

Shape- and Fiber-Optimized Timber Composite Shells for Lightweight, Load-bearing Building Components

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Abstract

This research introduces Molded Oriented Strand Composites (MOSC) as a novel material system and computational framework for designing lightweight, material-efficient, load-bearing building components. MOSC leverages the moldability of wood strand composites to achieve form-driven structural designs and their suitability for robotic strand placement to define stress-informed fiber architecture. Material studies on species, strand dimensions, minimum curvature, and 3D forming limitations inform a design-to-fabrication workflow that integrates NURBS-based shape optimization, stress-oriented material placement, and structural assessment to generate fabrication data. Inspired by Nervi's corrugated roof for Hall C of the Torino Exhibition Palace, the research demonstrates a novel lightweight slab system consisting of a planar, walkable surface and a shape- and fiber-optimized MOSC shell attached below as reinforcement. The shell is dynamically corrugated to increase the system's stiffness and bending resistance while minimizing material use. A physical prototype measuring 2324 x 800 mm and weighing 34.8 kg was produced, loaded to 3 kN/m², and compared with FEA simulations. A deflection of 5.8 mm demonstrated its compliance with standard deformation limits. By integrating experimental development, computational shape-optimization, and automated fabrication, this research demonstrates MOSC as a viable material system for structurally sound, material-efficient timber components.

Keywords: Oriented Strand Composites, Molded Timber Structures, Shell Structures, Shape Optimization, Material Efficiency, Fiber Orientation, Lightweight Structures, Computational Workflow.

1. Introduction

Oriented Strand Composites (OSC) are known for their resource efficiency, as they can use an average of 83% of the tree, compared to 37-39% for lumber-based timber [1]. Moreover, OSC can use low-value wood, such as branches and small or malformed trees, and can be made from softwoods and hardwoods. All the above make OSC a relevant material for resource-efficient and climate-resilient construction.

Beyond these known attributes, OSCs are also suitable for three-dimensional molding, thereby enabling form-driven mechanical performance at the building component level. In addition, because it is possible to discretize the material into its constituent strand unit, design, and manufacturing methods from the field of stress-oriented fiber-reinforced composites become available.

The present paper provides an overview of the areas of study that converge in this research and a general description of the research workflow. It focuses on the development of a lightweight slab component and the computational design, optimization, and fabrication methods that enable its prototyping. Material developments and testing, as well as automated prototype production by our collaborating company, Strong by Form SpA, are in the scope of this paper.

2. Background

This research follows the principles of Co-design introduced by the Cluster IntCDC at the University of Stuttgart and the Max Planck Institute [11], in which material and building systems, computational methods, and cyber-physical fabrication are developed in an interdependent manner. To this aim, methods and principles from various research domains, including three-dimensionally molded oriented strand composites for load-bearing applications, stress-oriented discretely reinforced composites, shape optimization for plate reinforcement have been studied.

2.1. Three-dimensionally molded oriented strand composites for load-bearing applications

Research in the field of OSB manufacturing has established that the performance of oriented strand composites (OSC) results from the interplay of their many production variables. Among them, wood species density, strand dimension, and strand orientation play a key role in determining the composite's performance [2].

Most studies on molded oriented strand composites have focused on OSB sandwich cores for lightweight load-bearing panels (Fig. 1). A dry-forming method for wood fiber sandwich cores was patented by [3]. Hollow-core sandwich panels with OSB as both core and facing material were successfully evaluated in [4], [5], [6].

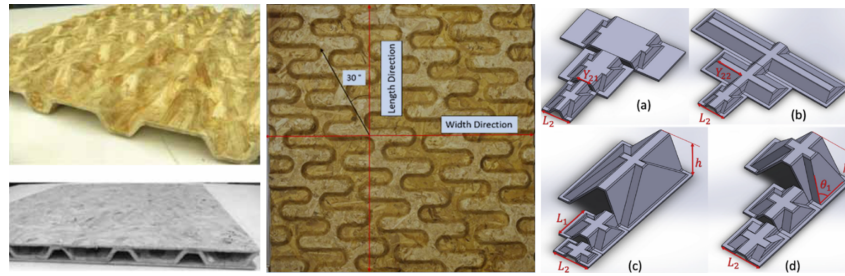


Figure 1: Reference work on molded OSB cores. [4] left, [5] center; and [6] right.

2.2. Shape optimization for plate reinforcement

Shape optimization is a widely used technique for finding high-performing shell designs. Several studies have tackled the problem of stiffening plates through shape optimization [7], [8]. Other studies have optimized reinforcements for plates or shell structures by adding rib patterns or simultaneously optimizing shape and topology. However, the authors have found no precedent for using a shape-optimized shell to reinforce a plate as a collaborative structure.

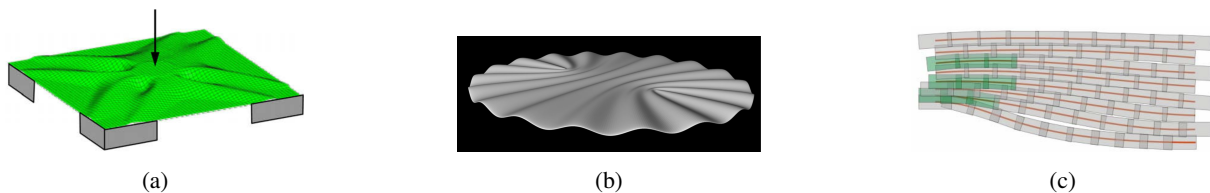


Figure 2: Reference work on shape optimization of plates (a) [7] and (b) [8], and (c) Fiber Patch Placement [9].

2.3. Stress-oriented composites

Wood strands and veneer trims can be understood as highly anisotropic cured composite fragments. Therefore, analytical models developed for fiber-reinforced polymers (FRP) can be used to describe the mechanical properties of veneer and strand-based composites. Research on Fiber Patch Placement (FPP) provides a valuable framework for MOSC to inform patch dimensions, location, orientation, and

layup [9]. In FPP, prepregs of UD fiber patches are robotically placed following principal stress lines to improve strength in parts with complex stress paths (Fig. 1). Compared with orthotropic layups, strength improvements of 28% to 100% have been reported [9], [10].

3. Methods

The present research on shape- and fiber-optimized molded oriented strand composites (MOSC) comprises three main areas of study: strand composite development, slab design and optimization, and prototype production and testing (Fig. 3). This paper introduces the computational design and optimization methods for the production of lightweight slab components.

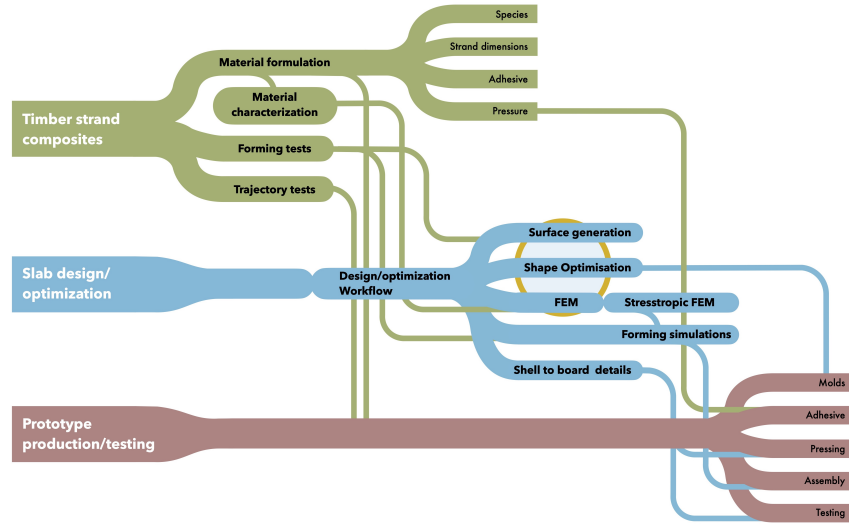


Figure 3: Research workflow diagram, of which the Slab Design and Optimization is covered in this paper.

3.1. Material inputs

Preliminary material explorations not covered in this paper provided a set of design guidelines and the mechanical data required for the FEA analysis. A composite material made out of Norway Spruce (*Picea abies*) strands, Henkel Loctite HB S709 Purbond PUR adhesive and Bafatex viscose scrim (Bafa 120/10) was prepared. Optimal strand dimensions were defined as 130 x 20 mm, representing a good trade-off between mechanical strength and suitability for following curved trajectories with low void and overlap content. The minimum curvature radius for dry strand molding was set to 20 mm, following the test procedure in [12]. Forming tests identified challenges with deep synclastic shapes due to material overstretching, while forming deep single-curvature shapes showed low challenges. A series of mechanical tests was performed following DIN EN 789 to characterize the composite material as shown in Table 1.

Table 1: Mechanical properties of unidirectional MOSC material.

Orientation	Young modulus (MPa)	Tensile strength (MPa)	Compressive strength (MPa)	Shear modulus (MPa)	Density (kg/m ³)
0°	8262	21.41	24.8	506.8	523
90°	381.4	4.4	4.8	-	523

3.2. Slab design and optimization

To demonstrate the structural potential of MOSC for load-bearing structures, a slab concept was developed inspired by Pier Luigi Nervi's corrugated roof slab in Hall C of the Torino Exhibition Palace [13]. The roof features corrugated thin ferrocement modules connected to prefabricated thin concrete plates that form the roofing surface. This design not only results in a material-efficient solution for spanning structures but, like most of his work, adds character to the interior space.

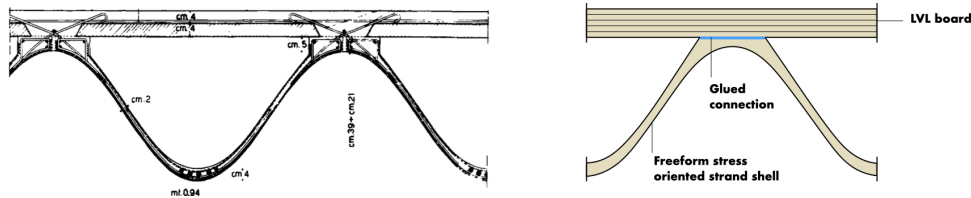


Figure 4: Pier Luigi Nervi, Torino Exhibition Palace, Hall C, 1950 (left). Concept for a timber composite solution based on Nervi's principle (right).

The present method uses Nervi's structural principle to resolve a lightweight wood-composite slab. A top plate works predominantly in compression and resists point loads, while the undulating surface -working primarily in membrane- transmits from the lower parts of the waves acting as tension chords; and the upper part of the slopes keeping the separation between the compression plate and the tension chord by acting primarily in compression (Fig. 5)

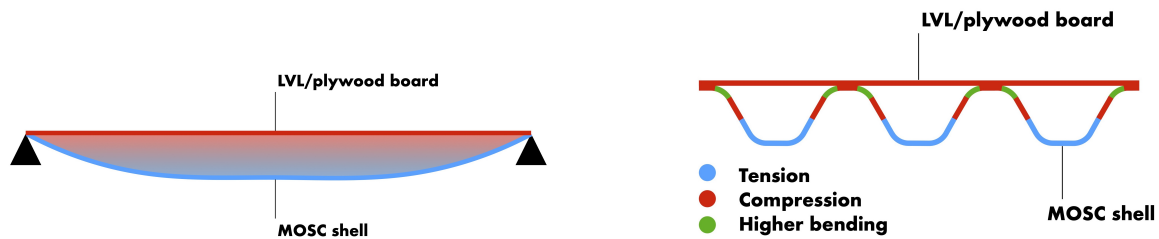


Figure 5: Schematic side view (left) and cross-section of the slab concept (right)

Generally, corrugations exhibit high bending stiffness in the span direction and low membrane stiffness in the transverse direction [8], but when attached to a plate that blocks their transverse deformations, they reduce transverse bending. Depending on their cross-section- they may concentrate bending in the contact zone with the plate.

3.3. Design-to-fabrication workflow

This research introduces a design-to-fabrication framework for the design, evaluation, and production of lightweight spanning components. It integrates custom material data, component design and optimization, structural analysis, and fabrication techniques within the Rhino/Grasshopper environment. The workflow consists of three modules: (i) Shape Optimization, (ii) Design Validation, and (iii) Prototyping (Fig. 6).

3.4. Shape Optimization

A CAGD-based shape optimization workflow is implemented as a flexible design platform capable of handling diverse support conditions and component shapes and dimensions. The geometry is created by lofting a series of NURBS curves, whose control points are manipulated along the Z-axis by a multi-objective genetic algorithm. The use of a doubly symmetric design reduces the optimization loop time

by controlling only $\frac{1}{4}$ of the surface points (Fig. 7). Aside from the symmetry, the methodology remains valid for generating non-symmetric designs.

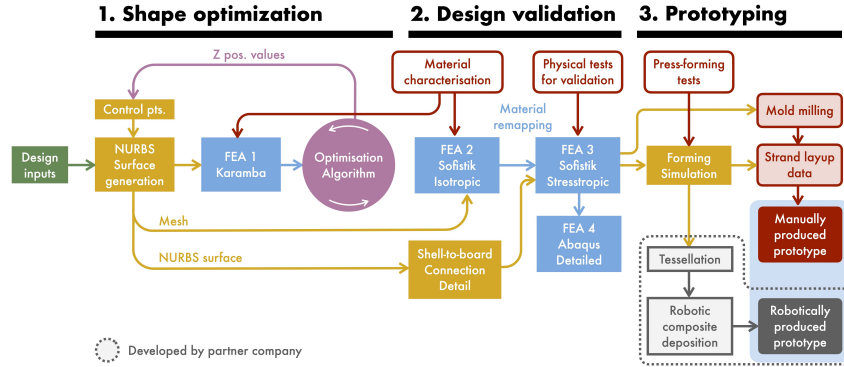


Figure 6: MOSC design-to-fabrication workflow.

To control the geometry, an optimization loop was implemented using Karamba 3D 2.2 and Octopus as multi-objective genetic algorithm with the objective of minimizing mass and deflection. The support conditions were defined as simply supported, and a distributed load of 3 kN/m^2 applied. 15 mm LVL was used as plate material and 10 mm of MOSC for the shell. To enable a collaborative structural response between the shell and plate, the shell and plate meshes were connected at a threshold of $Z \geq -20 \text{ mm}$, where vertex-to-vertex high-stiffness springs were created to simulate a glued connection.

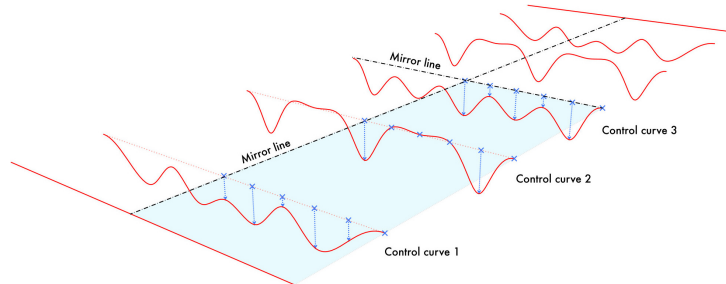


Figure 7: NURBS surface generation approach.

3.5. Post-rationalization steps

The integration of all slab design constraints, such as minimum curvature thresholds and geometric interdependencies between plate and shell, was deemed too computationally heavy for an optimization loop. A post-rationalization step was introduced to rectify the surface generatrix curves to meet the 20 mm minimum radius requirement (Fig. 8). In a subsequent step, regions of the shape that reduced the contact surface between shell and board and could potentially overstretch the material were eliminated (Fig. 8).

3.6. Design validation

The Sofistik 2020 finite element analysis package, which uses higher-order mesh elements than Karamba 3D and supports multi-layer materials, was used to conduct three types of analyses. The first (FEA 1) retrieves the principal stress vectors for each mesh quad, which are used by a second analysis (FEA 2) to reorient the material direction for each quad. A third analysis (FEA 3) is performed with an orthotropic layup to benchmark against the stress-oriented material. Support conditions and loads were equivalent to those used during shape optimization (Fig. 9).

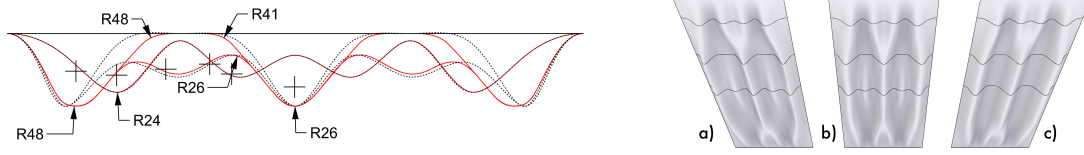


Figure 8: Curvature correction (left): In black segmented line the original curves and in red the curvatures with curvature above 20 mm. Design evolution (right): a) Shape-optimized design; b) design with corrected curvature radii; and c) simplified design used for the prototype

The LVL plate is modeled as a single-layer material 18 mm thick, whereas the 10 mm MOSC shell is modeled as a three-layer material with thicknesses of 3.33 mm each. The two outer layers were parallel to the material's orientation vector, and the central layer was perpendicular to it. Each of these layers used the UD composite of Table 1.

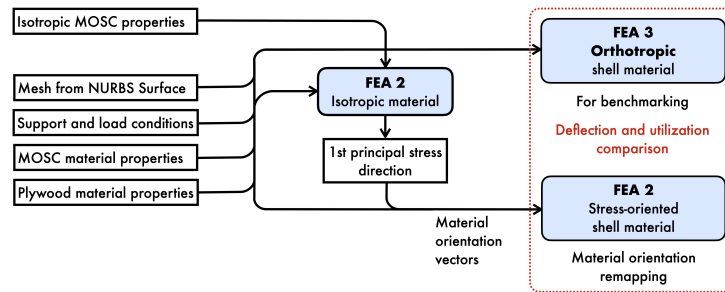


Figure 9: Material remapping workflow, analysis and benchmarking with orthotropic material.

In the first iteration of the workflow -used to manufacture the first prototype- FEA 2 was performed assuming an orthotropic material for the MOSC. This induced an unintended distortion in the principal stress vectors that fed FEA 2, resulting in an inefficient strand architecture. A revised version of the vector map was produced using an isotropic shell material with the mechanical properties of the 0° orientation (Fig. 10). Although this approach does not accurately describe the material, it removes the bias of a predetermined material orientation, resulting in a more efficient stress pattern. A second prototype produced by the partner company Strong by Form used this updated approach.

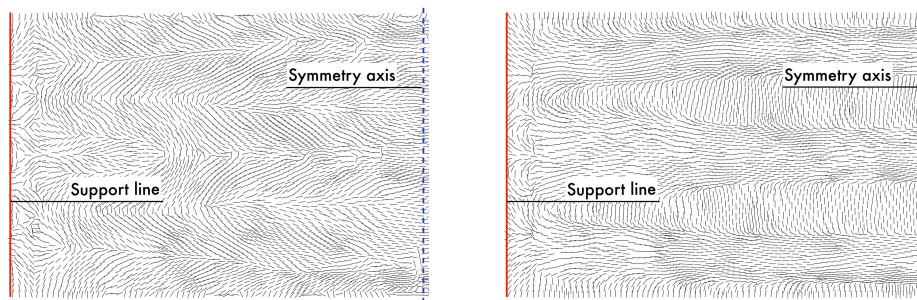


Figure 10: First principal stress vector field produced with an orthotropic base material (left) and with an isotropic material (right). Only half slab is represented.

3.7. Prototype production

3.7.1. Shell-to-plate connections

Prior research on molded strand composites for sandwich cores have identified core wall buckling and crushing [4] and interface shear debonding [6] as relevant failure modes. Given that the MOSC shell near the contact area is mostly singly curved and is compressed against the board, a secondary corrugation was integrated to prevent buckling [14] and improve bending stiffness near the contact area. In addition, there was a negotiation between the known 20 mm minimum radii and providing enough contact surface between shell and board to prevent shear failure in the bonding line. The microcorrugation was solved by lofting alternated cross-sections with small curvature radii and a large contact surface, with ones with a large radius but with minimal contact surface (Fig. 11).

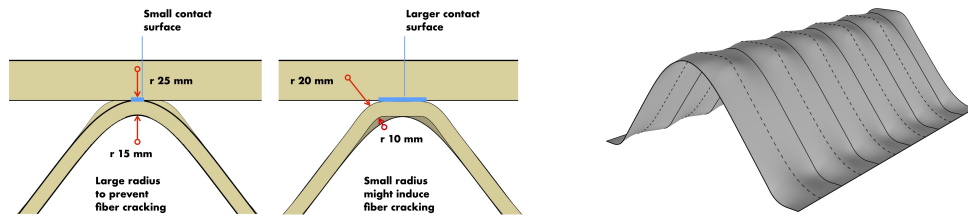


Figure 11: The two type of cross-section at the connection area (left), and a sequence of curves lofted with alternated cross-sections.

3.7.2. Strand Packing Algorithm

To design the mat's pre-pressing flat state, the Rhino "SquishBack" command was employed. Despite the algorithm relying solely on geometrical transformations, the results yielded a shape that captured the main geometrical deformations during pressing. In this procedure, the surface and its vector field were flattened and then used to develop an agent-based Strand Packing Algorithm (Fig. 12). The algorithm balances various objectives, such as minimizing voids and overlaps between strands, maximizing the number of strands per layer, and avoiding gap overlaps between layers that could lead to weak stress-transfer zones.

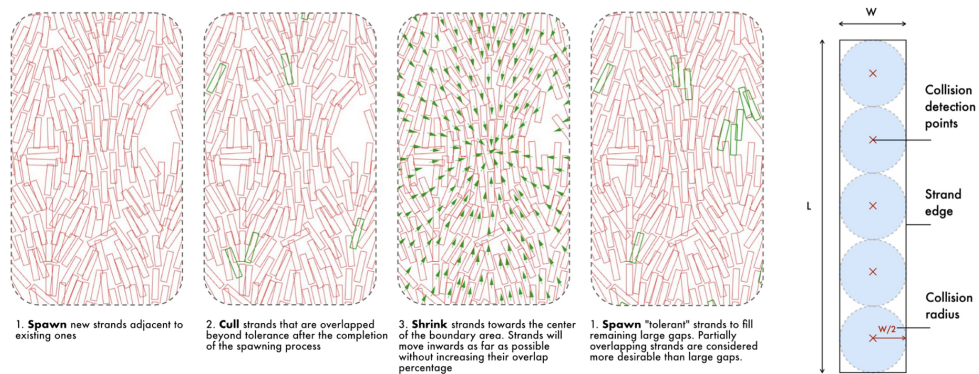


Figure 12: Sequence of steps of the packing algorithm (left) and strand agent with collisions detection points (right).

4. Results

The resulting prototype measured 2324 x 800 mm and consisted of an 18 mm LVL board glued to a 10 mm MOSC shell. The LVL board was over-dimensioned due to LVL's thickness availability in the market, but similar performance could have been achieved with lower thickness.

A first prototype was produced by a) manually placing strands over the transportation scrim mesh

following the position and orientation map; b) depositing 4 + 4 strand layers oriented using the tensile stress map and 4 layers following the transversal stresses orientation; c) robotically applying 170 g/m² of 1K PUR layer between each strand layer; d) press-molding it with 0.2 N/mm². Once cured, the shell was trimmed, sanded in the contact zone with the board, glued with 1K PUR, and pressed together with 0.2 N/mm², resulting in a collaborative slab of 34.8 kg.

The concept for an automated procedure to place and orient single strands was successfully demonstrated in parallel by producing a representative fragment of oriented strands using a Universal Robots UR10 robotic arm equipped with a custom vacuum end effector.



Figure 13: Fabricated slab prototype (left) and robotic strand layup test.

The prototype was subjected to a non-destructive test using individually weighed sandbags to simulate a distributed dead load up to the design load of 606 kg, reaching a deflection of 5.98 mm, equivalent to span/298 (Fig. 14). Its deformation was measured at the bottom center of the shell and compared with the FEA simulation at the same point.

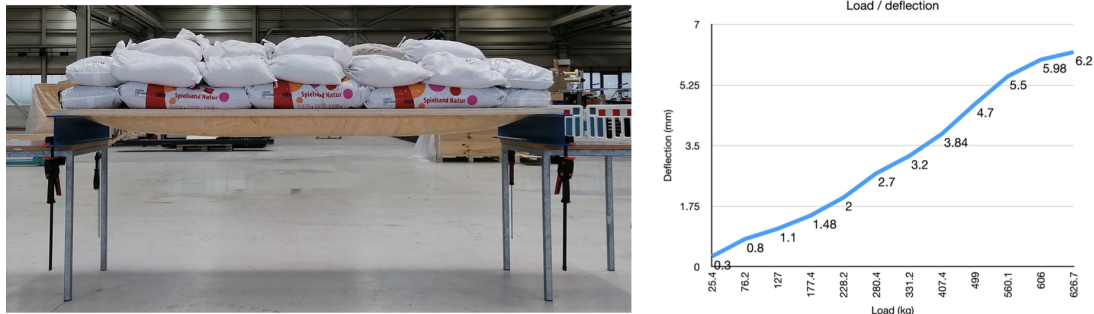


Figure 14: Prototype during load test (left) and load/deflection chart (right).

After reviewing the principal stress vector field as described in Chapter 3.6, the collaborating company, Strong by Form SpA, produced a second prototype using the updated data. The prototype was produced using their proprietary hardware and software for the layup and orientation of the strands, which are not covered in this paper. As shown in Fig. 15, the updated strand orientation reflects a more logical fiber orientation pattern.

The FEA model simulated a 3 kN/m² load, showing a deflection of 5.7 mm, which corresponds with the 5.98 measured in the prototype, providing a preliminary validation of the simulation. At the same time, an orthotropic fiber arrangement was compared with the stress-oriented material, displaying lower utilization limits and a more homogeneous stress distribution, particularly in zones where the stresses deviate from linear trajectories Fig. 15.

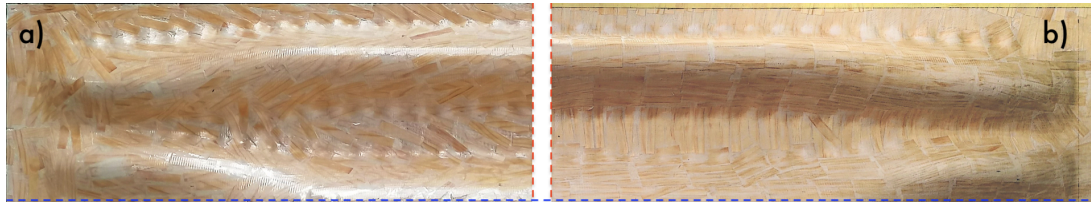


Figure 15: First prototype (left) and second prototype using updated orientation vector field (right).

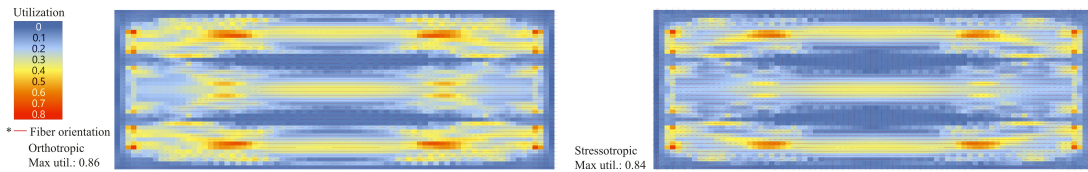


Figure 16: Analysis with an orthotropic material (left) and with a stress-oriented material (right).

5. Discussion

The present paper provides a reference base for the methods and principles that MOSC draws from engineered wood research, stress-tailored composites, shape optimization, and integrative design-to-fabrication workflows. It introduced a Nervi-inspired structural design concept that combines a flat plate with a shape- and fiber-optimized shell reinforcement to generate a collaborative, lightweight slab structure.

A material-informed design-to-fabrication method was presented in which shape optimization, stress-driven strand orientation, microcorrugation, and strand-packing algorithms are integrated into a computational workflow. This method was validated by producing a 2324 x 800 mm slab component weighing 34.8 kg, which, loaded with a distributed load of 3 kN/m² demonstrated the slab's load-bearing capacity and low weight. Its low deflection confirms that the slab's rigidity complies with design recommendations for residential timber structures. The research inaugurates the field of stress-oriented wood strand composites for lightweight applications, demonstrating the feasibility of such structures in an integrated cyber-physical workflow.

There remain, however, several open topics for future research. At the material level, it is required to develop suitable testing methods to capture material performance losses arising from local density variations caused by angular differences among strands and by material overstretching. The shape optimization algorithm could integrate design constraints such as minimum curvature radii and enable other support conditions. At the component level, further testing is required to assess long-term behavior, including creep, moisture effects, and durability. From the fabrication perspective, the scalability of the system remains a challenge. Fully automated strand placement at the speed and volume required by industry remains an open question. Finally, the structural system has been evaluated primarily under bending conditions to date. Future studies should investigate more complex load cases, including shear, dynamic loading, and connection behavior.

Overall, the here presented work outlines a pathway toward resource-efficient timber construction by combining computational design methods with material-informed structural design strategies. In doing so, it expands the architectural and structural potential of strand-based composites and contributes to the development of a new class of lightweight, high-performance slab components.

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