

TimberTwist — Wood in Rotation: A CNC-milled, actively-bent Timber-Membrane Canopy Prototype

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Abstract

TimberTwist — Wood in Rotation presents a full-scale canopy prototype that demonstrates an advanced zip-bending technique for timber on a new, larger scale. Zip-bending can be used to produce programmable curved and twisted timber elements. It creates a “zipped” composite from two zipper-shaped timber plates that interlock like a clothing zipper. A calibrated kerf pattern is CNC-milled into two planar wood layers, which are inserted into one another so that each layer elastically bends the other into the target geometry. Once the adhesive cures, the composite retains simultaneous curvature and torsion that realize a precomputed doubly-curved geometry. We detail an integrated architectural-engineering workflow translating form-found geometry into a wave-like CNC milling pattern, enabling self-assembling ribs that carry a high-tensile textile membrane for uniform pre-stress and increased geometric stiffness. The paper covers geometric form-finding, kerf pattern generation for CNC fabrication, non-linear finite-element sizing, and on-site manufacturing and assembly. Simulations predict an effective overall bending stiffness of approximately 43 900 kN cm² corresponding to a maximum vertical deflection of approximately 0.15 m under self-weight. Installed at the University of Stuttgart and developed with architecture students, the demonstrator illustrates how programmable curved timber elements can extend architectural geometries and enable large-span timber structures with a potentially reduced carbon footprint. It appears that there is currently still a deviation from the target geometry. This must be minimized in a future step. We conclude with lessons learned and directions for extending zip-bending toward programmable, load-bearing timber systems for architecture and construction.

Keywords: zip-bending, timber, tensioned membrane structures, active bending, shape analysis, architectural geometry, structural morphology

1. Introduction

The paper presents a case study of a full-scale active bending timber-membrane canopy (Fig. 1) that uses a novel manufacturing technique—zip-bending—to produce actively bent wood elements. We adopt a reciprocal design-analysis loop—treating architectural intent and structural behavior as co-equal drivers—and validate decisions through iterative simulation, prototyping, and full-scale assembly. The Institute of Building Construction is responsible for the architectural design, the geometric programming of the CNC milling processes, and the realization of the prototype. The Institute of Building Structures and Structural Design, took the lead in the structural design, detailing, and simulation. We document the complete workflow across consecutive seminar modules at the University of Stuttgart, from architectural form-finding and non-linear structural analysis to CNC fabrication. The prototype will be assembled on-site at the University of Stuttgart (Fig. 2) and will consist of three zip-bent timber-membrane

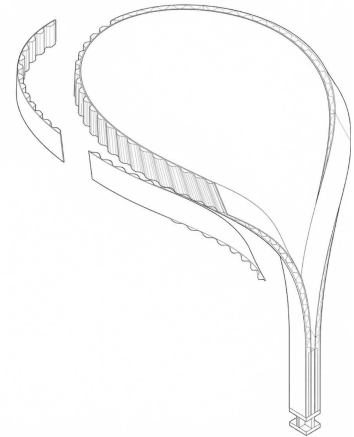


Figure 1: TimberTwist - Wood in Rotation: Full-scale bending-active canopy showing three zip-bent timber ribs, pre-tensioned high-tensile membrane, and support/anchorage points. Left image: Rendering photograph of the pavilion on the University of Stuttgart city center campus. Right image: Exploded schematic of the ribs as zipper-composite elements created by CNC-milled kerf patterns.

canopies. The project investigates how combining active bending with tensile membranes expands timber architectural typologies by enabling curved, organic geometries and how the anisotropic nature of wood (high stiffness and strength along the grain) together with controlled curvature can produce beneficial geometric stiffening effects.

This paper makes four contributions: First, it demonstrates the scaling of zip-bending to a 1:1 demonstrator with membrane-supported wooden ribs. It then describes a seamless workflow from the 3D target geometry to the CNC milling pattern and segmented assembly. Third, it presents a preliminary nonlinear finite element (FE) beam-membrane model for sizing and finally it documents manufacturing and assembly insights that reveal the relevant tolerances and limits of geometric accuracy on an architectural scale.

Building on foundational work in form-finding of tensile structures and bending-active systems/materials, this study extends prior research by combining zip-bent—a robotic, programmable method for inducing simultaneous curvature and torsion in timber—element with a membrane-stiffened rib system at full scale [1, 2]. Unlike earlier bending-active and tensile-timber hybrids that rely on linear bent elements, dynamic relaxation form-finding, or material-specific active bending, our prototype implements a zipper-composite fabrication that locks the actively bent form during manufacturing and thus does not require additional tensile elements to lock in the desired shape; the membrane in our system primarily provides global stiffening against external loads. In the next section we review relevant literature on form-finding, active bending, and timber materials to situate zip-bending within existing approaches and clarify the design and analysis choices used in this project.

Our approach integrates computational form-finding, parametric kerf-pattern generation, nonlinear finite-element sizing, and a CNC-based fabrication chain to translate target geometries into self-assembling zip-bent ribs. Starting from a doubly-curved spline geometry, we generate wave-like kerf patterns calibrated for lamella thickness and grain direction, simulate the assembled zipper-composite including geometric nonlinearity and membrane prestress to size member thickness and adhesive layout, and output CNC tool paths for milling and assembly sequences. This pipeline closes the loop between digital design and physical realization, enabling predictable, repeatable manufacture of large twisted timber ribs and their integration with a pre-tensioned membrane.

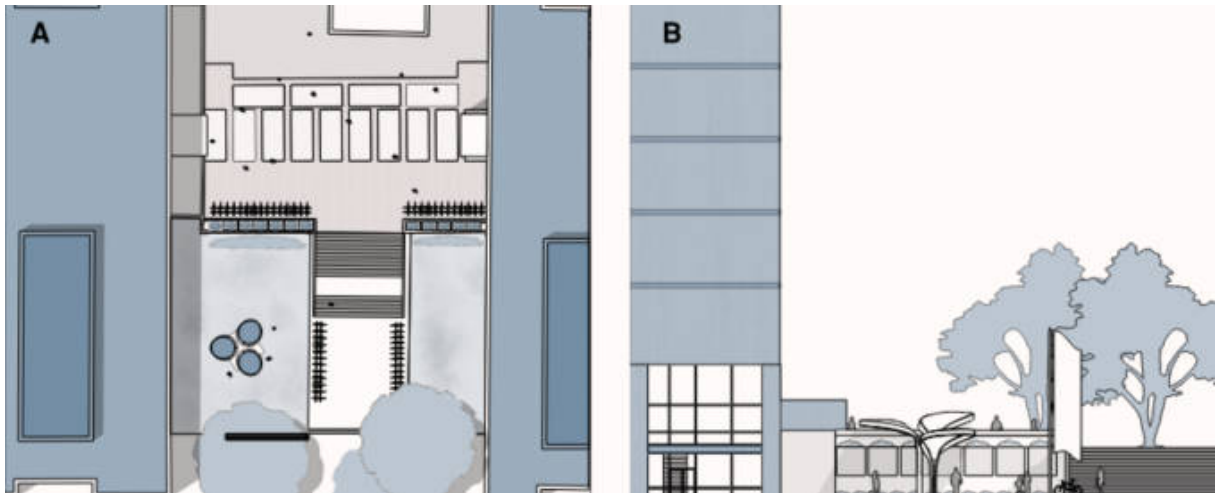


Figure 2: Planned prototype TimberTwist — Wood in Rotation at the University of Stuttgart: a) Lageplan, b) Ansicht.

2. Context

TimberTwist builds on research in lightweight tensile structures, bending-active systems, and programmable timber fabrication. The modern development of tensile architecture was strongly shaped by Frei Otto's membrane and cable structures, while computational form-finding methods such as dynamic relaxation enabled equilibrium geometries and internal force states to be calculated for pre-stressed membrane and cable systems [3, 4, 5]. These methods established an important basis for hybrid systems in which flexible surfaces interact with bending-active or linear elements.

Bending-active structures extend this logic by using elastic deformation as a self-forming and load-bearing mechanism. Previous research has shown that intentionally introduced torsion can improve geometric stiffness and expand the design space of plate- and rod-based systems [6, 7, 2]. This is particularly relevant for timber, whose anisotropic material behavior offers high stiffness and strength along the grain while still allowing controlled bending across weaker directions. Material limits, minimum bending radii, moisture sensitivity, and long-term deformation therefore remain central constraints for timber-based bending-active applications [8].

Recent work has addressed these constraints through fabrication strategies that program curvature and twist directly into timber elements. Robotic zip-bending uses CNC-milled kerf patterns to create two interlocking timber plates that form a bonded zipper-composite after assembly [1]. This approach allows curvature and torsion to be embedded into the timber component itself, reducing the need for external formwork or permanent tensile elements to maintain the desired geometry. Reported prototypes demonstrate achievable bending radii, limited spring-back after curing, and increased out-of-plane stiffness compared with single bent laminates, while also revealing practical limits related to lamella thickness, kerf resolution, adhesive performance, and fabrication tolerance.

The present work extends these approaches by integrating full-scale zip-bent timber ribs with a pre-tensioned membrane. TimberTwist investigates how programmable timber curvature, membrane stabilization, and realistic construction tolerances interact when the method is scaled to an architectural demonstrator.

3. Methodology & Design

The TimberTwist prototype was realized through an integrated, student-driven pipeline that converts an architecturally driven target geometry into fabricated, zip-bent timber self-supporting beams and

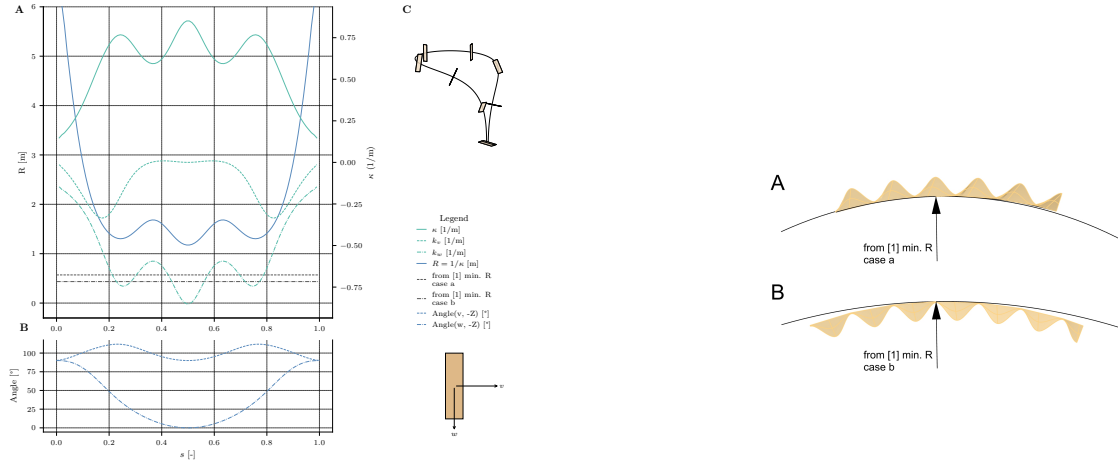


Figure 3: Left: Curvature analysis of the zip-bent timber beam geometry a) depicts the curvature and bending radii of the beam centerline as well as the decomposition of the curvature about two orthogonal cross-sectional directions v (major bending axis) and w (minor bending axis), b) shows the angle by which the timber beam cross-section is rotated w.r.t. the global downwards z -direction around the two orthogonal cross-sectional directions v and w and c) defines the cross-sectional coordinate system, where u is always the tangent vector of the timber beam curved centerline and v, w define the cross-sectional plane. The minimum bending radii for zippered timber composites are taken from [1] and differentiated by case a and b. Right: Depiction of the difference in elastic bending of zippered halves depending on the bending direction a) case a where the bending direction is opposite to the direction the zip teeth and b) case b where the bending direction is in the same direction to the zip teeth.

a membrane-stiffened structural system. First, an architectural form-finding stage, including physical experiments, defined a continuous, doubly-curved 3-D centerline spline with a rotating cross-section field, which encode the target curvature and twist and from which we generated parametric kerf patterns calibrated to lamella thickness, grain orientation, and allowable minimum bending radius. Next, the parametric kerf patterns along the 3-D target geometry were unrolled into flat geometries to enable translation into CNC toolpaths for fabrication; segmentation, assembly sequencing, and lap-joint detailing were developed to support on-site assembly. The target geometry of the zip-bent timber beam also defined the tensile membrane layout spanning the bounded inner area and a hinged connection detail between the membrane and the zip-bent timber edge. Finally, the assembled zipper-composite ribs were evaluated using geometric, nonlinear finite-element analysis that treated the pre-tensioned membrane as a coupled membrane-beam system: simulations assessed as-designed stiffness and deflection under self-weight and service loads, informed lap-joint and support detailing, and determined required lamella thickness and adhesive coverage to meet target performance.

3.1. Geometric form-finding

The target geometry for each rib is defined as a continuous, doubly-curved centerline described by a 3-D clothoid spline parameterized by arc length. A clothoid base was chosen because its linearly varying curvature produces smooth transitions between straight and curved segments and yields predictable bending radii along the span, which simplifies kerf calibration and reduces localized stress concentrations (Fig. 3). The centerline is paired with a rotating rectangular cross-section field: at each spline station the local Frenet frame (tangent u , normal v , binormal w) prescribes the cross-section orientation and the decomposition of curvature into principal bending radii k_v and k_w about the v and w axes (notation in Fig. 3).

To translate the target curvature and twist into a fabrication-ready zip pattern, a four-step geometric workflow transfers the spatial beam geometry into two planar timber components that can be CNC-milled

and assembled into the desired three-dimensional form.

First, rulings are generated on the middle surface of the curved beam. These rulings define the local zip-pattern orientation and the turning points of the sinusoidal tooth geometry. Following Naboni et al. [1], they encode both local bending radius and twist, linking the three-dimensional target shape to the two-dimensional cutting pattern.

Second, the outer lamella thickness is incorporated by projecting the rulings from the middle surface onto the two lateral beam faces. The projected endpoints define the zip-pattern boundaries and serve as control points for interpolated splines describing the individual teeth.

Third, the resulting three-dimensional zip geometry is unrolled into flat cutting patterns. Each tooth point is mapped to its corresponding position on the planar outer layer, preserving tooth sequence and spacing while producing manufacturable curves for both lateral sides and both interlocking timber components.

Fourth, the unrolled curves are converted into the final fabrication geometry. The planar zip curves are lofted into solid timber blanks, trimmed and segmented according to material dimensions, transport constraints, and assembly logic, and exported as CNC-milling data.

The tensile membrane is integrated into the same workflow as a shaping and stiffening element. Its footprint is derived from the upper boundary curve of the zip-bent timber beam and form-found as a minimal surface between the timber edge and the internal valley line. A steel cable along this valley acts as the main tensioning device, allowing the membrane to be prestressed and stabilized after installation. Along the timber edge, integrated eyelets at 150 mm intervals transfer membrane forces into the rib while remaining compatible with manual installation and adjustment.

A steel cable running along the central valley line of the membrane acts as the main tensioning device. This cable defines an additional internal boundary condition and allows the membrane to be prestressed after installation. By adjusting the tension in the cable, the membrane surface can be brought into its intended spatial configuration and stabilized against out-of-plane deformation. The cable therefore serves both as a geometric control element and as a structural component for introducing membrane prestress.

Along the timber edge, the membrane is attached at regular intervals of 150 mm. The connection is realized through timber eyelets integrated into the upper edge of the beam. This discrete attachment strategy transfers the membrane forces into the zip-bent timber rib while remaining compatible with the fabrication and assembly logic of the prototype. The 150 mm spacing provides a sufficiently close approximation of a continuous boundary condition, while still allowing the membrane to be installed, tensioned, and adjusted manually during assembly.

3.2. Structural analysis and design

Global analysis treats each zip-bent rib as a spatially varying, layered timber beam assembled from CNC-milled lamellae and bonded through the zipped adhesive interface. The model is intended for early-stage prototype sizing and sensitivity assessment, so the results are interpreted as design estimates rather than experimentally calibrated verification.

To balance fidelity and computational efficiency, the rib is idealized as a geometrically nonlinear 2D shell following the as-designed centerline. The shell represents two bonded C24 timber layers with total thickness $t = 80\text{mm}$ and nominal height $h = 300\text{mm}$. Orthotropic layer properties and local layer orientations are assembled into an equivalent multilayer shell stiffness. This homogenized representation captures global bending, torsion, and adhesive-interface effects, but it simplifies the actual wave-like tooth geometry and therefore cannot resolve local tooth stresses or detailed shear transfer.

The membrane is modeled as a geometrically nonlinear tensioned surface attached to the timber boundary with hinge-type constraints, representing flexible membrane anchors. A pre-tensioned edge cable runs along the membrane valley and terminates at a lower steel bar connecting the rib ends. Cable and bar

elements are included to represent the pre-tension load path and its geometric stiffening effect under external actions.

The analyzed actions are self-weight and imposed membrane/cable pre-tension in a structural form-finding step. Material behavior is linear elastic in the baseline model. Time-dependent effects such as creep, moisture-induced stiffness changes, adhesive viscoelasticity, and membrane fatigue are not included and are addressed as limitations below.

3.2.1. Material definitions and cross-section mapping

Orthotropic layer properties used to assemble the shell stiffness are taken from nominal C24 timber lamella data; values used in the FE model are listed in Table 1. The layered stiffness assembly procedure uses classical laminate theory adapted for orthotropic wood layers: each layer's stiffness matrix is transformed to the global section reference and integrated through the thickness to define the equivalent shell stiffness used in the FE model.

Table 1: Materials and key properties used in the numerical FE model

Element	Material	Dimensions	$E_{0,m}$	$E_{90,m}$	ν	G_0	ρ	Pre-tension
			[MPa]	[MPa]	—	[MPa]	[kg/m ³]	
LVL Zipped Timber Composite	C24 softwood	2x40mm layers, h=300mm	11000	370	—	690	420	
Membrane	PES-PVC Typ III	-	1220	810	-	14.5	$\approx 1.05 \text{ kg/m}^2$	$\approx 0.3 \frac{\text{kN}}{\text{m}}$
Steel Cable	St1570/1770	d=10mm	195000	-	0.3	-	7850	$\approx 1.0 \text{ kN}$
Steel Bar	S355	d=10m	210000	-	0.3	-	7850	

3.2.2. Construction lap joint and support conditions

For fabrication and transport, each rib is divided into segments connected by staggered butt-lap joints of approximately $l_{\text{lap joint}} \approx 0.50 \text{ m}$. The joints combine adhesive bonding with mechanical fasteners and are modeled as zones with reduced composite action to capture local shear transfer and stiffness discontinuities caused by interrupted grain. Outside the joint zones, the rib is represented by a coupled multilayer shell formulation.

The rib bases are modeled as clamped supports, corresponding to bolted steel plate connections anchored to concrete foundations. Membrane and cable connections are represented by pinned or hinge-type constraints. Support geometry and connection detailing were derived from FE reaction forces using conservative timber bearing and fastener design assumptions.

3.2.3. Numerical FE results

Figure 4 summarizes the FE post-processing for one zip-bent timber-membrane rib under self-weight and membrane/cable pre-tension. Internal moments and rotations are transformed into the local beam frame before extracting stiffness quantities along the normalized rib coordinate s . The bending response is described by two principal effective bending stiffnesses, $EI_1(s)$ and $EI_2(s)$, obtained from a local coupled fit between bending moments and curvature components. This avoids unstable point-wise stiffness ratios near curvature zero-crossings. The torsional response is expressed as an effective stiffness $GJ_{\text{eff}}(s)$, fitted from torsional moment and twist rate.

The results show that the rib behaves as a spatially varying anisotropic member rather than a prismatic beam with constant section properties. The strong and weak bending stiffnesses differ by roughly

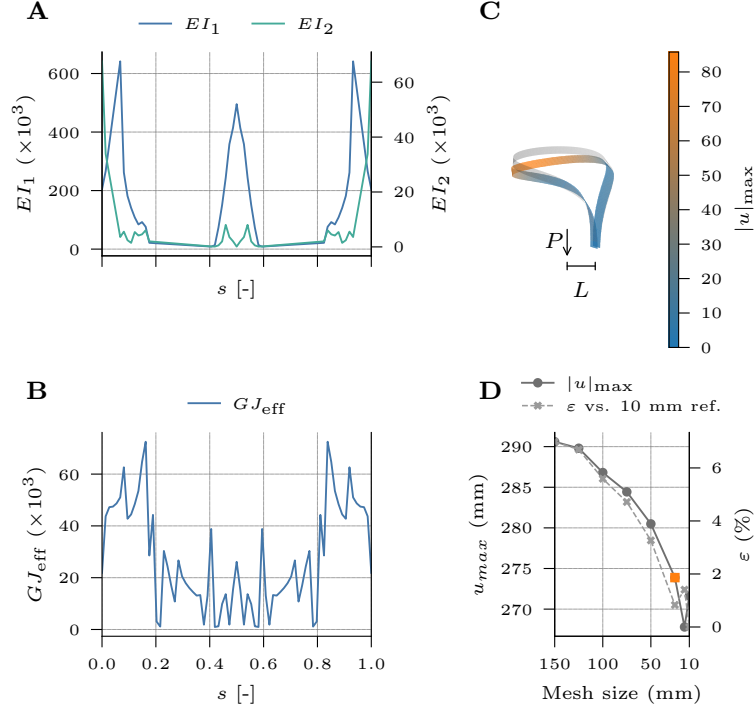


Figure 4: FE analysis of one zip-bent timber-membrane rib under self-weight and membrane/cable pre-tension: (a) principal effective bending stiffnesses $EI_1(s)$ and $EI_2(s)$, obtained from a local coupled bending fit along the normalized rib coordinate; (b) effective torsional stiffness $GJ_{\text{eff}}(s)$, fitted from torsional moment and twist rate; (c) scaled deformed shell geometry coloured by total displacement magnitude u ; and (d) mesh convergence of the maximum displacement $|u|_{\text{max}}$ relative to the finest reference mesh.

one order of magnitude, while local variations result from changing curvature, cross-section rotation, lap-joint modeling, and membrane boundary interaction. The deformed-shape plot visualizes the displacement field, and the mesh study confirms that the selected discretization lies within the converged range for the displacement quantity used in the sizing study.

For comparison with a simple cantilever estimate, $P = 1.4 \text{ kN}$, $L = 1.098 \text{ m}$, and $u_{\text{max}} = 140.7 \text{ mm}$ give a global effective stiffness of approximately $PL^3/3u_{\text{max}} = 43\,900 \text{ kN cm}^2$. This value should be interpreted only as a system-level comparison stiffness of the rib-membrane assembly; the local bending and torsional stiffness distributions are reported in Fig. 4.

3.2.4. Limitations and validation strategy

In the current coupling the membrane primarily stabilizes the canopy against wind-induced shape changes, rather than substantially increasing the rib's intrinsic flexural rigidity—generated predominantly by the curvature and torsion of the rib cross-sections. Quantifying any global stiffness contribution from membrane-rib interaction requires an experimentally calibrated coupling (adhesive shear tests, lap-joint shear/rotation tests, and membrane-edge load transfer measurements) and targeted sensitivity studies. Although the plotted $EI_1(s)$ and $EI_2(s)$ (see Fig. 4) account for coupling between the two bending directions, the post-processing does not identify full bending-torsion coupling; $GJ_{\text{eff}}(s)$ is fitted independently from torsional moment and twist rate. The present analysis considers only self-weight and form-finding pre-tension; full design appraisal must include representative external load cases (wind, snow, and service live loads) and staged full-scale load tests to validate the FE model and the support/anchor details. Finally, long-term phenomena (creep, moisture-induced stiffness



Figure 5: Left: Gluing a segment using wooden clamps along each ruling line in the correct direction and position to allow for the twist; Right: Assembly of the vertical scarf joint

changes, adhesive relaxation, and membrane fatigue) were omitted here and should be addressed through accelerated environmental conditioning, monitoring of prototypes in situ, and durability testing—alongside exploration of fabrication strategies (e.g., material-efficient additive approaches) to better align material placement with required stiffness.

4. Prototype manufacturing and construction

Fabrication and on-site assembly were carried out with architecture students across two seminar modules, covering parametric modeling, detailing, foundation design, zipper-composite assembly, adhesive bonding, membrane cutting, and installation [9, 10]. For production, the timber frame was divided into five individually zipped segments and joined by vertical scarf joints that preserved the clothoid rotation through the connection. CNC milling was carried out by an external fabrication contractor (Fig. 5). The connection between segments was achieved through a vertical scarf joint, which likewise incorporated the milled geometry so as to maintain the continuous rotation of the clothoid through the joint itself. The milling was carried out by an external fabrication contractor.

Working at a 1:1 scale and under real-world fabrication tolerances proved to be an integral component of the learning process, bringing to light a number of issues that had not been apparent from the digital model alone. Several insights emerged during the practical phase. The thickness of the adhesive joint between the two interlocking lamellae has a non-negligible influence on the final geometry, see in Figure 6: even small variations in joint thickness accumulate along the rib and cause the assembled form to deviate from the digital target. This sensitivity is characteristic of compliant systems in which curvature is an emergent property of the assembly sequence rather than a feature directly encoded in any single component. Similarly, minor localized inconsistencies in adhesive application produced measurable distortions in the cured final form, confirming the system's sensitivity to fabrication precision.

A further observation concerns the assembly sequence: because the rib geometry develops incrementally as the two zipped panels are interlocked, the partially assembled element tends to jam—that is, the next tooth cannot be brought into position because the opposing side is blocked. The bonding operation must therefore be executed as a single, continuous global motion to the greatest extent possible. Related to this is the observation that any attempt to force the assembly by applying pressure to the end of a partially zipped rib produced visible cracking along the lamellar edges; the implication is that the deformation must be driven by the cut pattern itself rather than by externally applied end pressure. Finally, it proved both practical and effective to provide each segment with unambiguous registration marks in the form of milled alignment holes prior to bonding. These served a dual function: they provided reliable visual reference points during assembly and simultaneously drew the geometry into the correct position through the mechanical engagement of the holes.

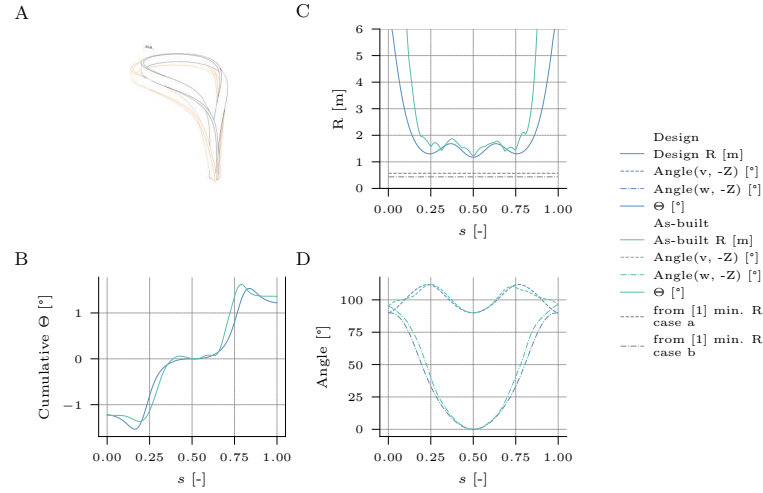


Figure 6: Comparison of design versus as-built zipped beam geometry for a single prototype depicted as: a) a 3D depiction of the zipped beam, b) a overlay of the radii of curvature, c) a overlay of the angles by which the zipped timber beam cross-section is rotated w.r.t. to the global downwards oriented z-direction around the two orthogonal cross-sectional directions v and w and d) comparison of the cumulative change in cross-section rotation along the zipped timber beam measured against the midpoint of the timber beam centerline.

5. Conclusion and further research

The TimberTwist prototype demonstrates that the zip-bending technique can be scaled from small laboratory specimens to a full 1:1 canopy structure, and that the resulting curved and twisted timber members can be effectively integrated with a pre-tensioned textile membrane to form a coherent, geometrically stable system. By fixing curvature and torsion within the timber itself, the method expands the design vocabulary of timber architecture, enabling expressive, doubly curved building forms without mechanical bending jigs or permanent cable bracing.

The prototype has shown that the planned and simulated shape is not fully achieved. Due to the constantly changing curvature of the clothoid, it is difficult to quantify the deviation numerically, but it is evident in Figure 6 that although it appears at first glance a relatively large difference at the midpoint along the zip-bent timber rib between design and built geometries, when quantifying the deviation in terms of radii of curvature along the timber rib the differences are much smaller than they appear visually. A significant challenge and result of this is that any curved design geometry where the curvature approaches zero is difficult to control for during manufacturing of the zip-bent timber ribs and small deviations add up over a given length. In addition, several areas warrant further investigation.

First, the geometric accuracy of the fabricated elements relative to the design intent requires refinement. Reducing the deviations documented during this prototype phase—and thereby tightening fabrication tolerances—remains a prerequisite for reliable deployment under architectural production conditions. Toward this end, the development and optimization of a parametric CNC milling model would provide a systematic basis for adapting the cut geometry efficiently to varying target curvatures while ensuring the level of precision required in industrial contexts.

Second, in its current implementation the process is associated with substantial material loss: the sinusoidal cut pattern removes approximately 50% of each flat panel during CNC milling. The resulting offcuts cannot readily be reused for additional ribs, as their geometry is tightly coupled to the target curvature of the originating element. This material loss must be weighed against the structural and assembly advantages of the technique—including its elimination of active bending rigs and the simplicity

of its connection logic. Future research should therefore explore the potential of additive manufacturing processes as an alternative or complementary fabrication strategy, with the specific aim of reducing material waste while preserving the geometric flexibility that characterizes the zip-bending approach. Additionally, future work should explore the zip-bending approach with a additive manufacturing process as it would mirror the concept from active bending of only requiring material in locations where additional stiffness is required from a structural analysis perspective and lead to a more systematic investigation of the stiffness distributions produced by different families of cut patterns—for a given target geometry. This would then enable the deliberate optimization of the cut design itself, and open a path toward actively bent curved timber elements whose stiffness, weight, and material consumption are co-designed to architectural and structural objectives.

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