Re-VoxLam Truss. Topology optimisation and reclaimed voxel lamination of horizontal wood structures.

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Abstract. Despite its potential to decarbonise the built environment, wood is often found on construction sites as a source of waste rather than building material. In Denmark, wood is mainly used for temporary structures envisioned for short life cycles and single use, after which it is destined for incineration, defining it as "sustainable energy". This research proposes an innovative design-to-fabrication process for sourcing timber waste as a valuable matter for a novel typology of structural elements, thereby extending their lifecycle and carbon sequestration capabilities. The work employs a voxel-based approach to designing and optimising complex wood structures, utilising computational stress analysis to determine material layouts reflecting the reclaimed stock. The physical construction voxels, with specific material strength and fibre orientation, are laminated into a functionally graded composite structure, namely the Re-VoxLam Truss. This prototype is demonstrated as a proof-of-concept of the proposed approach for decarbonising construction and upcycling wood waste.

Keywords: Digital craft, Reclaimed timber, Voxel lamination, Multi-material structural layouts, Additive fabrication, Topology optimisation.

1 Introduction

Due to its renewable nature, high strength-to-weight ratio and carbon storage properties, Wood is a fundamental resource for decarbonising the future built environment. However, in construction sites, wood is often a source of waste. In Denmark, construction and demolition waste is estimated at 4.5 million tons/year, 35% of the total national waste (Regeringen Denmark, 2020). Approximately 55,000 tons of timber are used yearly for temporary structures such as scaffolding and formworks, ending up pretty soon in the cascading scenarios. On Danish construction sites, various initiatives have been undertaken to reclaim wood elements for eventual reuse in construction projects; however, a large portion of the collected material is deemed unusable and destined for incineration, defining it as “sustainable energy” (Danish Environmental Protection Agency, 2020). In particular, all timber elements shorter than 800 mm do not meet the reuse criteria in state-of-the-art practice and are inevitably selected for burning - with adverse environmental and economic impacts.

This low re-utilization rate of structurally intact timber, in reference to the increasing demands for its employment in the built environment, is generating a significant circularity gap and a need for innovative solutions to postpone the end-of-life of these elements and extend their carbon storage timeframe.

CREATE Center at the University of Southern Denmark has developed a series of research projects looking at extending the life-cycle of timber elements involving design-for-disassembly (Kunic et al., 2021), implementing circular design principles in timber assemblies (Naboni et al., 2021), as well as implementing material digital twins capable of ensuring that materials can be easily tracked and reutilised (Kunic et al., 2023).

Extending these principles to re-circulating timber construction waste has massive potential for the decarbonisation of the industry. Starting with such a premise, this research aims to reuse timber waste with no perspective for construction repurposing as a valuable matter for a novel typology of structural elements and, by doing so, effectively extend their life-cycle and carbon storage potential. Our aim is maximising the reuse of wood elements of any species, typology, size and source.

2 Approach

This paper introduces Re-VoxLam, a novel approach for voxel-based lamination of reclaimed wood waste. In computer modelling, a voxel is a notational element that defines an individual unit of a discretised 3D object. Adopting the framework described in (Naboni and Kunic, 2019), this work implements a workflow for the structurally optimised design and additive fabrication of three-dimensional beam elements made of reclaimed wood parts, whose material attributes, i.e. material strength and fibre orientation are explicitly defined within a structure. Since the material properties of reclaimed wood are most often unknown, with no information on species, strength class, and degree of conservation, in our work, *density* indirectly measures *material strength* (Buschow et al., 2011).

To maximise the available reclaimed stock, a multi-material three-dimensional Topology Optimization (TO) is employed, which relies on voxel-driven computation. As a result, the voxels store information on the required *material strength*, which allows for the best allocation of differently graded wood pieces according to stress levels within a structure. Further on, *fibre orientation* is fundamental to achieving efficient structural utilisation in anisotropic materials. Compared with existing engineered wood, our approach enables topologically complex structural layouts, where reclaimed wood voxels are aligned to calculated load path trajectories with discretised vectors of 0°, +/-45°, and 90° angles in XYZ. Voxel-based attributes provide a notation system for wood composite structures with Functionally Graded Material (FGM). Variations of properties and composition are relative to the available material stock. The voxel-based design is materialised through a prototypical fabrication process, where cuboidal parts of known material strength and orientation are physically located at specified XYZ coordinates within a structure (Fig. 1).

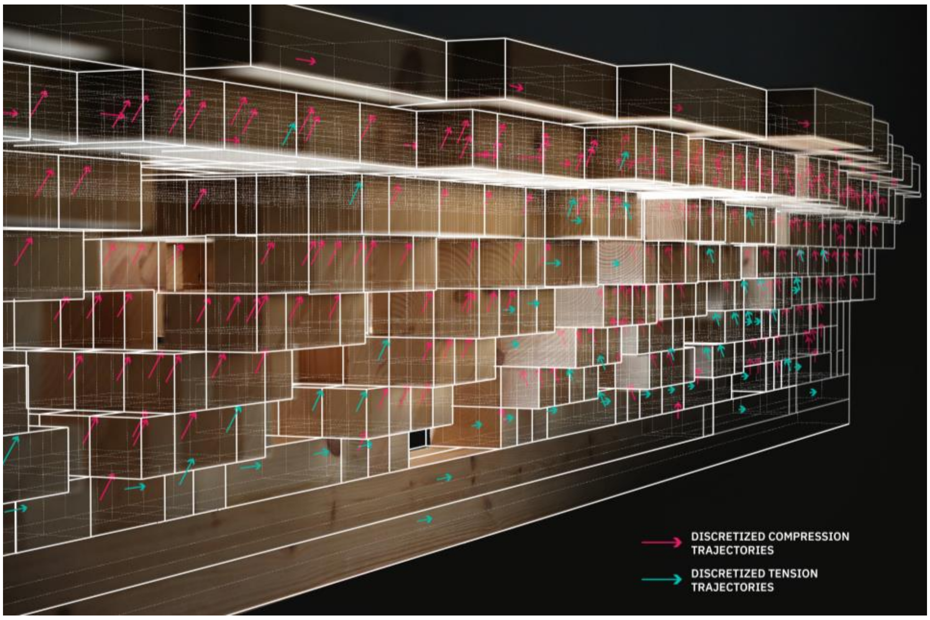

Figure 1. Close-up view showing the one-to-one correspondence between the digital attribute information and physical prototype.

3 Methodology

The Re-VoxLam method was tested in a proof-of-concept experiment, with a workflow consisting of (1) material reclaiming, sorting and classification, (2) computational design and (3) fabrication of a load-bearing horizontal structure (Fig. 2). In the current practice, these are made of mass timber elements or, more rarely, using optimised cross-laminated timber with web and box elements (LignoTrend, 2023). Following preliminary tests to identify a suitable fabrication procedure and basic mechanical behaviour of Re-VoxLam elements, a full-scale prototype was designed using 3D TO.

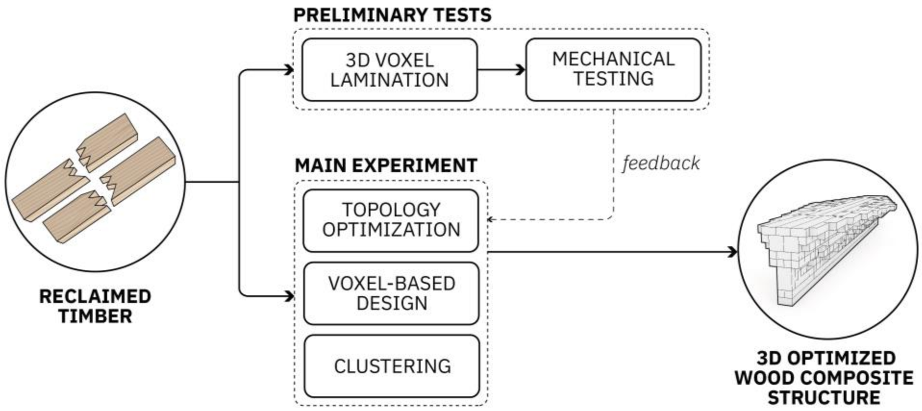

Figure 2. Voxel-based design-to-construction workflow for 3D-optimised wood composite structures.

1.1 **Preliminary Structural Test**

A three-point bending test was performed on a beam specimen which was topologically optimised and laminated with a voxel resolution of 25 mm, 76% retained material compared to standard beam elements, within a bounding box of 800x100x150 mm. The specimen was simply supported onto two rolling pins at a span of 700 mm in a Zwick/Roell Z050 with a 50 kN load cell (Fig. 3A). The material layout was determined considering three different material densities with discretised fibre orientations (0°, +/-45°, 90°).

Figure 3B shows the force/deformation curve, where the specimen had an initial localised shear failure of glue interfaces starting from 25.3 kN (A) with the highest flexural strength of 35.7 kN (D) and a consequent deformation of 21.6 mm. At this point, the continuous bottom layer completely cracked under tension stresses and activated the above tensional layer until the complete failure of the structure. The specimen had multiple localised shear failures (A-D) where the glue bonding was insufficient, probably due to excessive tolerances and inconsistent glue applications in the voxel lamination process. Interestingly, the structure found alternative load paths after these localised failures, showing ductile behaviour. Proper voxel alignment and consistent glue applications were critical factors for appropriate bonding and improved structural behaviour.

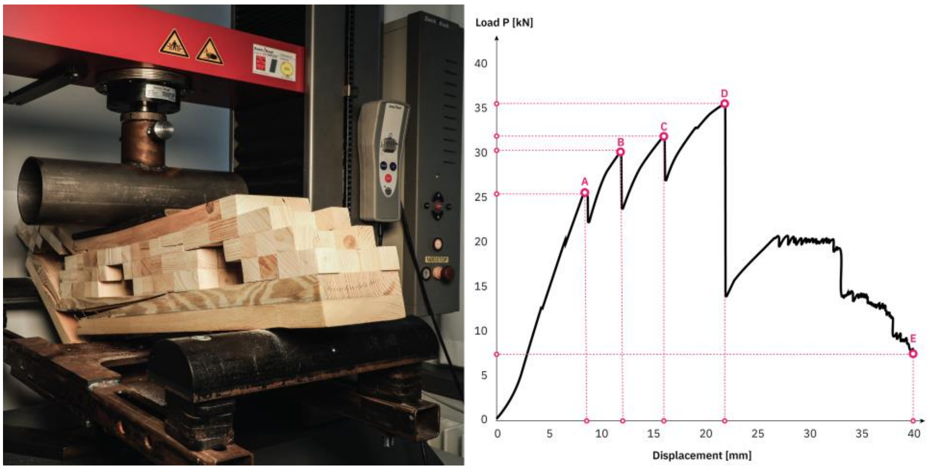

Figure 3. A) Final failure in 3-point bending of the tested beam specimen; B) The force-deformation curve shows the overall performance from the mechanical test of the preliminary prototype. Point A visualises the first fracture.

1.2 Computational Workflow

The computational design workflow was developed through algorithmic procedures employing Millipede, a plug-in for Grasshopper 3D (Michalatos and Kaijima, 2014), to provide rapid structural analysis of linear elastic systems and optimise 3D volumetric elements (Fig. 4). As previously mentioned, the design process is based on and informed by the available reclaimed stock. Firstly, the voxel resolution is defined in response to the most commonly reclaimed wood thickness, which, in this case, was set to 40 mm. Subsequently, design and structural boundary conditions are defined in the computational design space: the three-dimensionally shaped beam volume (0,287729m^3), distributed (1.8kN/m^2) and mid-span (7kN/m^2) loads, material definition and fixed constraints for the horizontal structure. The TO solver iteratively adjusts the shape of a structural element and the material density values within the voxels to obtain the required structural stiffness while minimising the overall volume (Fig. 4A). Principal Stress Trajectories (tension/compression) were obtained across the volume (Fig. 4B), and discretised into 0°, +/-45° or 90° in three-dimensional XYZ coordinate space (Tam and Muller, 2015) (Fig. 4C). Finally, material density ranges are distinguished based on Von Mises stress values (Krenk and Høgsberg, 2015) and considering the previously sorted reclaimed stock (Fig. 4D). In the case of the Re-VoxLam Truss prototype, two material densities were used. Neighbouring voxels with equal attributes, e.g., the same fibre orientation and material density, are clustered to minimise the material preparation in the fabrication workflow.

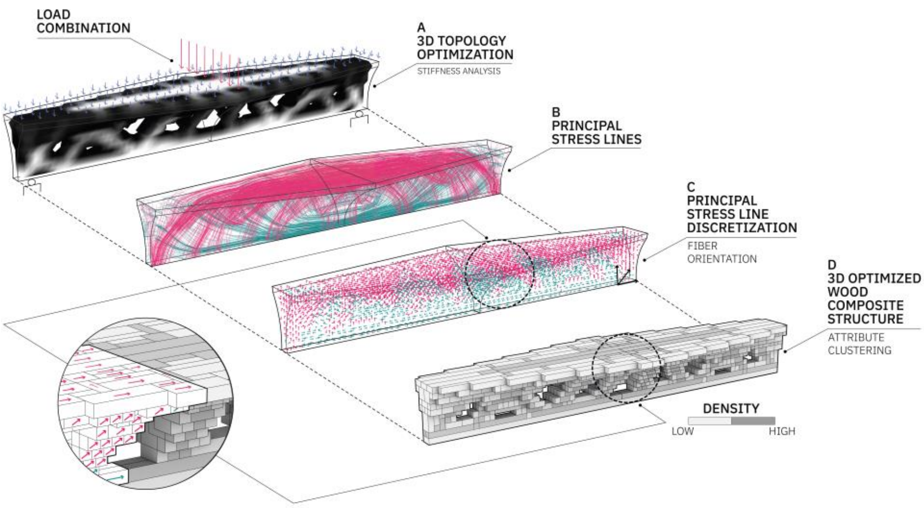

Figure 4. Schematic visualisation of the physical boundary conditions and data extraction for the final 3D-optimised wood composite structure.

1.3 Fabrication Workflow

Material preparation - Fifty-five meters of wood of different species, dimensions, and levels of structural integrity was collected from three local construction sites (Fig. 5). To prepare the materials for their new function, firstly, the foreign elements such as concrete marks, nails and screws were physically removed, after which the materials' conditions were visually evaluated. Roughly 5% of the elements were found unusable and therefore discarded due to a high amount of fractured areas and decomposition caused by moisture. Since the current practice still lacks a valid method for categorising the structural properties of reclaimed wood (Dansk Standard, 2019), in this proof-of-concept work, the material was classified by the measured density as an indirect reflection of the mechanical properties. The reclaimed material varied from 370 to 570 kg/m^3. Two strength (density) classes were defined, below and higher than 500 kg/m^3.

Figure 5. Wood waste on the construction site (left); Reclaimed wood cleaning and sorting (right)

Voxel Production **-** To produce physical voxels informed by the computational models, the cleaned and sorted reclaimed wood pieces were planed and cut into elements with a cross-sectional height of 40mm, equivalent to the computational voxel unit. Considering the previously defined computational voxel clusters with shared material attributes, the physical voxel clustering was performed, obtaining cuboid units of homogeneous material strength and fibre orientation. This was structurally beneficial, reducing glue interfaces in tensional elements. The strategy streamlined the subsequent lamination process by reducing the number of voxel elements in the final structure and reducing production waste and manufacturing time.

Volumetric Lamination **-** The produced voxel clusters were glue laminated using a moisture-resistant, quick-setting PVA glue, fulfilling the requirements for D2 structural class applications with a minimum shear strength of 10 N/mm^2 at standard ambient conditions (Dana Lim, 2020). The lamination process was broken down into a two-step layer-by-layer additive process composed of (i) *in-layer voxel aggregation*, where voxels within the same layer are glued for about ten minutes within vacuum bags (Fig. 6). This is considered an effective technique for bonding geometries that cannot be laminated mechanically (Svilans, 2023); and (ii) *inter-layer voxel lamination* - of voxel clusters and aggregations across the different layers under vertical pressure, using clamps and lashing straps (Fig. 7). Where necessary, unbonded voxel elements were used as temporary supports to stabilise inclined geometries.

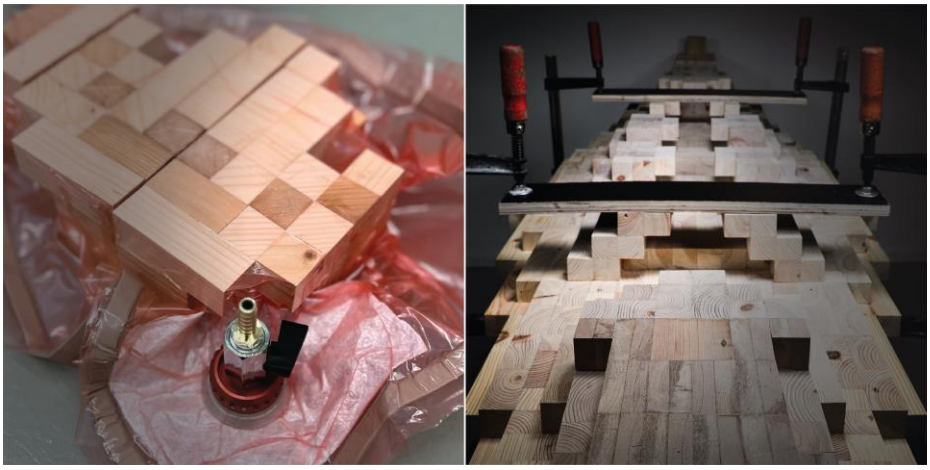

Figure 6. In-layer voxel aggregations lamination in the vacuum bag (left); inter-layer voxel lamination using clamps (right)

4 Results

Re-VoxLam Truss, a 3000 x 800 x 400 mm horizontal structure prototype consisting of 10 voxelised layers, was successfully realised, employing the above-described design and fabrication methods (Fig. 7). The prototype is composed of 1288 voxel clusters in 20 sizes with recurrence varying from 0,1% to 46.2% (Fig. 8), for a total weight of 110 kg - equivalent to 187 kg of CO_2, thus upcycling the construction waste and preventing it from incineration and its consequent emissions.

During the realisation of this prototype, about 80% of the reclaimed wood was successfully reutilised. The prototype fabrication procedures were distributed in the following way: material collection (1.3%), material preparation (3.7%), voxel production (10.7%), in-layer lamination (9.6%), and inter-layer lamination (74.7%). This last phase was critical to reducing tolerances, and particular attention was spent on ensuring a gapless bonding in the composite. In turn, good overall accuracy was observed, with around 7% of visible gaps (0.5-1 mm) occurring in the structure. This is considered reasonably low for a proof-of-concept prototype. As observed in mechanical testing, such weak bonding interfaces cause sudden strength drops, but the structural redundancy allows for alternative reorganisations of the load paths.

Figure 7. Bottom view of the Re-VoxLam Truss. Voxel density aggregations and lamination techniques are used to realise the complex 3D geometry.

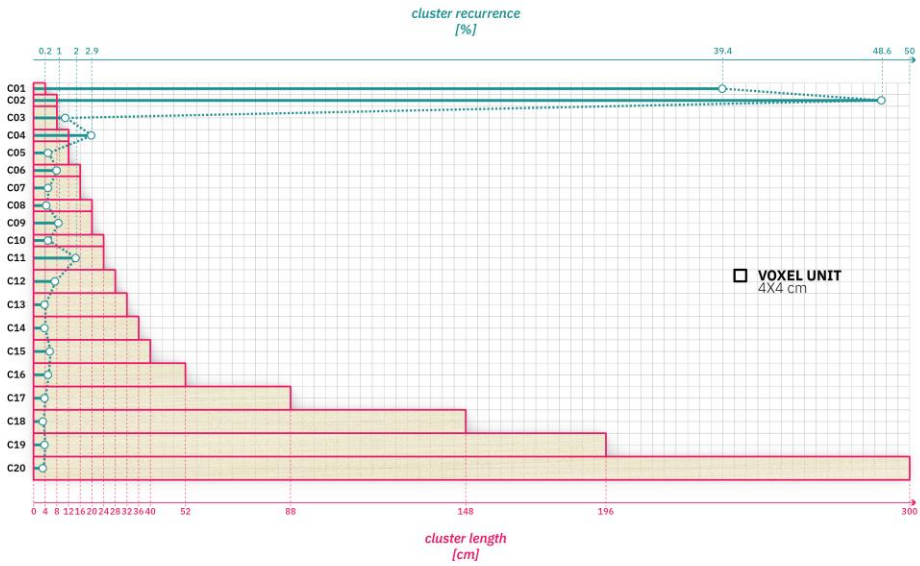

Figure 8. Dimensional overview of the voxel sizes and the proportion applied in the Re-VoxLam Truss.

The developed computational workflow proved to be sufficiently agile for quick design iterations and adjustments driven by the available reclaimed stock, structural requirements for the horizontal load-bearing structures, and different design decisions. The introduced voxel clustering ensured that tensional areas in the structure use continuous elements and minimise the glued interfaces, improving the overall structural behaviour. The completed prototype (Fig. 9) was installed into two massive end supports that restrained the structure's translations and rotations. The empirical testing involved one to four individuals walking, running, and jumping on the structure. This testing revealed no noticeable deformations or tilting, demonstrating that it maintains a relatively stable and rigid state.

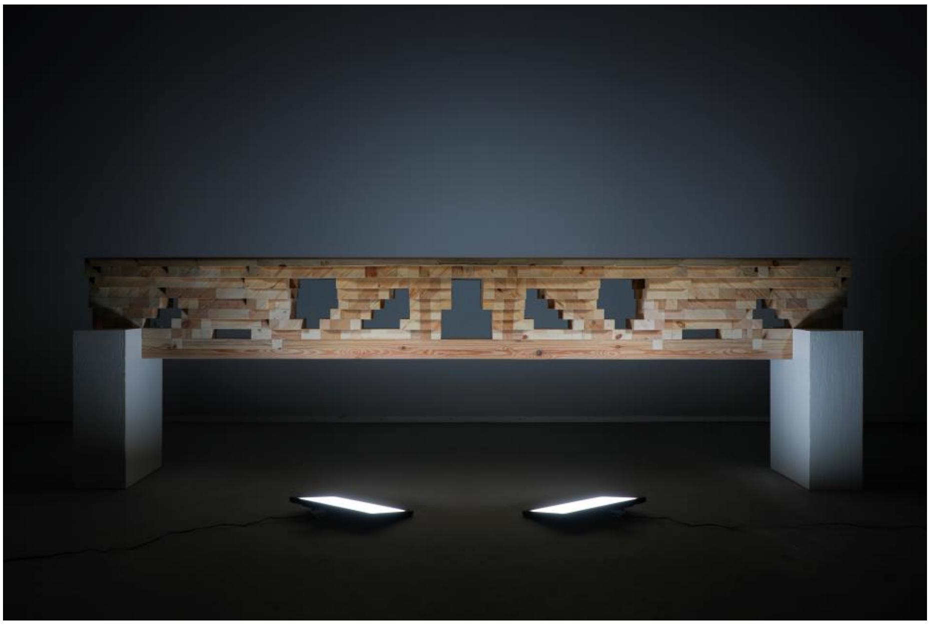

Figure 9. Re-VoxLam Truss prototype

5 Discussion

Re-VoxLam (Fig. 10) has the potential to be a pioneering step towards reclaiming wood construction waste into structural elements and effectively extending the life cycle of timber, preserving its carbon store for longer. This experiment successfully proves a design, fabrication and structural concept with a high potential for decarbonising the built environment. The presented method opens exciting perspectives for 3D optimised structures in wood, expanding the design freedom of timber construction from typical bi-dimensional and frame-like systems to three-dimensional functionally grading articulated forms. The future developments of this research will focus on various aspects across scales, from the material level to the overall structural design, scalability and real-world applications. These will include the development of tailored TO for discrete anisotropic structures, the structural characterisation of large Re-VoxLam structures, and fabrication automation, employing industrial robots to reduce production time significantly.

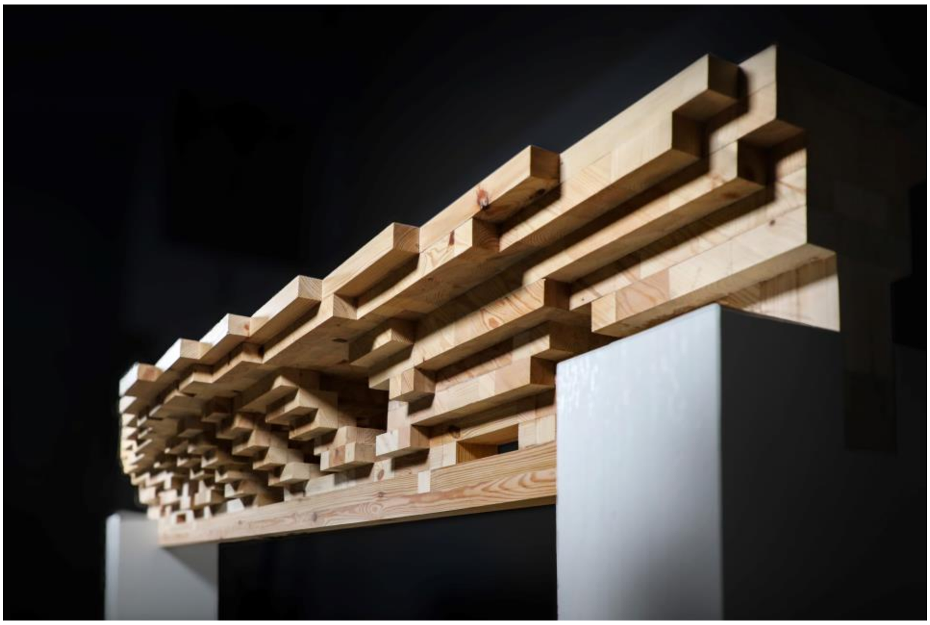

Figure 10. Perspective view of the Re-VoxLam Truss prototype

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