerical matching and vector-based spatial localization. This algorithm is compiled as a plugin for the Rhino3D/Grasshopper software environment and is publicly accessible, along with example files, in a GitHub repository (Reisach, 2023b). It achieves a geometric aggregation of offcuts into non-standard curve-based structures.

The database contains an entry for every offcut, including an ID and the three main dimensions. These measurements were taken manually to streamline the process, avoiding the need to work with scanned high-resolution 3D models, which proved unnecessary. Building upon previous work on free-form timber structures, the placement process is optimized, smoothly discretizing the free-form shapes while reducing material waste during fabrication. As these shapes are composed of a large number of discrete offcuts, the algorithm also computes dry wood joints to connect them all, creating cohesive structural elements. Ultimately, this computational design method generates fabrication data, enabling each element to be cut as designated in the digital blueprint.

2.2 Digital Fabrication

In this research project, we are dealing with a large number of unique offcuts. Using these offcuts to construct the previously conceived free-form designs requires bespoke angled cuts for each element. Such tasks are impractical to perform manually and are therefore best suited for digital fabrication. To accomplish this, we employed two digital fabrication setups (see Figure 2). The first setup featured a Universal Robots UR10e, equipped with a custom end-effector, holding a BIAX RE 2860 milling spindle, and a Robotiq 2F-85 gripper with a stroke span of 85 mm. The robot was controlled using HAL Robotics, a plugin for Rhino3D/Grasshopper, enabling a virtual simulation of the fabrication, and, as such, a seamless transition from design, detailing, and toolpath generation within the same environment. This system was used for prototyping and testing assembly logics and constraints (see Section 4.2). The second setup was employed for fabricating the specimens used in the strength tests (see Section 4.1), and the final offcut elements for the demonstrator (see Section 4.3). It involved a MAKA 5-axis CNC machine, controlled with the Tebis CAM software. To generate the toolpaths and fabrication instructions in Tebis, the relevant geometrical data had to be transferred from Rhino3D. Both setups proved effective and efficient, allowing to integrate, calibrate, and validate the computational design approach, while producing the physical specimens and the final prototype elements.

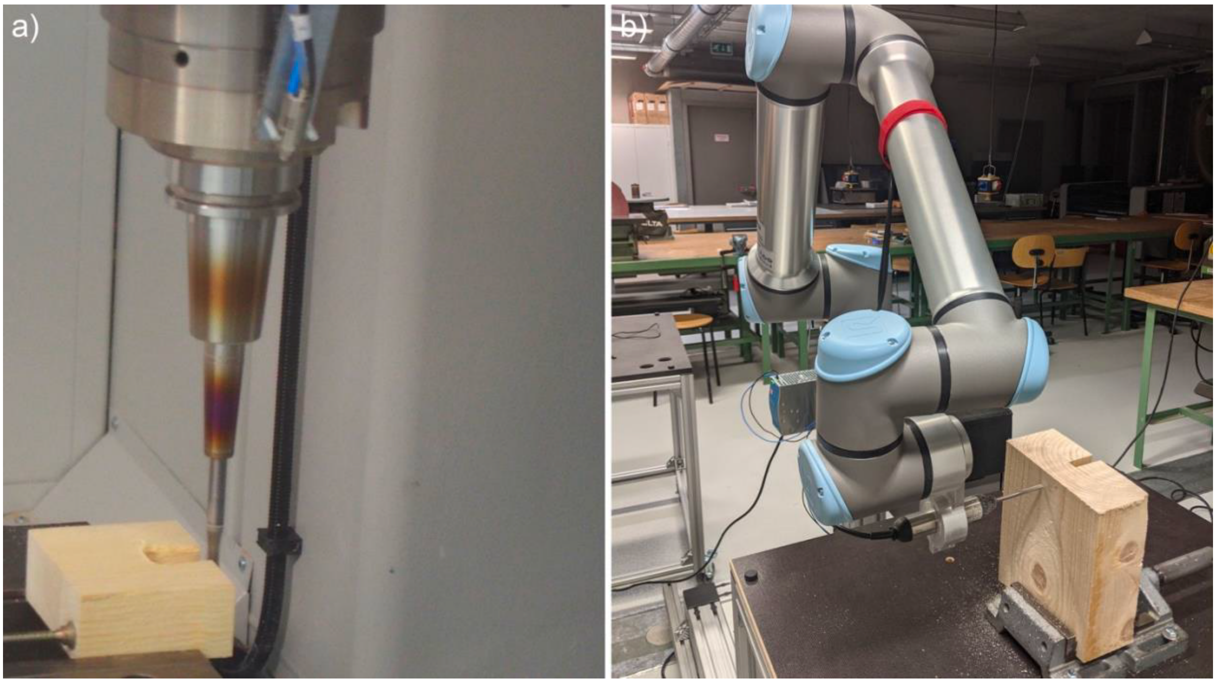

Figure 2. Digital Fabrication Setups: a) Maka 5-Axis CNC Machine, Milling a Specimen for the Strength Tests. b) UR10e Robotic Arm, Milling the Joint of an Offcut for the Prototype With a Custom End-Effector. 2022.

2.3 Material Grading Through Quantitative Assessments

The utilization of waste wood, specifically offcuts in this research, carries inherent risks due to the unique and obscure history of each element: Some of these elements may have been exposed to weathering, while others were discarded due structural defects or solely due to aesthetic imperfections such as blue mold or knots. Moreover, gaining a comprehensive understanding of the qualities of these offcuts, and waste wood in general, poses a significant challenge and remains a major barrier to their reuse and repurposing (Browne et al., 2022). Despite working with offcuts of Norway spruce (Picea abies) with a strength class of C24 according to EN 338:2016 (European Committee for Standardization (CEN), 2016), there are currently no certification standards for any type of waste wood. To attain the clarity necessary for the structural use of these offcuts, we conducted a series of destructive strength tests in accordance with EN 408:2010+A1:2012 (European Committee for Standardization (CEN), 2012). This included a tension strength test parallel to the grain and a shear strength test perpendicular to the grain (see Figure 3).[5]

Each test included six specimens, with half of them featuring two loose spline joints (group 1), and the other half having one loose spline joint (group 2). Each group contained the minimum number of specimens to achieve statistical significance. The comparison of results, specifically the median

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[5] Conducting bending tests would have been beneficial as well. However, due to limited resources, this was not possible in this work.

maximum force of the groups, aimed to understand the influence of the quantity of joints present. While these results offer insights into the suitability of the loose spline joint typology, they also provide an indication of the reclaimed wood's general suitability. The testing procedure simulates the actual use case of the timber elements and joints, both made of the same reclaimed wood.

The maximum dimensions of the specimens were 150 mm × 35 mm × 90 mm, as determined by the universal testing machine (UTM) used for these tests. In the end, we compared the results obtained with the UTM to standard values of Norway spruce with a strength class of C24 according to EN 338:2016 (European Committee for Standardization (CEN), 2016)

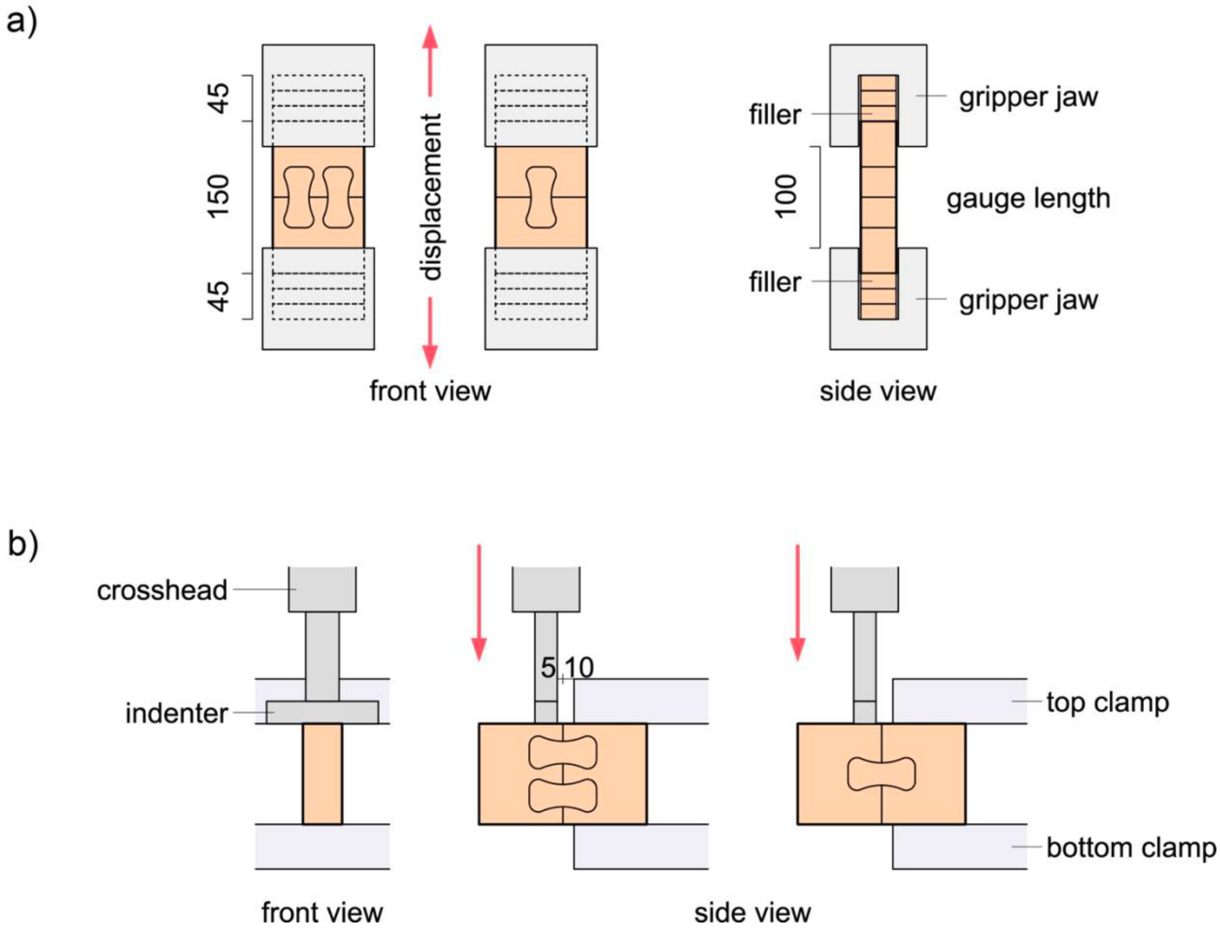

Figure 3. The Setups of the Strength Tests: a) Tension Strength Test, b) Shear Strength Test. 2022.

3. RESULTS

3.1 Strength Tests

The setup of the tension strength test is depicted in figure 3.a). The standard testing procedure requires reaching the maximum load, i.e., the point of failure, in 300 s ± 120 s (European Committee for Standardization (CEN), 2012). To reach this target, we set the crosshead movement speed of the UTM to 1 mm/min with a pre-loading cycle of 0.1 kN. With these settings, the UTM pulled each specimen until failure, indicated by a rapid fall in load capacity. Figure 4 portrays the results of the tension strength tests, with the values on the x-axis representing the displacement *u* [mm] and the values on the y-axis representing the load *F* [kN]. Specimens 1–3 (group one) have two loose spline joints, and specimens 4–6 (group two) have one loose spline joint.

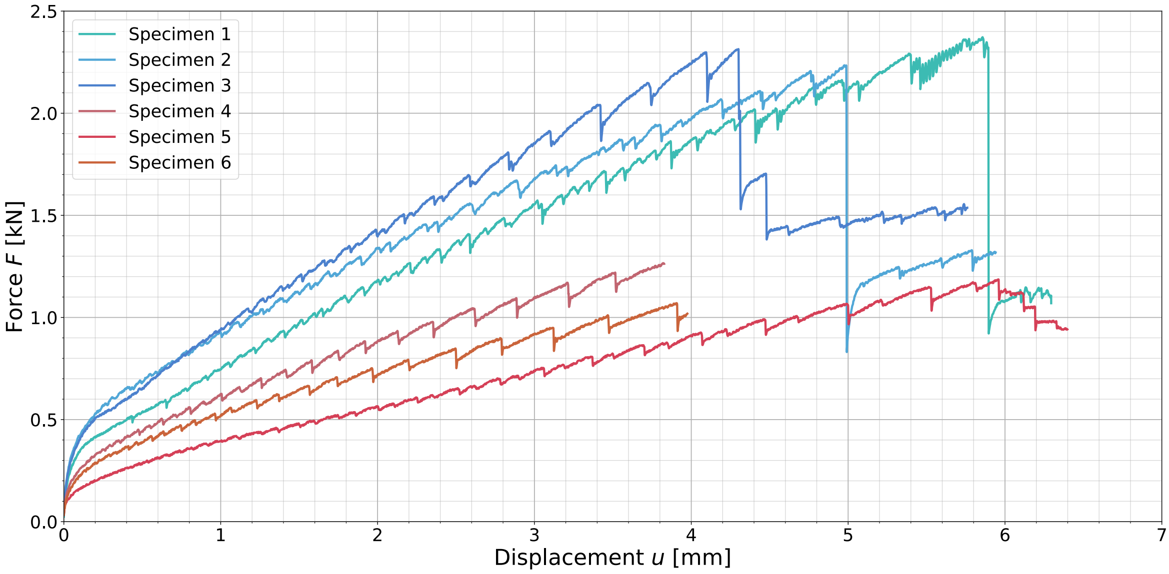

Figure 4. The Results of the Tension Strenght Test. 2022.

The graph shows a steady increase in load and displacement, with fluctuations caused by slippage and deformation of the timber components, until the tension is too high and the specimens fail. The maximum load capacity of group one was 2.23–2.37 kN, with a displacement of 4.30–5.86 mm, whereas group two demonstrated a maximum load capacity of 1.07–1.26 kN with a displacement of 3.82–5.96 mm. The tension strength parallel to the grain is calculated according to EN 408:2010+A1:2012 (European Committee for Standardization (CEN), 2012), where:

$$f_{t,0} = \frac{F_{max}}{A}$$

With F_{max} [N] being the maximum load and A [mm^2] the surface area, i.e., the minimum cross-section of one loose spline joint. For each group, we calculated the median value of F_{max}. The resulting tension strength parallel to the grain of group one is 1.88 N/mm^2, and for group two is 1.92 N/mm^2:

$$f_{t,0} = \frac{2306N}{2 \times 612.5\ mm^2} = 1.88\frac{N}{mm^2}$$

$$f_{t,0} = \frac{1174N}{612.5\ mm^2} = 1.92\frac{N}{mm^2}$$

The results suggest a linear relationship between the number of joints and the maximum load, as specimens in group one, with two loose spline joints, exhibited double the load capacity compared to group two. This implies that both groups possess similar tension strength parallel to the grain, with a permissible deviation of 2%. In comparison to standard C24 softwood with a tension strength of 14.5 N/mm^2 (European Committee for Standardization (CEN), 2016), our specimens demonstrated only 13% of this capacity. However, it's important to note that our strength tests primarily reflect the load capacity of the components, specifically the joints, rather than the waste wood itself. Additionally, transversal forces played a significant role, with the joints acting as wedges and causing the wood to split. We will provide a more comprehensive interpretation of these results in Section 5.

The setup of the shear strength test is depicted in figure 3.b). Here, the UTM clamps the specimens on one side and vertically pushes the other side with an indenter, inducing shear forces. Again, the procedure requires reaching the maximum load in 300 s ± 120 s. To stay within this time constraint, we set the crosshead movement speed of the UTM to 2 mm/min with a pre-loading cycle of 0.1 kN. Figure 5 portrays the results of the shear strength tests. Again, the values in x represent the displacement u [mm], and the values in y represent the load F [kN]. Specimens 1–3 (group one) have two loose spline joints, and specimens 4–6 (group two) have one loose spline joint.

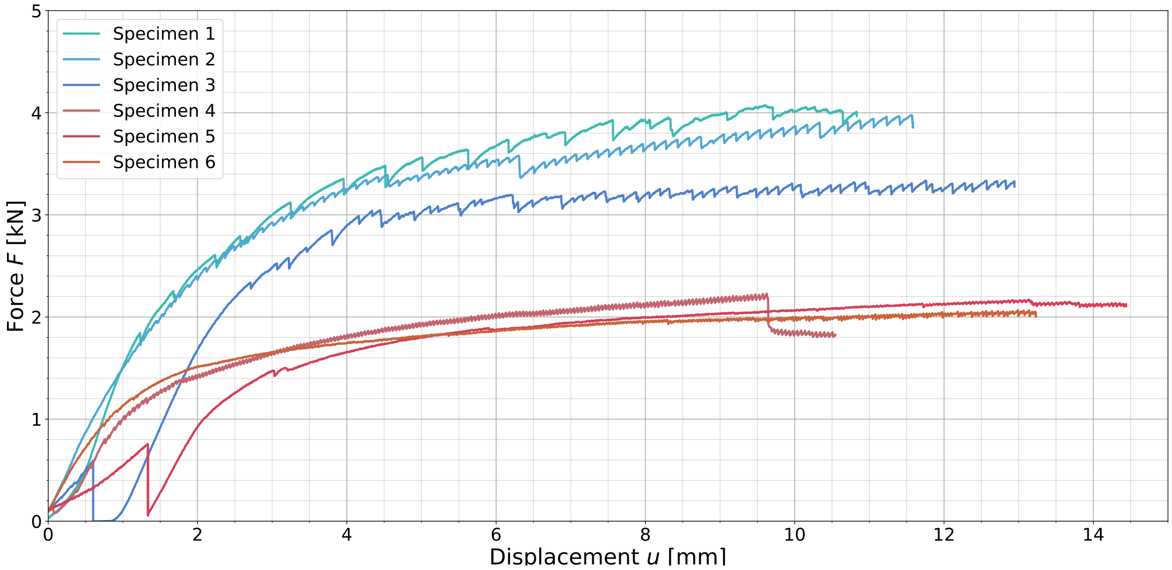

Figure 5. The Results of the Shear Strenght Test. 2022.

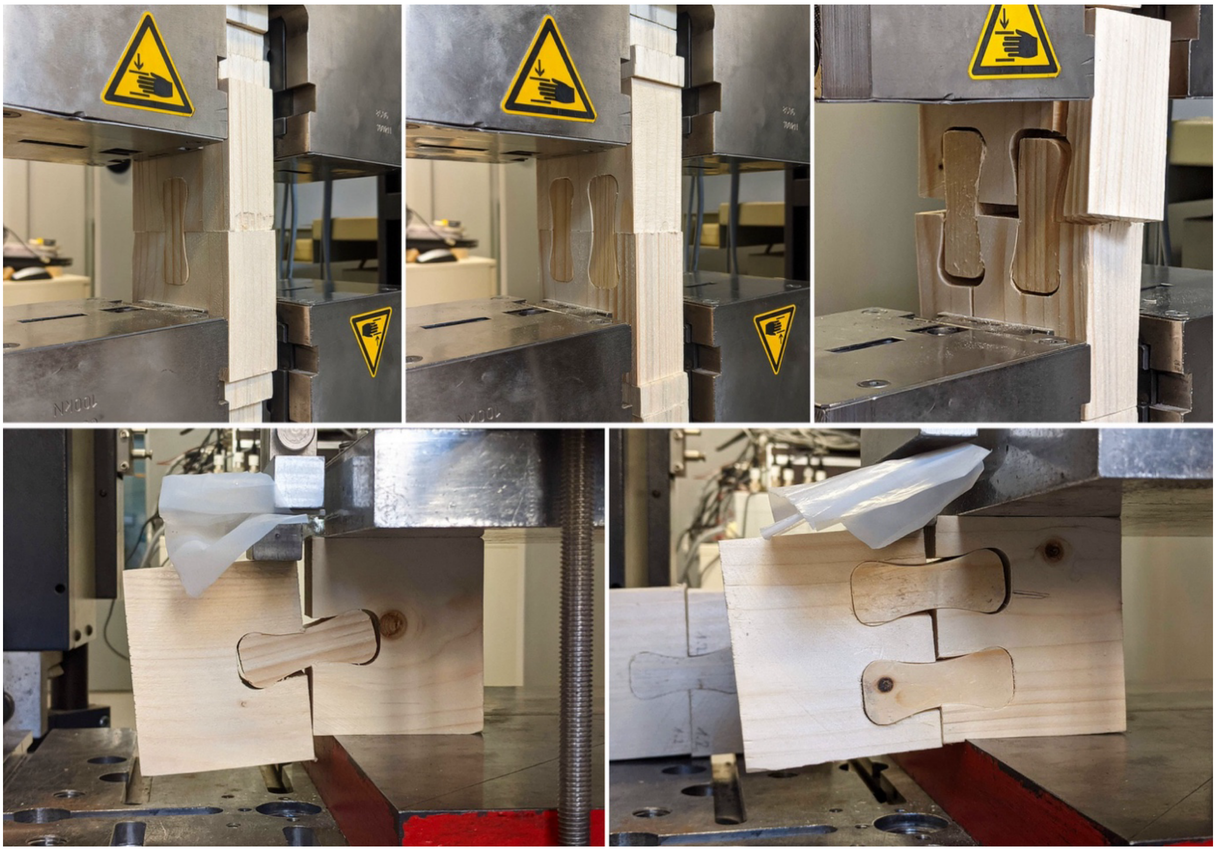

Figure 6. Strength Testing of the Specimens: Top: Tension Strength Test at the Beginning and the End the Test. Bottom: Shear Strength Test at the End of the Test. 2022.

The graph shows a steep increase as the loads are rising. This trend eventually flattens off with the loads staying almost constant, even though the displacement is still increasing. This is probably due to the material properties of Norway spruce, which is a softwood with high elasticity, making it difficult to break through shear testing. The maximum load capacity of group one was 3.3–4.1 kN, and of group two was 2.1–2.3 kN. To calculate the shear strength perpendicular to the grain, we use the same equation and procedure as before. The resulting shear strength parallel to the grain of group one is 3.1 N/mm^2 and for group two is 3.5 N/mm^2:

$$f_{t,0} = \frac{3795N}{2 \times 612.5\ mm^2} = 3.10 \frac{N}{mm^2}$$

$$f_{t,0} = \frac{2154N}{612.5\ mm^2} = 3.52 \frac{N}{mm^2}$$

However, we adjusted the calculation for group one after excluding specimen 3, because it had a crack that falsified the results. Accordingly, the new result for group one is 3.27 N/mm^2:

$$f_{t,0} = \frac{4025N}{2 \times 612.5\ mm^2} = 3.27 \frac{N}{mm^2}$$

These results indicate a linear relationship between the number of joints and the maximum load as well, despite the deviation between the two results being 7%. Compared to standard C24 softwood with a shear strength of 4.0 N/mm^2 (European Committee for Standardization (CEN), 2016), our specimens demonstrated a capacity of 82% (group one) and 88% (group two) of this reference value. In this testing setup, the bending strength of the material played a critical role since the specimens did not fail because of their elasticity. Failure was observed only in cases where pre-existing cracks were present (see Figure 6). Conversely, since more joints increase the stiffness of the component, they are less able to deform, which is potentially the reason why group two demonstrated a higher capacity to withstand the loads.

3.1 Research Prototypes

To test and verify the feasibility of free-form offcut structures, we fabricated several research prototypes, including initial hand-crafted ones. A critical aspect for building these prototypes with both digital fabrication setups was the way of securing offcuts to the machine table. The robotic actuator could access all sides except the back of the offcut, necessitating them to be placed upright. In contrast, the CNC setup offered more flexibility due to its size, allowing us to fix offcuts on the side and mill each offcut in one go, thus avoiding any repositioning.

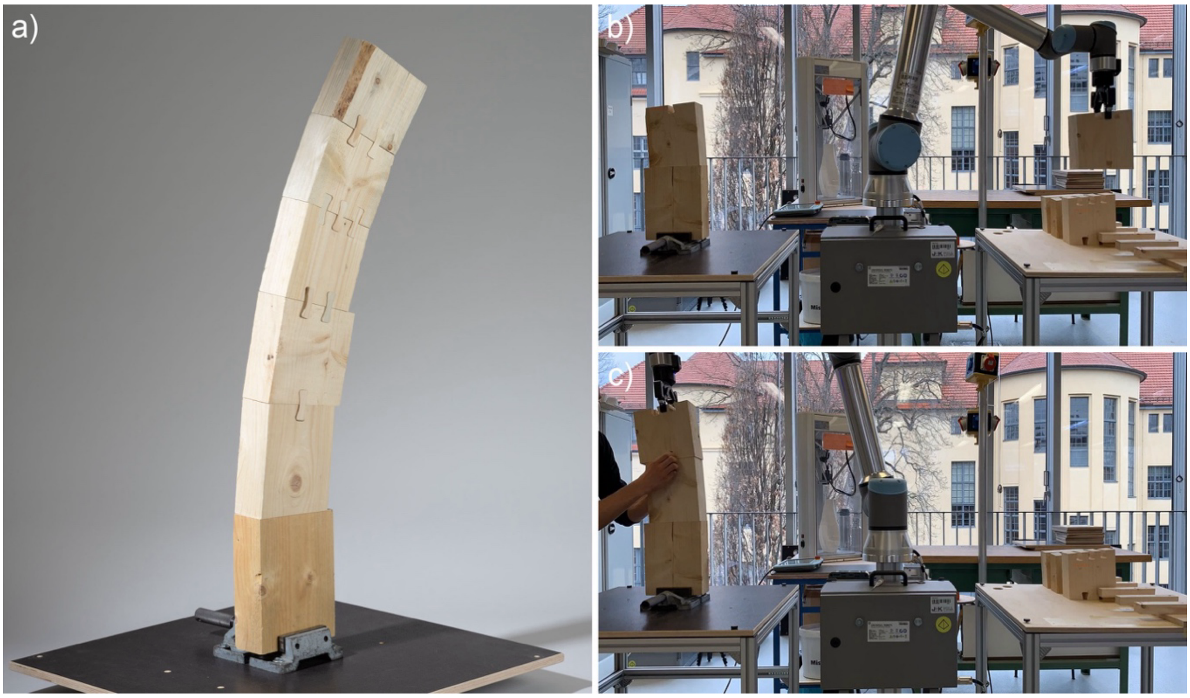

Figure 7. a) the Assembled Research Prototype. b) & c) Collaborative Human-Robot Assembly of the Research Prototype. 2022.

We established a functional setup, including determining the maximum feasible fabrication settings. With this setup, we constructed a research prototype consisting of six offcuts. The goal of this prototype was to demonstrate that the devised computational methods and, in particular, the design-to-fabrication workflow were both feasible and scalable. This prototype featured double curvature, involving internal torsion, which required angled cuts in a specific direction that could not be achieved by humans. Moreover, each connection consisted of a different set of dry wood joints, including two loose tenons and one to three loose spline joints, all without the use of adhesives. All components, including the joints, were fabricated using the robotic setup described in Section 3.2. Careful attention was paid to ensure that the fiber directions ran continuously in parallel with the shape.

The fabrication of the six offcuts and all the joints for the research prototype took 33.4 hours, highlighting the need for faster fabrication methods to achieve scalability. This process resulted in the production of 0.0041 m3 of waste. When comparing these figures to the same research prototype with a non-optimized random placement of offcuts, it becomes evident that the waste produced would have been 50% greater without the optimization algorithm. This demonstrates the success of the optimization algorithm in minimizing waste related to fabrication.

Finally, we also tested a collaborative human-robot assembly of this prototype. In this process, the robot picked up the offcuts from a predetermined spot marked by a scaffold and placed them at designated positions. It held each element in place until a human inserted the loose spline joints, which required dexterity. This process was repeated until the demonstrator was fully assembled (see Figure 7).

3.2 Research Demonstrator

The quantitative results of the strength tests and the empirical findings from the design and robotic fabrication of the initial prototypes formed the foundation for the buildup of a larger demonstrator structure. As such, we referred to an extreme and exemplary structural typology, allowing to effectively test and validate our approach, while enabling the extrapolation of our findings to other typologies and applications. The design of this 1:1 scale demonstrator featured three arches arranged in an equilateral triangle enclosed by a circle with a diameter of 3.5 meters. The arches varied in height, measuring 1.25 meters, 1.5 meters, and 1.75 meters, each exhibiting a 30-degree torsion to ensure a precise meeting of their bases. For the structural aggregation, we required 81 offcut elements, with the first arch composed of 24 offcuts, the second of 25, and the third of 32. These offcuts were connected using 162 loose spline joints, with each pair of offcuts secured by two dry joints, in accordance with the recommendations derived from the strength test results.

The next step was preparing the material. Managing a database of several hundred elements posed a significant challenge, and even when these elements were sorted, it still required a substantial amount of effort to gather specific offcut elements as designated by the digital model. Fortunately, since the material had been stored in a dry enclosed space, there was no need for a re-assessment of the meticulously pre-selected material. Once the required offcuts were gathered, they were transported to the CNC machine. Subsequently, fabrication instructions for each offcut were generated in Tebis by importing the geometric data from Rhino3D. Conversely, the loose spline joints were mass-produced from the same wood, with an additional 0.1 mm milled off their idealized size to ensure both easy insertion and a snug fit.

The milling of the offcuts for the demonstrator took approximately 35 hours and resulted in 0.075 m^3 of waste. The complete demonstrator had a material volume of 0.23 m^3, with 0.22 m^3 accounting for the offcuts and 0.01 m^3 for the joints. Once all elements were milled, they were sorted according to their arch and sequence. This step was crucial for identifying any missing parts. Subsequently, each arch was assembled on the ground, with the spline joints being manually secured. The assembly process did not require scaffolding or any other buildup devices and could be completed within approximately 15 minutes for each arch. Once assembled, each arch was carried to the designated exhibition site at the Bauhaus-Universität Weimar, Germany, being put into their final position and mechanically fixed.

Two of the arches (arch 1 and arch 2) featured great stiffness in all directions, while the largest arch leaned slightly outward. This phenomenon may have been caused by a) the shrinkage of the loose spline joints, which introduced tolerances, and b) the mere quantity of short offcuts used in the aggregation, increasing the number of connections required. However, this leaning did not compromise the overall structural stability of arch 3. In a subsequent exhibition, where the demonstrator was disassembled, stored, and reassembled, additional precautions were taken. Tension belts were placed around the demonstrator's feet to prevent slipping and to ensure a robust connection. Following this (second) exhibition, the structure was again disassembled, with some parts stored and others incinerated.

Figure 8. The Demonstrator, a Pavilion-Like Installation, Showcasing the Potential of Repurposing Offcuts for Free-Form Timber Structures. It Proves That the Conceived Computational Design Methods and Digital Fabrication Processes Are Suitable to Build Such Offcut Assemblies, Featuring a Unique Aesthetic Expression Driven by the Unprocessed Material. It Further Proves That These Digital Technologies Can Be Drivers for Circular Construction Practices. Photographs by Michael Braun, 2022.

4. DISCUSSION

The results of Section 4 highlighted the apparent necessity of several methods discussed in this paper for repurposing timber offcuts for architectural applications. In particular, destructive strength testing has proven to be essential for grading and quantitatively assessing the material and joint behavior under load conditions. In general, the results indicate that the material might be suitable for structural use cases as long as no cracks are present. More specifically, the findings suggest that increasing the number of joints distributes forces more evenly, leading to enhanced stiffness, stability, and increased tension and shear strength of the connection. Moreover, the size of the loose spline joints should be proportional to the component size to achieve a more realistic behavior of the connection. While these results are promising, conducting tests on more and larger components could yield more statistically significant insights. Additionally, enriching the methods by performing finite element analyses and bending tests would further enhance the comprehensiveness of the study. Ultimately, the strength tests have provided sufficient insights to proceed with prototyping. The recommendation is to use at least two joints, and preferably three or four joints for larger assemblies, thus emulating finger joints.

These insights are complemented symbiotically by the reversibility of the timber-only joints. Grüter et al. demonstrated that the strategy of design-for-disassembly, employed in this context, enables easier repairs and future component reuse if the joints are reversible (Grüter et al., 2023). Paired with reduced assembly and disassembly times (Finch & Marriage, 2019), such joints have the potential to enhance the competitiveness of circular economy principles in the construction industry (Grüter et al., 2023).

The complex geometry of the offcuts, their quantity, unique cuts, and their spatial relationship in free-form assemblies justify the use of computational design methods and digital fabrication processes. Together, this specific design-to-fabrication workflow has proven to be feasible and scalable, as evidenced by the design and construction of the prototypes and the demonstrator. In particular, this workflow has enabled the fast and robust generation of geometries and fabrication data, facilitating the manufacturing of unique offcuts with precise and tight-fitting connections under digital guidance. The optimized planning method effectively minimizes material waste related to fabrication. While the material loss in the form of sawdust can reach up to 25% of the material used, it remains below the industry standard of up to 50% (Höglmeier et al., 2015). However, this also implies that our method has the potential to reintroduce 75% of reclaimed timber into the resource cycle. Furthermore, the optimized placement of offcuts emphasizes pronounced curvatures with short elements, ensuring that the wood fibers conform to the flow of the free-form shape. This smoothness contrasts with the jaggedness of the unprocessed offcuts, as their height remains unchanged. Additionally, the research prototype and demonstrator both highlight the unique aesthetic and functional potential of digitally placed timber offcuts, where natural material phenomena such as blue mold, knots, and bark residues became distinctive design features. This notion raises the question of whether every piece needs to be perfectly clean, or if we should instead embrace the unique history of each element, allowing them to convey their stories in order to perform in new ways (Reisach, 2023a). Often seemingly weak-looking elements are much more powerful than thought. Ultimately, these full-scale examples indicate that the conceived workflow enables the effective and efficient repurposing of non-standard timber waste in large quantities, demonstrating the potential of computational methods and digital fabrication to empower the principles of the circular economy in wood manufacturing, advancing the industry towards circular digital timber construction.

5. CONCLUSION

In this paper, we have demonstrated the general potential of using computational methods and digital fabrication in circular timber construction. These methods, particularly the bespoke workflow developed for repurposing offcuts, proved indispensable when effectively and efficiently dealing with a large quantity of unique elements. Despite the technical challenges posed by the used fabrication approach, which were either relatively slow or difficult to automate, they successfully proved a bespoke manipulation of individual offcut elements, achieving a distinct geometric complexity and detailing required for tightly fitting components for structural assembly.

The material's history posed a significant challenge for digital fabrication: When working with reclaimed wood, there may even be remnants of metal nails hidden within the material, potentially causing damage to machinery and tools. Specifically, when dealing with offcuts, the challenge is to avoid damaging the material during fabrication, as it may contain hidden cracks. Furthermore, it is essential to acknowledge that, while digital fabrication holds great potential for advancing circular economy principles in construction, these fabrication systems require powerful bespoke software tools and integrated workflows. After all, each material varies in terms of size, history, durability, and intended future use cases.

Beyond the fabrication and material-related challenges, the logistics of managing a system with a considerable large number of unique offcuts or other elements suitable for reuse presents more significant—and often overlooked—challenges. This includes the capture and digitization of waste materials, where selecting a suitable method and toolset is crucial. While scanning objects with, for example, photogrammetry or lasers can produce highly accurate geometric shapes and 3D models, it often requires extensive post-production and -rationalization, despite the availability of increasingly sophisticated software solutions. Other methods, such as outline detection using computer vision or a manual measuring approach, being part of the presented research, can expedite the process and yield accurate results. On that scope, an even greater challenge lies in managing a large database of physical objects connected to the digital design-and-fabrication workflow. Since all elements are unique, implementing a standardized storage system can be challenging and would require frequent adaptations and changes as materials are added or removed. Additionally, this system would demand significant physical storage capacities, raising questions about its economic feasibility. In the end, a crucial question is whether it might be more practical to computationally automate or batch-select a few elements just-in-time and optimally place them, thus avoiding the logistical complexities of managing a large and diverse database, while simultaneously acknowledging the reduced capacity for sequence optimization.

Finally, another challenge arises from the absence of certification and assessment systems for working with waste wood. The destructive strength tests conducted in the framework of this research provided valuable insights and confidence that free-form offcut structures are generally achievable.

However, considering the volume of usable material available for scaling this concept, this approach may not be a feasible option. As Browne et al. have pointed out, one potential solution to this dilemma might involve incorporating structural redundancy or the application of simple typologies and use cases, until better assessment systems and standards become available (Browne et al., 2022).

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AUTHOR CONTRIBUTIONS

Dominik Reisach: Conceptualization, methodology, demonstrator design, prototyping, fabrication, strength testing, writing, and editing.
Stephan Schütz: Supervision, conceptualization, editing.
Jan Willmann: Supervision, conceptualization, editing.
Sven Schneider: Supervision, conceptualization, editing.

DECLARATIONS

Competing interests The authors declare no competing interests.

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