

Rethinking elastic timber gridshells

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ABSTRACT: This work presents an innovative construction concept for timber gridshells, integrating active bending, CNC fabrication and carpentry joints, using high-performance *Eucalyptus globulus* LVL. This engineered wood product enables a fast and dry bending process. The research focuses on material properties, connection system and meshing strategies, all of which are explored and discussed in relation to existing timber gridshells. The curving capacity of the new product is first evaluated through mechanical flatwise bending tests. Next, an innovative connection system concept is presented, offering a comprehensive solution for the nodal joint and the multilayer system, by means of a CNC carpentry design that harmonises structural performance, aesthetic appearance and ease of assembly and disassembly. Some geometric explorations are further introduced to generate orthogonal patterns compatible with the proposed joint solution. The successful realisation of several models underlines the potential of this approach for the construction of elastic timber gridshells.

1 INTRODUCTION

Timber gridshells are highly efficient and aesthetically appealing structures, acquiring their load-bearing capacity and stiffness primarily from their shape. They are particularly suitable for medium- and large-span roofs. Their design has undergone significant evolution in recent decades, generally categorized into three approaches based on the type of element used.

The first approach involves timber gridshells constructed with straight timber elements but complex steel nodes, such as the *University of Exeter Forum* gridshell, the *Pods Sports Complex*, or *Crossrail Place Canary Wharf*. The second approach utilises continuous curved and warped laminated timber elements (pre-curved gridshells), as seen in the *Solemar Therme* (Figure 1a), the *Centre Pompidou-Metz* (Figure 1b), or the *Swatch Headquarters* (Figure 1c). The gridshells developed using these two approaches, have fully realised the potential of advanced design techniques and CNC technologies, demonstrating their ability to build sophisticated shapes and joints with extreme precision. However, they are hampered by the complexity and high costs associated with manufacturing the numerous singular components.

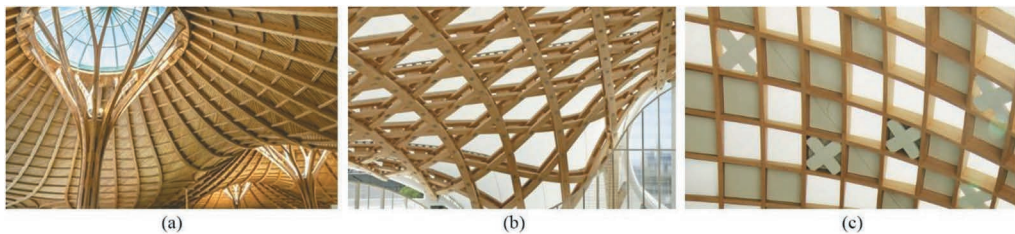


Figure 1. (a) *Solemar Therme*, Germany; (b) *Centre Pompidou-Metz*, France (Source: Dalbera, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0/>, via Openverse); (c) *Swatch Headquarters*, Switzerland.

The third approach concerns elastic gridshells (Figure 2), built by elastically bending thin, long, and initially straight timber laths on-site to achieve the desired shape. Notable examples of this last type include masterpieces such as the *Mannheim Multihalle*, *The Savill Building* (Figure 2a), and *The Weald and Downland Living Museum* (Figure 2b), which followed Frei Otto's design concept of deployable quadrangular meshes. Other examples include the *Polydôme EPFL* in Lausanne, the *Expo-Dach* in Hannover (Figure 2c), and the *Reithalle* in Uzwil (Figure 2d), which adopted Julius Natter's concept of ribbed shells made of mechanically laminated geodesics. Elastic gridshells stand out for their minimal material requirements and cost-effectiveness, achieved by using straight laths and thereby avoiding the need to manufacture and transport curved elements. However, the use of moderate-strength timber products has required a very slow bending process, typically carried out over several weeks with laths at a high moisture content to facilitate stress dissipation and prevent premature breakage.

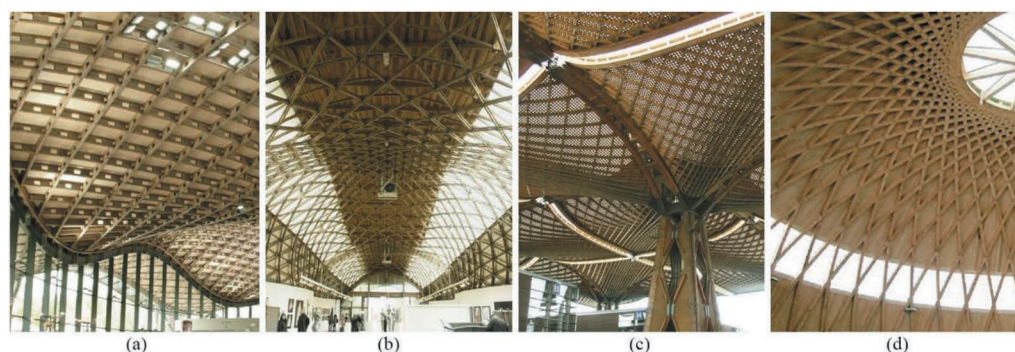


Figure 2. (a) *Savill Building* in Windsor, UK; (b) *Weald and Downland Living Museum* in Chichester, UK; (c) *Expo-Dach* in Hannover, Germany; (d) *Reithalle* in Uzwil, Switzerland.

This work presents a new construction concept for timber gridshells that combines the advantages of elastic timber gridshells and pre-curved gridshells by integrating the principles of active bending, CNC fabrication, and carpentry joints, using a novel high-performance *Eucalyptus globulus* LVL, which allows for a fast and dry bending process, overcoming many of the limitations associated with traditional elastic gridshells. The study focuses on three key aspects of the design and construction of these structures: material, connection systems, and meshing strategies, each of which is explored and contextualised in relation to previous timber gridshells.

2 NEW HIGH-PERFORMANCE ENGINEERED TIMBER PRODUCT

ce of timber species and product is one of the first and most important decisions in the design of an elastic timber gridshell. Traditionally, finger-jointed solid timber with moderate strength, produced from different softwood or hardwood species, has been used in elastic gridshells, often made to order (not commercial products) from wood sourced from nearby forest resources. For example, oak and larch were used in *The Weald and Downland Living Museum* and *The Savill Building*, respectively, and were considered to have strength classes D30 and C30 (Harris et al., 2003, 2008). However, in practice, even when using very thin laths (20-50 mm), the initial stresses from the bending process can exceed the material's characteristic bending strength, which rarely rises above 30 N/mm². Obviously, the simplest solution is to reduce the curvature of the laths, but this directly contradicts the structural principle of gridshells, which relies on shape to provide load-bearing capacity.

One option to reduce the initial bending stresses and ensure the required structural reserve to withstand the remaining loads is to wet-bend the timber elements very slowly, over weeks or even months (Harris et al., 2003, 2008). However, this procedure has significant cost implications, as it demands prolonged on-site presence of personnel and auxiliary resources.

An alternative to wet bending is the use of high-performance timber products that allow for rapid, dry bending while still maintaining considerable structural reserve. In this regard, there is

research focused on the development of finger-jointed solid timber and glued laminated timber made from *Eucalyptus globulus* L., which achieves high characteristic bending strengths of up to 55 N/mm² (Lara-Bocanegra et al., 2020a) and has been used in the construction of the *PEMADE gridshell* in Spain (Lara-Bocanegra et al., 2020b) (Figure 3a). Another recent elastic gridshell, where the laths were bent dry, is the *Wisdom Stockholm gridshell* (Figure 3b), which used laminated veneer lumber (LVL) made from spruce (Slabbinck et al., 2023). This product reduces the impact of defects by using thin, glued veneers, achieving a characteristic flatwise bending strength of 50 N/mm² (LVL S grade by Stora Enso).

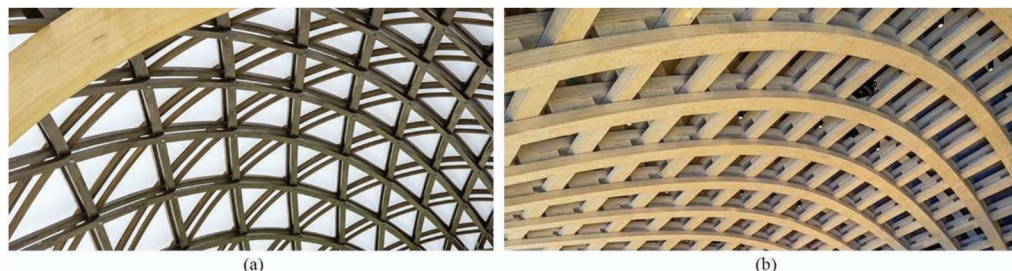


Figure 3. (a) *PEMADE gridshell*, Spain; (b) *Wisdom Stockholm gridshell*, Sweden.

In order to achieve large curvatures and perform dry bending while maintaining a high structural reserve, the authors are developing a new high-performance LVL using *Eucalyptus globulus* L. Moreover, as it is produced in board format and can be easily machined with standard 3-axis CNC machinery, it offers multiple and interesting possibilities from both design and manufacturing perspective, such as the manufacture of laths with variable thickness or width, and the integration of shear blocks with the laths, allowing the laths to be fully finished without the need for further manual work (see Section 3).

In the design process of elastic timber gridshells, one of the most critical aspects in relation to the chosen material is maintaining control over the minimum radius of curvature that can be achieved. Although the minimum design radius depends on rheological, mechanical, and geometrical parameters, as well as the material's safety factor (Lara-Bocanegra et al., 2020a), it can be roughly evaluated as the product of the ratio $E_{m,0,mean}/f_{m,k}$ and the lath's semi-thickness. This $E_{m,0,mean}/f_{m,k}$ ratio provides a straightforward and effective means of comparing the bending capacity of various species and products at a glance. To assess the bending capacity of the proposed product, LVL boards made from *Eucalyptus globulus* Labill sourced from the Iberian Peninsula (Figure 4a) were produced with a thickness of 41 mm, consisting of 22 veneers. Two configurations were manufactured: all veneers oriented in the same grain direction (S-layout), and the third veneer from the outer sides oriented crosswise (Q-layout).



Figure 4. (a) LVL made of *Eucalyptus globulus* L; (b) flatwise bending test of a eucalyptus LVL specimen.

Standardised flatwise bending tests were carried out according to the European standard EN 14374:2004, using LVL specimens of 100 mm width and a test span of 30 times the beam depth (Figure 4b). The bending strength ($f_{m,0}$) and the global modulus of elasticity ($E_{m,g}$) were determined. Characteristic values (5th percentiles) for strength were estimated by applying parametric methods, as specified in EN 14358:2016.

The characteristic strength values for eucalyptus LVL resulted in 109.1 N/mm² and 71.6 N/mm², with mean modulus of elasticity values of 23,149 N/mm² and 16,619 N/mm² for the S and Q layouts, respectively.

Figure 5a shows the relationship $f_{m,k}$ - $E_{m,0}$ with points corresponding to various strength classes and LVL products made from different species. As can be seen, the characteristic value of flatwise bending strength resulted more than 2.3 times higher than that of pine LVL-S and more than three times higher than that of C30 or D30 strength classes. Furthermore, the modulus of elasticity of eucalyptus LVL-S was approximately double that of the aforementioned strength classes.

The bending capacity (ratio $E_{m,0,mean}/f_{m,k}$) corresponds to the slope of the line connecting each point to the origin. It can be observed that all LVL products present a ratio below 300, with the lowest values found for beech and eucalyptus LVL, which reach values close to 200. This indicates that these products allow for smaller bending radii.

Figure 5b shows the minimum instantaneous design radii ($R_{min,d}$) for some European strength classes, as well as for eucalyptus glued laminated timber (GL56-euca), pine LVL, beech LVL (Bau-buche) and eucalyptus LVL, in service class 1, under the load case of internal bending forces acting alone. As can be seen, eucalyptus LVL enables significantly smaller curvature radii compared to other species and products, highlighting its great potential for use in this type of structure.

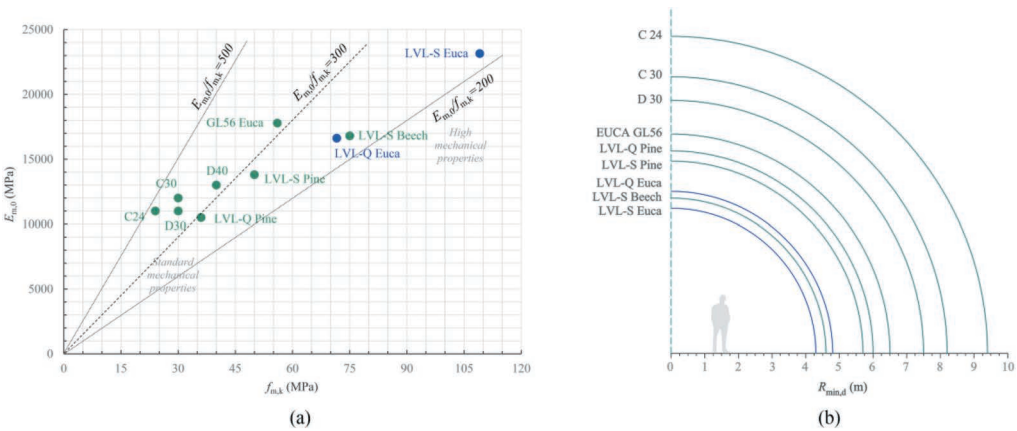


Figure 5. (a) Bending capacity of various timber products and European strength classes, and (b) Minimum instantaneous design radii of 41 mm thick laths.

3 TOWARDS A NEW CNC-MANUFACTURED MULTILAYER CONNECTION SYSTEM

When the cross-section of the timber lath is insufficient to resist bending stresses perpendicular to the plane of the structure, increasing the depth of the lath is typically not a viable solution. As previously mentioned, this would result in an unacceptable increase in bending stresses.

The usual solution involves using multiple layers of laths and mechanically connecting them after the deformation process, creating a multilayer composite system. This approach avoids increasing initial stresses and produces a composite section with significantly greater load-bearing capacity and stiffness than the individual laths. The connection must withstand the shear forces between layers and be as rigid as possible to maximize the efficiency of the composite profile. Various solutions have been implemented in this regard: the use of bolts at the nodes, as in the *Mannheim Multihalle* (Figure 6a), timber shear blocks fastened with screws to the laths, as in *The Savill Building* (Figure 6b), mechanically laminated multilayer systems, as used in ribbed shells

(Figure 6c), or a combination of shear blocks at the members with a patented steel connection at the nodes, as seen in *The Weald and Downland Living Museum* (Figure 6d).

It is worth noting that in elastic gridshells, the angle formed by the crossing laths at a node often varies throughout the structure due to the mesh pattern used (see Section 4). Furthermore, when the curving process is carried out by deforming the entire grid, as in the concept developed by F. Otto, the angle between the laths at a single node also changes during construction. For these reasons, the nodal connection must be solved with an element that allows for the relative rotation between laths, such as a bolt (Figure 6a-c) or a specially designed fitting (Figure 6d). The nodal connection and the multilayer system are among the key details in this type of structure from a constructive, mechanical, aesthetics and economic point of view.

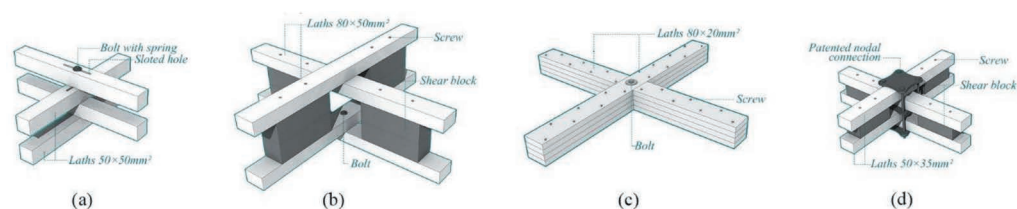


Figure 6. Joint solutions in elastic timber gridshells: (a) *Mannheim Multihalle*, Germany; (b) *Savill Building*, UK; (c) *Polydôme EPFL*, France; (d) *Weald and Downland Living Museum*, UK.

In pre-curved timber gridshells, it is common for the intersections between laths to be resolved using half-lap carpentry joints produced with CNC technology, as seen in the *Solemar Therme* (Figure 7a), the *Nine Bridges* (Figure 7b), or the *Swatch Headquarters* (Figure 7c). This type of joint offers several advantages, including ease and precision during assembly, maintaining a fixed angle between the elements, and providing significant translational and rotational stiffness thanks to the timber-to-timber contact between elements. However, these joints have the major drawback of causing a significant reduction in the cross-section and, consequently, a notable loss of load-bearing capacity of the element, which make it necessary to over-dimension it.

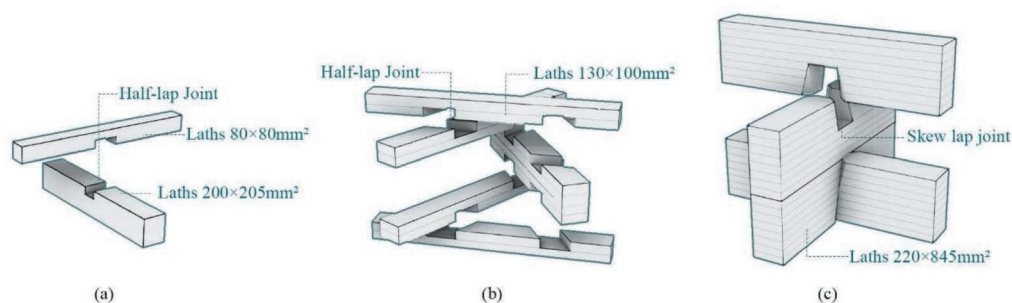


Figure 7. Joint solutions in pre-curved timber gridshells: (a) *Solemar Therme*, Germany; (b) *Nine Bridges*, South Korea; (c) *Swatch Headquarters*, Switzerland.

The proposed connection concept (Figure 8) combines the advantages of CNC joints used in pre-curved gridshells while avoiding the cross-section reduction inherent to half-lap joints. This is particularly important in elastic gridshells, where over-dimensioning the laths is not feasible without introducing unacceptable initial bending stresses. As a starting point, the proposed concept unifies the nodal connection and the multilayer system into a simple joint design that can be easily machined in LVL boards such as the one developed, using accessible 3-axis CNC machines.

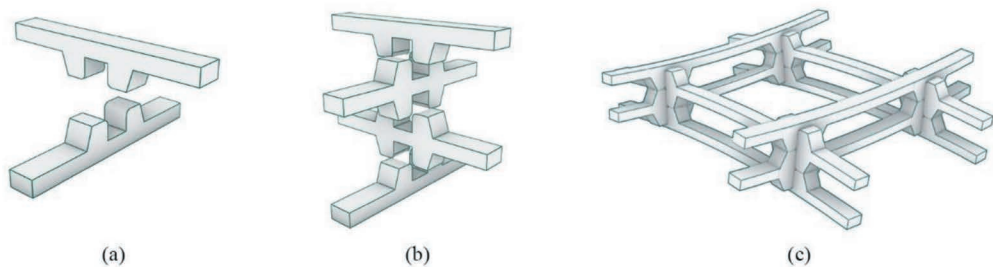


Figure 8. Proposed multilayer joint solution for elastic timber gridshells.

The proposed solution involves locally increasing the depth of the lath at the connection point, instead of reducing it as in half-lap joints. This approach allows a single element to both lock the rotation between laths (Figure 8a) and provide the necessary spacing to create a multilayer system (Figure 8b). Through a parametric design process, the distances between these elements in the upper and lower layers can be adjusted to achieve the curving of the members (Figure 8c), following a process similar to that of zipping up a zip (Martínez-Criado et al., 2024). This conceptual design also allows the integration of connection elements to transfer tensile forces between layers without relying on bolts or other solutions that require transverse holes, which reduce the cross-section of the laths as in traditional solutions (Figure 6).

4 NEW APPROACH TO MESHING USING PRINCIPAL CURVATURE LINES (PCL)

In elastic gridshells, the geometry of the structural grid is another critical issue to define in the early design stages. It is essential to know the trajectory of the curve network on the reference surface, which corresponds to the axes of the timber laths, to control the initial bending stresses.

The analysis of stresses in the timber laths due to their curvature can be performed through curvature analysis of the grid curves using the Frenet and Darboux trihedrons, deducing the normal and geodesic curvatures at each point of the curves. Based on the curvatures and knowing the lath cross-section and the material's modulus of elasticity, it is possible to obtain the bending moments in the two principal axes of inertia of the section and, consequently, the initial bending stresses (Roig et al., 2023).

In traditional elastic timber gridshells, two specific types of meshes have historically been used to generate the grid which, while imposing some restrictions from a design point of view, provide at the same time certain constructional or structural advantages.

On one hand, the approach developed by F. Otto is based on the premise that a flat, quadrangular grid made of continuous timber laths, connected by pinned joints spaced at constant distances and allowing rotation about an axis perpendicular to the grid plane, can be transformed into a grid on a doubly curved surface (Figure 2a, b). This transformation from a flat grid to a spatial one is possible due to the elastic deformation of the laths and the lack of in-plane shear stiffness during the

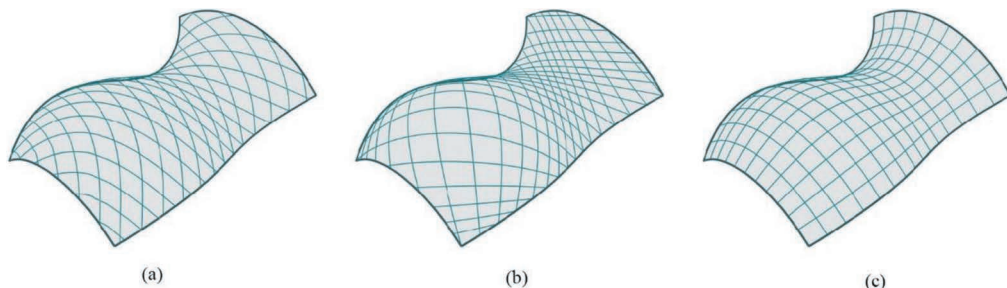


Figure 9. Anticlastic surface meshed with: (a) quadrangular mesh, (b) geodesic mesh, and (c) PCL mesh.

bending process. The resulting deformed grid inherently maintains the spacing between its nodes, which not only simplifies construction but also provides a compositional advantage by preserving a uniform grid appearance (Figure 9a). However, the resulting curves exhibit both normal and geodesic curvatures, inducing bending moments in both principal axes of inertia of the timber laths. This characteristic explains why the cross-sections of the laths in such structures tend to be square (Figures 6a-b, d). For instance, in the *Mannheim Multihalle*, laths with a cross-section of 50×50 mm² were used.

Alternatively, the concept introduced by J. Natterer revolves around creating a grid of high-inertia profiles by mechanically laminating multiple layers of overlapping laths, arranged along two geodesic curve directions on the surface (Figure 2c, d). Unlike F. Otto's approach, this type of meshes does not maintain a constant distance between nodes (Figure 9b) and, therefore, cannot be constructed by deforming the entire grid at once. Instead, it requires curving each lath individually. The significant advantage of this mesh type is that geodesic curves have no curvature in the tangent plane of the surface (i.e., zero geodesic curvature). Consequently, the laths bend only along their weak axis of inertia. This property allows for the use of laths with a much greater width than those employed in Otto's approach, as is the case with the *Polydôme* in Lausanne, where laths with a cross-section of 27×120 mm² were used (Figure 6c).

The concept proposed here investigates the use of orthogonal meshes in elastic gridshells, which are consistent with the proposed joint system. Specifically, it explores the potential of principal curvature lines (PCL) meshes. PCLs are characterized as a network of orthogonal curves aligned with the directions of maximum and minimum normal curvature at each point of the surface (Figure 9c). This type of mesh has not yet been applied to permanent elastic timber gridshells but has been used in pre-curved timber gridshells, such as the *Solemar Therme* in Bad Dürkheim (Figure 1a), and in some steel gridshell structures like *Shubert Club Bandshell* in St. Paul, Minnesota.

PCL meshes offer several construction advantages beyond their orthogonality at nodes. Notably, unlike quadrangular or geodesic meshes, the four nodes of a single face in a PCL mesh form nearly planar quadrilaterals. This characteristic allows the quadrilateral to be covered with a single planar element, avoiding the need for two triangular elements as made in the quadrangular-mesh gridshell of the *Chiddingstone Castle Orangery*. Additionally, PCLs have zero geodesic torsion, meaning the timber laths are not subjected to initial torsional stresses. However, in general, PCLs exhibit both normal and geodesic curvature, which implies that, as with quadrangular gridshells, the cross-section dimensions of the laths tend to be similar.

To validate the proposed concept, several scale prototypes were developed applying different strategies to generate the PCLs and the connection system concept described in Section 3. Figures 10a, c show the model of a structure resulting from finding the PCLs from a given reference

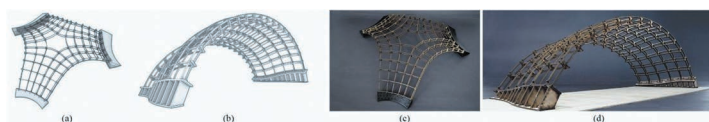


Figure 10. Scale models created with different PCL mesh strategies: (a, c) top-down, (b, d) bottom-up.

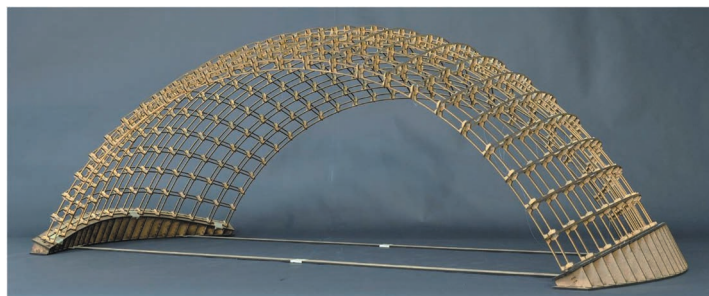


Figure 11. Model of a synclastic surface created using a PCL mesh with a bottom-up strategy.

surface (top-down strategy). This approach makes it difficult to control the curvatures of the PCLs, which is a drawback for the design of elastic gridshells.

Figures 10b, d and Figure 11 illustrate models of structures corresponding to an anticlastic and a synclastic surface, respectively, where the PCL network was generated following a bottom-up strategy using Monge surfaces (Gonzalez-Quintial & Martín-Pastor, 2024). This approach offers the significant advantage of enabling precise control of the PCL curvatures from the early stages of the design process.

5 CONCLUSIONS

This research presents the key aspects of an innovative design concept for elastic timber gridshells, combining CNC fabrication and carpentry joints, using high-performance *Eucalyptus globulus* LVL.

Investigation of the product's mechanical properties through flatwise bending tests highlights its high strength and stiffness. This allows for a fast, dry bending process and significantly smaller curvature radii compared to other products, offering considerable constructive and structural advantages over traditional solutions.

A meshing strategy based on Principal Curvature Lines is proposed for the design of elastic gridshells, which provides interesting features, such as orthogonal crossings at the nodes and the possibility of covering each quadrilateral of the grid with a single planar element.

An innovative multilayer connection system, made using CNC technology, is presented. This system is consistent with the developed product and the proposed meshing strategy, ensuring orthogonal connections, aesthetics, and ease of assembly and disassembly.

The successful fabrication of several models demonstrates the feasibility and versatility of this approach, highlighting its potential to advance the construction of elastic timber gridshells.

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