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ORIGINAL PAPER

3DWoodWind: robotic winding processes for material-efficient lightweight veneer components

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Abstract
Winding processes are known from fiber composite technology for highly resistance lightweight components for aviation. These fiber-based processes work predominantly with synthetic composites made of carbon or glass fibers. For the construction industry, these additive processes are very promising and resource-efficient building processes, but they are still hardly used in timber construction despite the very high level of digitalization and technical development. The 3DWoodWind research project uses a continuous strip of thin veneer as a sustainable alternative as its application material. Its natural fibers are intact, continuous, and tensile. In the project, three-dimensional winding processes were developed for material-efficient hollow profile lightweight components made of wood. We describe the material system, composed of suitable combinations of veneers and adhesives, and develop computational design methods for filament layout and robotic fabrication methods. We also show an open-source prototype development method, necessary for efficient prototyping. Through several fabrication case studies, we demonstrate the capabilities of the production process, and investigate suitable architectural applications. These hollow lightweight components could save large amounts of material in timber construction and serve as a substitute for concrete or steel components in the future. We conclude by discussing possible applications in the construction industry and future research possibilities.

Keywords Robotic fabrication · Digital design · Timber construction · Additive manufacturing · Winding

1 Introduction

1.1 Timber-based fabrication techniques for hollow profiles

Equipment and methods for winding veneer into round cross-sections were patented as early as the first half of the twentieth century and have been reanimated in the last 20 years. The patents are divided into the winding of strips in cross layers or in the same winding direction [P1, P2] and the concentric winding of veneer sheets [P3, P4]. Currently, veneer winding is carried out using the technique originating from paper technology. This is evidenced by the development of round wrapped columns for columns from Kyoto in Japan (Hata et al. 2001; Inaba et al. 2003). The aim of these developments was to transfer the wood structure of fibrils to structural elements made of wood. Hata et al. (1998) published corresponding conceptual drawings based on the winding technology of cardboard rolls. Based on this technology, marketable round hollow profiles made of wound thin veneer layers have been implemented by the company LignoTUBE (Beck and Taranczewski 2014). According to this company, hollow sections with a diameter of up to 100 mm and a length of up to 6 m can be produced (Lignotube 2022). However, these are limited in terms of production technology to a circular, constant cross-section. Through use in bicycle frames and mechanical testing, it has been shown that the wound circular hollow sections can exhibit high density-specific strength (Gilbert et al. 2020). However, hollow sections made of wood were also produced using other processes. Wooden sections were glued in rings, for example, to produce poles or columns for the construction sector. The primary need cited is the replacement of poles for overhead power lines. Two approaches can be distinguished: one uses compressed wood that is partially consolidated toward the edge as a result (Wehsener et al.

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2014), and the other uses alternating trapezoidal cuts that produce an approximately round tube (Piao 2003). In both processes, the manufacturing process is organized discontinuously. More recent studies show the winding of bamboo veneer with added resins for use in sustainable piping products (Chen et al. 2019). In the NaHoPro project, the University of Kassel and the HNEE Eberswalde investigated the winding of veneer to circular profiles and subsequent forming processes into rectangular profiles (NaHoPro 2021).

1.2 Fiber-based winding techniques with biomaterials

Flax, hemp, and ramie are among the natural fibers with the highest specific modulus of elasticity and tensile strength. However, a great deal of variability in the literature should be noted. In general, geography plays an important role in the selection of fibers in terms of availability (Pickering et al. 2016). Applications of biofiber composites in the automotive industry have been investigated (Bledzki et al. 2006). Electro-, dry-, and wet-spinning of cellulosic materials has made it possible to produce submicron fibers and ultra-fine filaments with a strong, oriented structure (Lundahl et al. 2017). The extraction of natural fibers for modern technical use achieves a fiber yield of around 25% (Paulitz and Gusovius 2007). The ecological footprint of natural fibers depends on the country of cultivation and the associated transport routes and corresponding emissions, in addition to the complex manufacturing process. For example, the ecological footprint of the natural fibers hemp, flax, jute and kenaf is between 350 and 975 kg CO_2-eq per ton of fiber for the countries of origin Germany and India (De Beus et al 2019). For architectural production, various research projects are currently investigating new methods, as the robotic winding of mainly carbon and glass fibers (Prado et al. 2017; Solly et al. 2020; Sorrentino et al.2017; Quanjin et al. 2018; Minsch et al. 2017), to form lightweight structures. While impressive structural capacities can be reached with these materials, their ecological impact should be carefully considered, since the production of carbon fibers results in an estimated 30.000 kg CO_2-eq per ton of fiber (Meng et al. 2017) and in 1700–2500 kg CO_2-eq per ton of fiber for glass fibers (Barth and Carus 2015). A review on winding techniques with natural fiber filament was done by Ansari et al. (2017). At the University of Stuttgart, a moldless fabrication technique using natural fiber-reinforced polymer (NFRP) through a combination of fiber placement and filament winding was investigated (Costalonga Martins et al. 2020). Kenaf-based winding processes for reinforced polymer composites were studied by Misri et al. (2015). In terms of the production process, fiber-based winding techniques can employ relatively tight bending radii, allowing the possibility of winding only around the endpoints of a mold and, therefore, eliminating some of the necessary molding form material. Since the process requires the fibers to be fully impregnated with resin, the application tooling and winding technique can be rather challenging to avoid clogging of the application tool and to maintain the necessary tension on the fiber placement. The fiber volume fraction, the ratio between fibers and resins, is generally around 30–40% for fiber layups used in the boat industry and up to 70% in highly precise applications in the aerospace industry (Gurit 2022). Compared to wood-based materials, this value is nevertheless significantly lower, since a material-to-adhesive ratio of approx. 95% can be achieved for veneer components, for example (Dataholz 2021).

1.3 Robotic fabrication research approaches

Since its inception around 2 decades ago (Kohler et al. 2014), the adoption of robotic arms as fabrication tools for architectural research and, more recently, production has consistently expanded (Willmann et al. 2018). While this expansion has had a significant impact on the field, software approaches towards the simulation and programming of robotic manipulators specifically suited for architectural purposes have followed a more erratic development. This has much to do with the contingent and open-ended nature of architectural research, which often hinders the ability to effectively define shareable and reusable software solutions (Kaijima and Michalatos 2008; Mackey and Sadeghipour 2017). Several software toolkits (Schwartz 2013; Braumann and Brell-Cokcan 2015; Elashry and Glynn 2014; Soler 2016), mostly built around the Rhino and Grasshopper CAD environment, have been proposed in recent years. The reliance of such systems on closed source models, forced often the need for the development of entirely new tools, whenever the limits of the tool in use would not allow specific tasks. This is particularly true for the integration of sensing and actuation in robotic end-effectors, which could only rely either on the robot manufacturer's pre-defined interfaces, or resort to custom solutions for each application. More recently, within the Compas ecosystem (Van Mele et al. 2017), the development of the open-source framework for robotic programming CompasFab (Rust et al. 2018) offered a relevant model for open-source software development in architecture. Despite its merits, the heavy reliance on the ROS programming environment (Quigley et al. 2009) means that significant robotics and programming knowledge is required for the basic setup of a robotic system. While all these developments have significant merit in making robotic programming more accessible in architecture, a shared open-source adaptable approach that integrates all aspects of a robotic process for the specific purpose of architectural production is still lacking.

1.4 Contribution

The main contribution of this research is the development of three-dimensional winding processes for material-efficient hollow profile lightweight components made of wood. Industrial winding processes currently predominantly use synthetic composites made of carbon or glass fibers, or are very limited in their geometric forming possibilities.

The 3DWoodWind project offers a sustainable alternative also to bio-fibers, that have a relatively large carbon footprint because of their energy-intensive sourcing. We used a continuous strip of thin veneer strips as the application material. Its natural fibers are intact, continuous, and tensile. With the help of an open-source, modular soft- and hardware approach, we developed computational and fabrication methods for geometrically variable, high-performance hollow section lightweight components.

2 Methods

This section contains a detailed description of the material system, composed of a timber filament and adhesives (Sect. 2.1), computational design methods for generating the winding layout (Sect. 2.2), and a flexible modular robotic process development and control using open-source tools (Sect. 2.3), that was employed for this research.

2.1 Material system

2.1.1 Timber filament

As winding filament, a range of soft- and hardwood types were considered, encompassing spruce, fir, maple, beech and oak wood, all of which can be manufactured to continuous veneer filaments. Due to its high strength properties and existing integration in structural timber construction, veneer wood made of spruce/fir and beech was selected as the basis for the material system. The wood filament is manufactured from thin veneer strips, which are, as cut-off parts from larger sheets for furniture surfaces, a waste product of the veneer industry. These thin and short strips can be combined through finger-jointing to create endless rolls (Fig. 1). For small-scale investigations, a width of 24 mm and—depending on the radius of curvature of the component geometry—a material thickness of 0.3–0.5 mm was used. The minimum bending radius can be further reduced using a one-sided fleece lamination (e.g., cellulose fleece) as a reinforcing layer. Very thin veneers receive additional stabilization through the reinforcement layer and thus become more flexible, which increases the field of application for geometries with small radii of curvature.

2.1.2 Adhesives

When selecting a suitable adhesive system, the investigations focused on products that permit use in outdoor applications and are specially developed for load-bearing glued wood construction (Jowat 2021b). For the investigations, different 1- and 2-component adhesive systems based on polyurethane, EPI and PVAc were tested. All tested adhesive systems were provided by the industrial partner Jowat SE. The curing time of the adhesives was an important factor for the investigations and subsequent process integration, since it can be defined as rather short for a direct curing and robotic pressure contact during the fabrication process, or very long, if the curing is required after production. This and including other adhesive properties, as the viscosity, can have an impact on the resulting fabrication strategy and necessary tooling. We tested a range of adhesives—classified according to their respective bases: polyurethane (PU), emulsion polymer isocyanate (EPI) and thermoplastic polyvinyl acetate (PVAc).

Fig. 1 Left: 24×0.5 mm beech veneer filament, on a custom spool. Middle: cellulose fleece coating on the back of the veneer. Right: close-up of finger-joint of veneer strips

2.2 Computational design of filament layout

For the filament layout of robotic winded timber components, we investigated the geometric constraints and properties for straight extrusions and free-form surfaces with varying cross-sections. To achieve a good material distribution and avoid twisting of the filament, we used geodesic lines as the basic geometric component for the filament layout generation. For surfaces with a varying curvature, geodesic line segments can be calculated locally, creating a segmented winding curve. The winding lines can serve later as the direct toolpath for the specific robot orientations and movements.

2.2.1 Winding geometry of simple extrusions

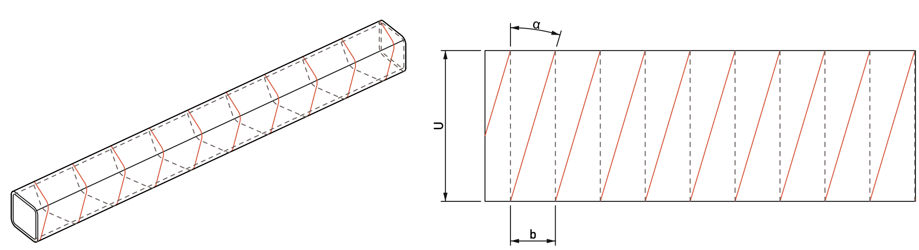
To produce jointless, uniform hollow profiles, three decisive parameters are decisive for the winding angle: (1) the circumference of the unwound surface, (2) the number of veneer strips per layer and (3) the veneer width. Depending on these parameters, the starting angle of the geodesic line (winding line) can be derived (Fig. 2). The profile is divided parallel to the cross-section into segments of equal size corresponding to the width of the veneer strip. To produce a jointless component, the starting point of the second rounding of the profile must be exactly at the same point as the endpoint after one rounding. The calculated angle must be redetermined after each layer, since the diameter, and thus, the circumference increase as a function of the material thickness of the veneer. This results in a slight decrease in the winding angle: the wider the profile becomes, the flatter the angle, therefore, becomes. Likewise, the winding angle changes as a function of the veneer width. The wider the veneer strip, the steeper the angle becomes. The number of veneer strips per layer is also decisive for the calculation of the starting angle. By increasing the number, the angle can be increased many times over. If, in addition to the number of veneers, the width of the veneer is also changed, the resulting winding angle increases more sharply.

2.2.2 Winding geometry of doubly curved surfaces

For the pattern generation for doubly curved surfaces, we investigated application patterns that minimize filament twisting. For this, we developed two different approaches. The first approach was developed for tubular geometries that can be described with a single NURBS surface. The second approach was developed for free-form meshes. To avoid and minimize twisting of the filament, since it can only bend in one direction, both approaches constructed winding lines such that if they are unrolled, they form a straight line. Theoretically, the winding lines are locally geodesic (subdivisions of the winding line), however, if the entire combined winding line is considered, the winding line is not geodesic since the winding line itself does not always have to follow the shortest path between the start and end point of the line.

2.2.3 NURBS-based approach

Generation: First, a surface is created and divided into sections along its length. This can be a surface of revolution, but it can also have an asymmetric cross-section. Then the starting point of the winding line at one of the two edges is defined, and the starting angle of this winding line. From this, the tangent of the starting line is calculated. With an iterative optimization procedure using Newton's method and numerical differentiation, the winding lines of the individual segments are determined as follows. At the starting point, the endpoint of the line is estimated by extrapolating the tangent, since the line was generated on a flat surface. A geodesic line is created between the start point and the estimated endpoint. The absolute distance between the tangent at the starting point of this line and the desired tangent is calculated. If the distance is relatively small, the optimization is aborted because both tangents coincide. If the distance is relatively large, the endpoint is shifted by a small step in the *u*-direction on the surface. With this numerical differentiation, we know how sensitive a change in the endpoint is to the initial tangent of the winding line in that segment. Using this information, we can estimate a new position of the endpoint using



$$\tan(\alpha) = \frac{x * b}{U} = \frac{\text{amount of veneer stripes per layer} * \text{veneer width}}{\text{perimeter}}$$

Fig. 2 Generation of winding lines for a square profile

Newton's method. From here, we repeat the process until we find a relatively small distance between the desired tangent and the tangent of the starting point of our geodesic line. When a geodesic line is found with a small error, we update the desired tangent for the beginning of that line for the next segment. To obtain a straight line when we unroll it, the tangent of the beginning of the line in a segment must match the tangent of the end of the line in the segment before it. The nurbs-based process is illustrated in Fig. 3, Left).

2.2.4 Mesh-based approach

While the above-described NURBS-based approach provides a high degree of accuracy in computing winding lines, it is nevertheless limited, as it can compute only on surfaces with defined bi-dimensional *uv*-domains. To provide a more flexible, although less accurate, approach for the generation of winding lines, a method based on mesh geometry is proposed (see Fig. 3 right). The method follows the same steps outlined for the NURBS-based approach, but, rather than relying on the *u*–*v* surface coordinated for defining the direction of the winding line growth, it relies on a user-defined direction vector. Furthermore, the method to identify the geodesic segments at each step is updated to work with mesh geometries, combining a shortest-path calculation on the mesh edges (Deleuran, 2014) with a further smoothing process based on the geodesic curvature flow method (Surazhsky et al. 2005), as implemented in the MeshPath plug-in for Grasshopper (Sagat and Remesıkova 2017).

2.3 Robotic process development and control

2.3.1 Open-source methodology

To develop and execute the described fabrication process, several hardware and software components are required to be integrated and synced in a single flexible workflow. As the project was developed as a first prototype both within research and teaching, it was necessary to utilize an adaptive process to integrate all the elements using flexible open-source tools, which have partially been developed by the authors (EDEK Uni Kassel 2021; Stefas et al. 2018). These tools allowed to integrate the different components, providing different levels of access with varying degrees of complexity, allowing to compartmentalize and distribute across the project team the knowledge required to operate the whole process (Fig. 4).

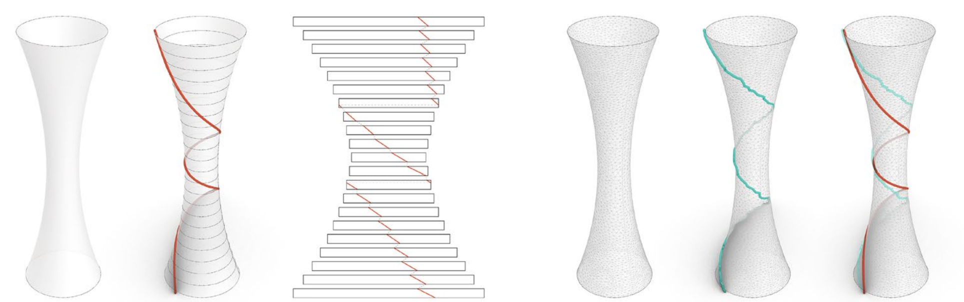


Fig. 3 Left: generation of winding lines using the nurbs-based approach. Right: generation of winding lines using the mesh-based approach

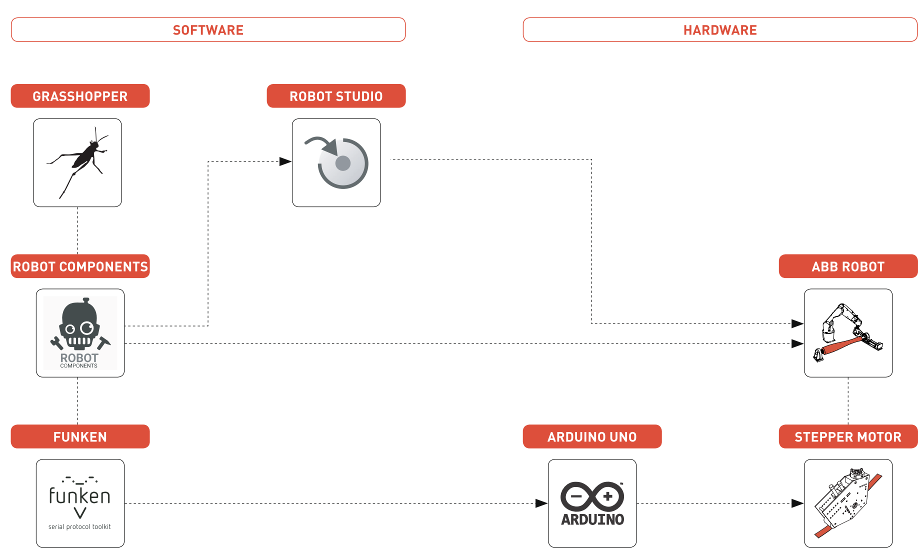


Fig. 4 Open-source software framework: a set of open-source software was developed, "Robot Components" and "Funken", that were designed to intuitively interface with the robot kinematics as well as with tool functionality and control. The goal is a modular and flexible integration with the robot hardware. "Robot components" provides a simulation and automated code generation in grasshopper with a deep access to ABB controller functionality. "Funken" allows control and processing of signals and stepper motors used for robot end-effectors

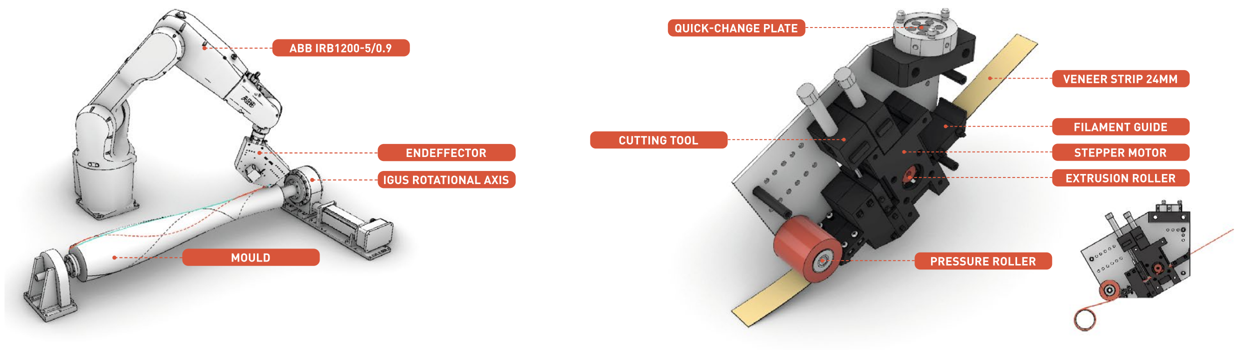


Fig. 5 Left: general robotic setup, using an industrial robot arm, horizontal positioner with external motor, winding mandrel and custom end-effector. Right: end-effector design for wood filament extrusion. The veneer strip is pushed forward through the filament guide by an extrusion roller attached to the stepper motor. The pressure roller applies the veneer precisely and the pneumatically actuated knife cuts the veneer according to a winded layer

2.3.2 Kinematic simulation and control

The 6-axis industrial robot and the external workpiece positioner were programmed with the open-source toolkit "Robot Components" (EDEK Uni Kassel 2021). The toolkit is a plug-in for the Rhino and Grasshopper CAD environment. The advantage of this toolkit is that it is specifically developed for programming ABB robots. In this toolkit, we aimed to strictly follow the programming logic and workflow of the RAPID programming language. Each component in the visual programming environment Grasshopper represents a single RAPID instruction which makes it a flexible and intuitive tool to use for both research and education. In addition, this approach makes it possible to easily extend the toolkit with RAPID instructions and declarations that are not part of the toolkit yet. For the advanced users of the programming environment, we provided an open API to build their own custom workflows and components.

2.3.3 Electronic systems development and control

For the control of robotic end-effector components, as well as for control of the external axis in the first two setups described in Sect 2.3.4, the Funken serial protocol toolkit was used (Stefas et al. 2018). Funken is an open-source toolkit used to simplify communication between different microcontroller and other electronic systems, relying on an event-based architecture for the control of different actuators from a variety of software interfaces. For the specifics of the project described here, Funken was used to enable the control of both end-effectors and external axis by sending commands from the Grasshopper algorithmic environment to Arduino-compatible microcontrollers. In addition, a routing set of functions were added, allowing to control the external components concurrently through software (e.g., Grasshopper) and through the robot IO signals. This allowed higher flexibility during prototyping, enabling the process to be fully automated through RAPID code instructions, while also maintaining software access for adjustments, testing and fixes during program execution.

2.3.4 Robotic fabrication setup

We developed a robotic fabrication process that can apply a continuous veneer filament through an extrusion method, similar to processes used in aerospace manufacturing like Automated Tape Laying (Lamontia et al. 2003). For our extrusion method, we used 6-axis industrial robot arms. For our case studies, the ABB IRB1660ID with a maximum reach of 1.55 m and an IRB1200 with a maximum reach of 0.9 m were used (Fig. 5). The IRB1200 was placed on an external linear axis to be able to manufacture tubular elements with a length of one to two meters. We used an external rotational axis to rotate the workpiece. The filament can be provided on spools as used for 3D printing, that are mounted directly to robot.

2.3.5 Setup-dependent toolpath strategies

For robotic control and subsequent fabrication, a tool path was generated from the previously generated winding lines. Since we worked with different setups, we developed three different toolpath strategies. The decisive parameters, which must be synchronized and coordinated with each other, are as follows: (a) extrusion speed of the filament, (b) speed of the external rotational axis and (c) the TCP speed of the robot itself. Depending on the part geometry, the parameters can be kept either constant or variable. For our initial studies with the external rotational axis that was controlled by a stepper motor and a microcontroller (Arduino), we kept the velocity of rotation constant. After successfully prototyping the process, we replaced the stepper motor of the workpiece positioner with a motor unit that was fully integrated into the controller of the robot. For this setup, the rotation speed of the workpiece positioner is calculated by inverse kinematics of the controller. It is not necessary to keep the rotation speed constant since the robot controller calculates and adjusts the speed given the positions and defined tool center point speeds. Another consideration was the extrusion velocity of the filament. As for the initial setup of the workpiece positioner, the extrusion of the filament was controlled by a stepper motor and a microcontroller.

2.3.6 Robotic end-effector design

We developed a custom robotic end-effector, which features an extruder, a cutting blade, and a silicon roller (Fig. 5). A cutting device was needed, since for applying multiple layers of veneer, the filament must be cut and reapplied. The cutting blade was controlled by an electromagnetic valve and the extruder by a stepper motor. The silicon roller was used to either apply pressure on the filament when the end-effector was directly placed on the mandrel, or in case the end-effector was placed with a certain distance to the mandrel to maintain tension in the filament. We applied the adhesive manually between the layers.

3 Case studies

3.1 Fabrication case studies

To demonstrate the geometric and manufacturing possibilities and limits, we designed and manufactured several case study prototypes, both for straight extrusions of circular and rectangular cross-sections and free-form rotational surfaces.

3.1.1 Hollow-core circular and rectangular profiles

Rigid hollow sections form simple, uniform geometries. The hollow sections are, therefore, also suitable for series of simple, identical standard components such as round or rectangular sections. We tested several layer structures with varying patterns and different fiber directions (uni- and bidirectional), both for round and rectangular profiles. Therefore, we used a layer structure consisting of seven layers of 24 mm/0.35 mm beech veneer. In the first test setup, only one veneer stripe per layer was used. The orientation of the stripe is alternating on every layer (clockwise/counterclockwise) with a resulting winding angle of approximately 8.5° (round section) and 9° (rectangular section). For the second test, we used one and six veneer stripes per layer, again alternating on every layer clockwise/counterclockwise. The layer structure starts and ends with one veneer stripe in the first and last layer. Using six filaments per layer, the winding angle of each stripe increases from 8.5/9° up to approximately 65.5° for the round tube and 69° for a rectangular profile (Fig. 6).

As winding mandrels, circular and square profiles made of steel, aluminum and plastic were investigated. The winding mandrels have a large contact area between the formwork and the veneer. Due to the resulting contact pressure, the wound hollow profiles were difficult to remove from the mandrels in initial investigations after the adhesive had cured. To optimize the removal of the cured components, tests were also carried out with various release layers—including PA and PVC film and a special release agent. A simple, cost-effective, and ecological alternative was found using conventional baking paper. In contrast to rigid hollow sections, the formwork made of individual tubes and spacers for angular sections offer greater variability in shaping (Fig. 7).

The end-effector design described in Sect. 2.3 was used, which allows a direct application without the necessity to apply moisture. With 24 mm/0.35 mm beech veneer, we were able to wind circular cross-sections of 50 mm diameter and rectangular cross-sections of 40 mm diameter with a 4 mm edge radius without the need for steaming the veneer

Fig. 6 Circular (left) and rectangular (right) profiles were wound with 24 mm/0.35 mm beech veneer

Fig. 7 Left, middle: as formwork, we tested steel, aluminum and plastic profiles of both circular and rectangular cross-sections of 40 and 50 mm diameter. Right: for larger rectangular cross-sections, a formwork made of thin aluminum tubes (20 mm diameter) and variable spacers was investigated. The tubes were used to provide a minimum bending radius at the corners for the veneer

(Fig. 6). We used Jowat Jowapur® 686.60 PU 1 K dispersion adhesive, with a curing time of 45 min, which was applied manually between each layer. The initial contact pressure was produced by pulling the veneer band with the robot end-effector. For a final pressure and adhesive curing, we applied a vacuum bag for final pressure after all layers of the component were wound. Figure 8 shows the precise application of veneer filament on the square profile.

3.1.2 Hollow-core doubly curved components

For functional, structural, or also spatial purposes, it can be suitable to use components with varying and customizable forms. Therefore, we investigated the manufacturing of rotational surfaces with varying cross-sections. A doubly curved surface with a varying positive and negative Gaussian curvature was used as a base surface for the generation of the winding lines. The rotational surface has a length of 1200 mm, a varying radius of min. 112 mm to max. 259 mm. The generation of the winding lines was done using the

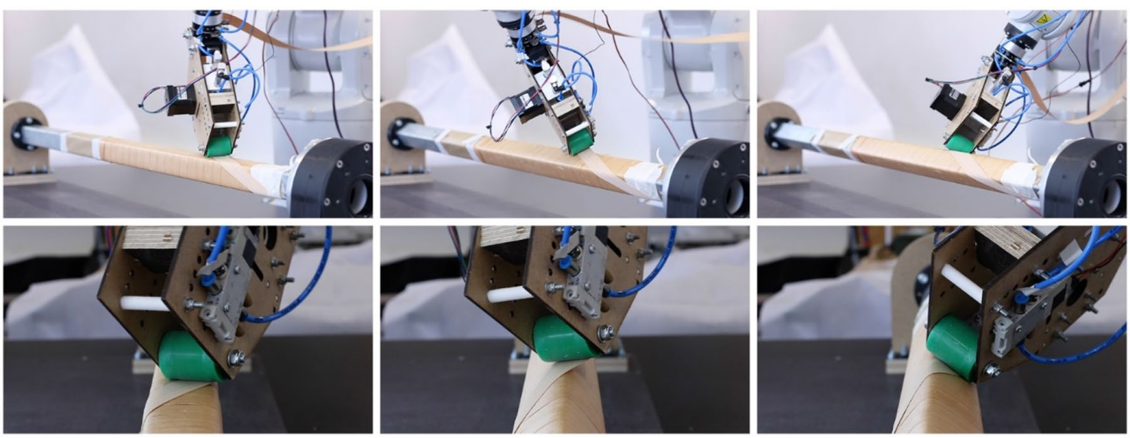


Fig. 8 Image sequence of square profile winding. Compared to round profiles, where the robot traverses a linear path, significantly more complex movements result due to the tool path along the rectangular profile. In addition, significant differences result with different winding angles, e.g., along a steep winding line with 6 veneer filaments per layer or with a much flatter angle with only one veneer filament

Fig. 9 Left: rotational surface with free-form section. Right: winding lines generation, to create an effect of braiding: 1st layer: 7 cw, 2nd layer: 7 ccw, 3rd layer: 7 cw (50% shifted), 4th layer: 7 ccw (50% shifted)

NURBS-based approach described in Sect. 2.2. In contrast to the regular profiles in the previous chapter, which are designed as a closed surface with consistent thickness and surface, a varying surface area needs to be covered by a consistent number of winding lines. This creates winding lines which space out or densify along the surface (Fig. 9).

Using CNC-milled ribs mounted on ring-shaped spacers, complex geometries can be realized with the help of rib formwork without the formwork itself having to remain in the manufactured component. The rings at the ends of the formwork form the receptacle for the rib elements attached to them, thus enabling universal use for various applications (see Sect. 4.4). To remove the formwork from the wound component, the rings are first detached from the internal winding mandrel and the ribs are then turned sideways one after the other so that they can be pulled out. This technique allows repeated use of the formwork element and thus multiple winding of a defined, complex geometry. For fabrication, we used the previously described larger robot a reach of 1.55 m. The formwork consisting of a winding mandrel with 125 mm diameter and a length of 1500 mm, a CNC-milled fixation circle of 288 mm diameter holding the CNC-milled ribs from 5 mm MDF was mounted on a rotational axis. A PVA adhesive was used to glue the several layers together (Fig. 10).

3.2 Architectural application

In addition to the development of the computational design and robotic methods described in the previous sections and the production of fabrication prototypes, we investigated the potential for the application of robotically winded timber elements in architectural design.

3.2.1 Geometric possibilities

In architecture, the geometry of components has a large influence on the structure, architectural function and use variations. We investigated the geometric possibilities by evaluating the design space of fabricable solutions, and created a library of forms that can be fabricated through winding. This was done through defining curvatures depending on width and thickness of the timber filament.

3.2.2 Component applications

For possible component applications, we evaluated solutions in architectural components, such as the use as a single element as a support, girder, free-form component or combined in a series of successive components as a ceiling or façade. This was done by evaluating the minimum and maximum fabricable sizes, which can be efficiently fabricated using stand industrial robotic equipment, available materials, and corresponding architectural dimensions for components.

3.2.3 Modular systems

Modular architecture can be characterized by a functional division into discrete, scalable, and reusable modules and the consistent use of clearly defined modular interfaces (Dahmus et al. 2000). In this context, modularity refers to the component level. Systems are used that are composed of separate, repetitive elements (standard units) that are similar in size, shape, and functionality. These can be interconnected, replaced, or added (Claypool et al. 2020). We investigated the suitability of robotically winded components for modular systems and in particular also for topologically

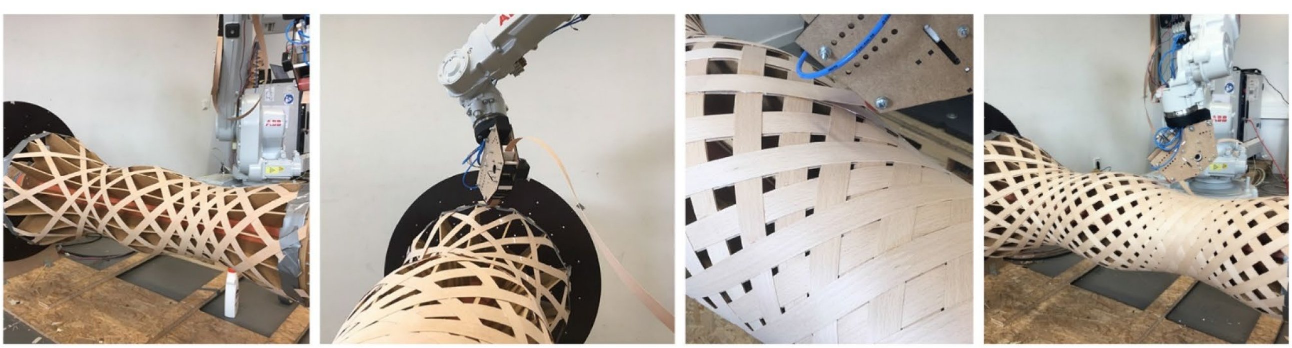


Fig. 10 Left: rib formwork, composed of a series 5 mm MDF plates that were CNC milled according to the surface design. At both ends, rings provide the precise spacing distance. Middle, right: fabrication of a 1200-mm-long customized component, with a varying diameter of 224–518 mm component with 28 winding lines. We used an ABB IRB1660ID industrial robot and a IGUS rotational axis. The varying geometry of the cross-section results in a winding pattern with opening and closing surface parts. Depending on the winding sequence, also braiding effects can be achieved

interlocking systems (Tessmann and Rossi 2019), in which the geometry of the component can create a stiff connection without the need for complex joinery. This was done through computational design studies using geometric analysis and design software, which was partly created by the authors (Rossi 2021; Weizmann 2021).

3.2.4 Winding patterns and surface design

We investigated the creation of irregular patterns for decorative purposes or also possible material optimization, which is, for the first purpose, mostly relevant for the outer or inner layers. For a variation of material distribution, the orientations of the filaments can be distributed and oriented. The following parameters are offering several design possibilities: first, the overall surface geometry with varying cross-sections is leading to pattern variations as the various curvatures on the surface itself immediately affects the generated winding line. Linked to this the starting angle of the geodesic is defining its path on the surface and as a result, the use of various individually oriented winding lines (e.g., clockwise/counterclockwise) is generating a first base pattern. This pattern can be extended by creating a braiding effect through ordering the winding sequence and also the distance between the several filaments (Fig. 10).

4 Results/discussion

4.1 Material system

We tested several 1- and 2-component adhesive systems based on polyurethane, EPI and PVAc, which were specially developed for load-bearing wood construction. Polyurethane adhesives (PUR) belong to the reactive adhesives and are available as 1 K systems with adjustable properties, making them well integrable in automatized applications (Bundesministerium des Innern, für Bau und Heimat 2021). Polyvinyl acetate adhesives (PVA) are physically setting adhesives that exhibit high adhesion to wood and other materials. Physiological harmlessness, short setting time and joint filling capacity, good water dilutability and compatibility with other waterborne adhesives are among the advantages of PVAc adhesives. Disadvantages are the sensitivity to creep of the glue line, thermoplastic behavior, and the nonresistance to moisture polymer and if such adhesive joints are exploited in a moist environment, its strength substantially decreases (Dunky and Niemz 2002). Emulsion polymer isocyanate adhesives (EPI) belong to the group of dispersion adhesives. The crosslinking with an isocyanate and the resulting chemical reaction significantly reduces the thermoplastic behavior. A cured EPI adhesive is hard to brittle, unlike a PVAc dispersion, which forms a viscoplastic film (Jowat 2021a). Its properties are thus similar to thermoset adhesives, which qualifies it for certain load-bearing joints (Brockmann et al. 2005). Considering the certifications for structural use, another variable is the type of wood which needs to be bonded, since most adhesives only have certifications for softwoods. Hardwoods are more challenging to join and the industry for structural timber is not yet fully accustomed to their use, therefore, few certified adhesive products exist. Another consideration is the proportion of wood filament to adhesives. Therefore, to keep the amount of adhesive in the composite material as low as possible, the thickest possible veneer should be selected from both an ecological and an economic point of view. This needs to be determined in relation to the surface curvature of the component, since low material thicknesses are necessary to achieve small curvature radii.

4.2 Computational design

For straight extrusion profiles, it is possible to generate a winding layout with relatively simple geometric rules, which varies according to the amount of veneer filaments per layer and their cross-section. In the computational winding generation, we studied, in particular, the possibility of orienting the different layers and thus the natural grain direction of the veneer. For optimized component properties and an increase in bending strength, there can be a combination fiber alignment in both the lateral and longitudinal direction. Figure 11 shows the analogy to the structure of a lignified cell wall. In addition, a crosswise ply structure prevents later swelling of the component, since wood swells less in the fiber direction. For more longitudinal directions, only certain angles are possible to create seamless components. In the small-scale investigations of circular and rectangular extrusion profiles, the focus was, therefore, on up to six veneer strips per layer, resulting in an angle of approx. 50°. In this way, a seamless component could be generated and produced, whose joint properties are not negatively affected.

For doubly curved surfaces, we investigated a NURBS-based and a mesh-based winding layout generation using locally geodesic lines. The NURBS-based approach provides a high degree of accuracy in computing winding lines, but it is limited to surfaces with defined bi-dimensional *uv*-domains. The mesh-based method enables the computing of geodesics of more complex geometries, as it relies exclusively on local information and does not require a 2-dimensional *u*–*v* domain. However, its accuracy and performance are both highly sensitive to the resolution of the base mesh. Increasing the mesh resolution leads to much higher accuracy to the result, but impacts negatively performance. With a careful balancing of the mesh resolution, resulting winding lines deviation from the ones generated

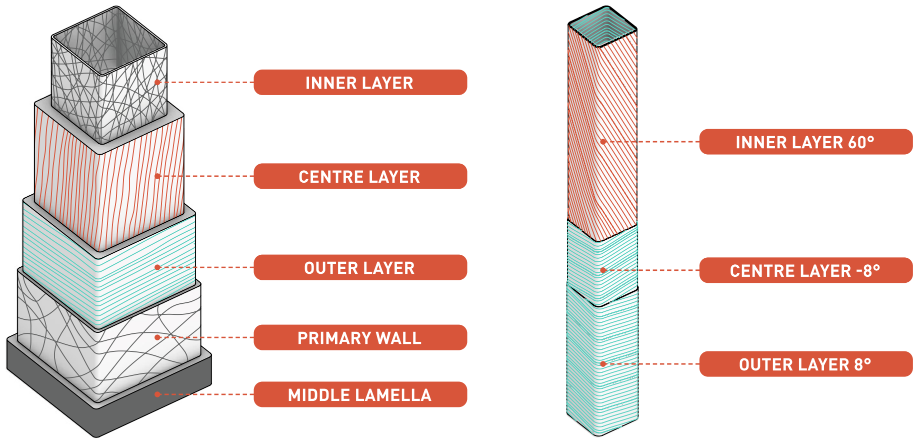


Fig. 11 Left: rigid structure of a lignified cell wall. Right: winded timber component with different fiber alignments

using a NURBS-based approach are negligible within the tolerances of the given fabrication process.

In contrast to straight tubes without varying cross-sections, the winding angle of free-form surfaces is not constant but changes on every single point of the surface due to the various curvatures on the surface itself. Therefore, winding lines in areas with a concave curvature are densifying, whereas lines in convex areas are spacing out. As a result of this not only the material distribution can be controlled by the component geometry, but also the fiber direction can change, e.g., from a more horizontal to a vertical direction. Regarding the geometric possibilities of the winding technique and the effects of the surface curvature on the winding line, we investigated several component geometries (Fig. 12).

In addition, curvature variations along the winding axis of the component result in winding patterns with open holes (see Figs. 9, 10). Thereby, it can be observed, that the larger the widest cross-section of the surface becomes, the larger the openings between the individual veneer strips become. A small cross-section in relation to the largest diameter can result in two or more veneer strips overlapping, depending on their width. This geometric principle directly affects the design process of the component.

4.3 Modular process development and control

The presented methods and results relied on the flexibility offered by the described open-source toolkit described in Sect. 2.3. Through the integration of Robot Components as a parametric robotic programming environment and Funken as a communication interface between robot, end-effectors and the programming environment, it was possible to prototype the process on a variety of different setups. This included shifting from an independently controller rotational axis to a robot-controlled setup, shifting the control from a Funken-driven stepper motor to an integrated ABB motor as an external axis defined within the RAPID robot program itself. In addition, the possibility offered by Funken to control extrusion in parallel from the RAPID program, as well as from the Grasshopper interface, provided a fast system for the calibration of extrusion and axis speeds, as well as other end-effector parameters. Finally, as some of the processes described in the paper were developed in the context of design studios, the proposed integration of Robot Components and Funken allowed encapsulating the complexity of each system in separate modules, allowing students with low programming knowledge to operate different elements of the system without requiring knowledge of the full robotic process control.

Fig. 12 Results of the generation of winding lines based on local geodesic curves on a range of different free-form rotational surfaces

Fig. 13 Case study prototypes of robotically winded components. Left: round profile with 7 layers of beech veneer. Middle: square profile with 7 layers. Right: free-form rotational surfaces with 4 layers

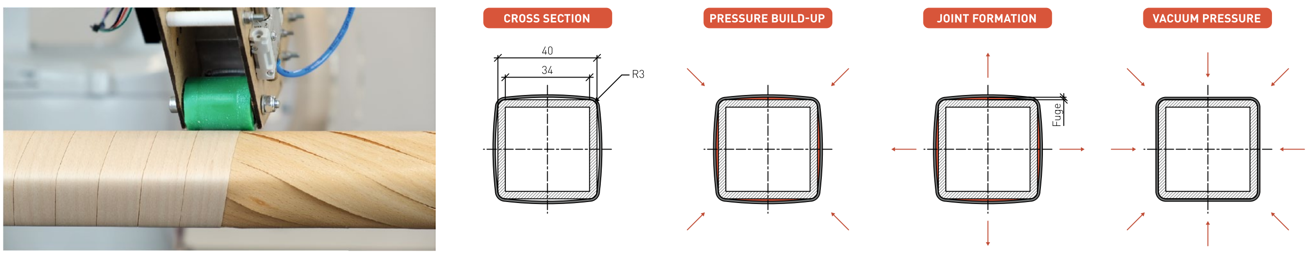


Fig. 14 Comparison of various solutions for pressing techniques. Alternatives to pressing using tensile force are build-up of pressure via the pressure roller installed in the end-effector during the winding process or subsequent pressing using a vacuum bag. Depending on the component geometry, it can be decided how the required contact pressure is applied

4.3.1 Robotic fabrication setup

With our robotic setup, modular tool design and control, we were able to successfully produce round, rectangular, and free-form rotational profiles with high precision (Fig. 13). The fabrication quality is thereby largely dependent on the selection, interplay and fine calibration between formwork, adhesive system, and winding strategy.

4.3.1.1 Formwork While standard solid winding mandrels can be used for winding surfaces of straight extrusions, for free-form surfaces, adaptable mandrels or formworks are advisable. The use of spacers of different sizes and shapes or variably adjustable spacers allows the formwork system to adapt to different cross-sectional geometries and enables, for example, the reproduction of tapered profiles. A further advantage results from the small contact area with the veneer, which makes it much easier to detach the wrapped component after production. A separating layer of non-sticky papers as used for rigid hollow profiles is, therefore, not necessary. Since the contact pressure in the winding process is applied only via the corners, the veneer risks to bulge at the flat areas. Subsequent pressing by means of vacuum is not easily possible due to the lack of contact surface.

4.3.1.2 Adhesive system For sufficient adhesion of the individual veneer layers to each other, contact pressure is needed depending on the adhesive system. The contact pressure required for this is between 0.6 and 1.0 N/mm^2 for the adhesives used. This guideline value results from the load-bearing glued wood construction with very long wood components, in which high pressing pressures are necessary to keep the joints as small as possible. In relation to veneer lumber on a smaller scale, the required contact pressure can be significantly reduced. In the robotic winding process, the wood veneer was kept in tension by the extrusion roller connected to the stepper motor, resulting in a contact pressure at the winding mandrel. Measurements with a tension/pressure gauge showed a tensile force Fs of approx. 20 N.

Tests showed that the pressure determined for round profiles via tension of the veneer is sufficient to join the veneer layers together, since the pressure builds up evenly along the profile. In rectangular profiles, on the other hand, the pressure in the winding process builds up at the corners of the profile, causing the veneer to bulge slightly on the straight surfaces and creating undesirable joints (Fig. 14). Especially with steeper winding angles, bulges occur in these areas, which can be pressed again with an additionally wrapped layer at a very flat angle.

Depending on the technology, this results in different requirements for the adhesive system, application, and programming. If the veneer is only held in tension, an adhesive with a relatively short curing time should be used. If the pressure can only be applied via the pressure roller, a very fast curing adhesive in the seconds range is required, which completely bonds the veneer layers together directly in the winding process. For both options, the adhesive application is integrated into the process and thus places high demands on the control and application system—in particular, the handling of adhesive systems with a very short curing time is much more difficult.

Another option is subsequent pressing by means of a pressure roller after each wound layer, which initially simplifies the toolpath, but at the same time slows down the process. Likewise, this can only be realized for certain geometries.

Another relatively simple alternative is subsequent pressing using a vacuum bag at the end of the production process. A longer build-up of pressure ensures controlled bonding of the veneer layers and requires an adhesive with a long curing time. In the case of curved surfaces (e.g., rectangular profiles), the pressure is distributed evenly over all surfaces by the vacuum bag, thus guaranteeing a homogeneous distribution of forces. This technique can also be used for geometrically more complex components. Another alternative to subsequent pressing using vacuum is represented by combination of adhesive systems, i.e., combining a hotmelt adhesive with a very high initial strength, which is only applied selectively, and a second adhesive, which provides the required final strength. This approach requires the use and integration of two application systems in the end-effector.

4.3.2 Winding strategies

Three winding strategies were investigated with different control parameters for extrusion speed, axis rotation velocity and robot tool center point (TCP) speed. For the first strategy, which keeps the velocity of rotation constant, we only needed I/O signals and communication between the microcontroller and the robot controller for stopping and starting the rotation of the external rotational axis, and to rotate the workpiece to the correct starting position. In the second strategy, the TCP speed was varied, while the other parameters are left constant. The third strategy allowed us also to change the rotation speed during movements. By partially changing the rotation speed, the resulting TCP speed was more constant with fewer peaks. Consequently, the fabrication process could be accelerated as the TCP speed could be increased due to more coordinated movements. As the initial setup of the workpiece positioner, the extrusion of the filament was controlled by a stepper motor and a microcontroller. For controlling the external rotational axis with the microcontroller, the simplest way was to keep the extrusion rate constant and use IO signals for starting and stopping the extrusion of the filament. Therefore, we primarily used strategy 2 in our investigations, to keep as many parameters as possible constant and to eliminate unnecessary sources of error. If the required pressure for the adhesive was applied by keeping tension on the filament during the fabrication process, the stepper motor for the extrusion could be either fully turned off or kept slow. This worked for the second as well as the third strategy. The direct integration of Funken into the Software environment (Sect. 2.3) also allows us to vary the extrusion speed during fabrication process for strategy 1. To keep both parameters—the extrusion speed as well as the velocity of rotation—constant, for strategy 2, only the start and end TCPs are oriented on top of the workpiece, unlike the other strategies where all TCPs are placed on top of it (Fig. 15).

4.4 Architectural applications

4.4.1 Geometric possibilities

In our experimental studies, we determined a minimum edge radius of 4 mm resulting from the limits of elasticity of veneer strips of 0.35 mm of thickness. Therefore, a range of different convex cross-sections from triangular to polygonal or round shapes is feasible for manufacturing. Asymmetric cross-sections can also be envisioned. We did not yet include partly concave cross-sections, since they require either extremely fast curing adhesives or complex molding processes, which we did not yet investigate. We also studied the various possibilities of cross-sections along components. Here, both positive and negative Gaussian curvatures can be achieved (Fig. 16).

4.4.2 Modular systems

Using standard robotics equipment, components with a maximum diameter of around one meter and a maximum length of 4 m can be efficiently manufactured. Combined with the described component geometries of the previous section, this results in various application options, e.g., use as a single element as a support, girder or free-form component or combined in a series of successive components as a short-span ceiling or facade, which can be aligned differently depending on their function. These application options can be combined in modular systems that only require few variable elements and are suitable, among other things,

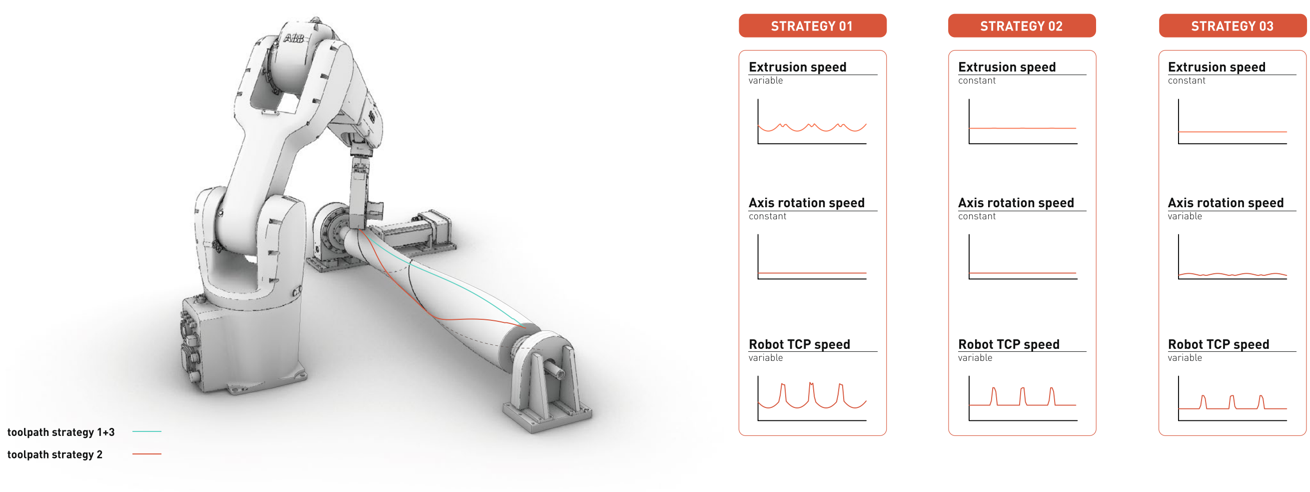


Fig. 15 Three different toolpath strategies: 1. axis rotation speed constant; extrusion and TCP speed variable. 2. Velocity of rotation and extrusion constant; TCP speed variable. 3. Extrusion speed constant; rotation and TCP speed variable

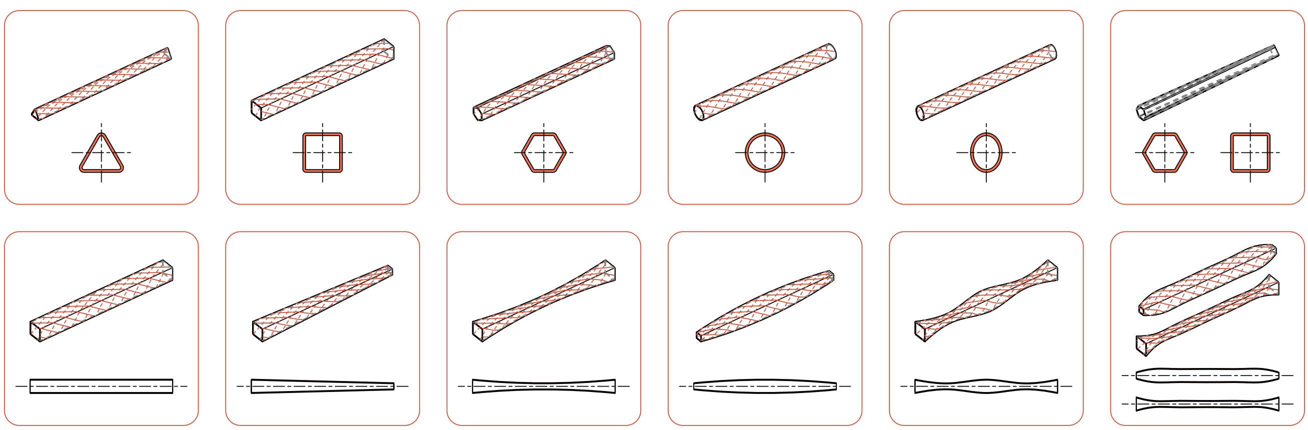


Fig. 16 Investigation of possible form catalogue for robotically winded timber components

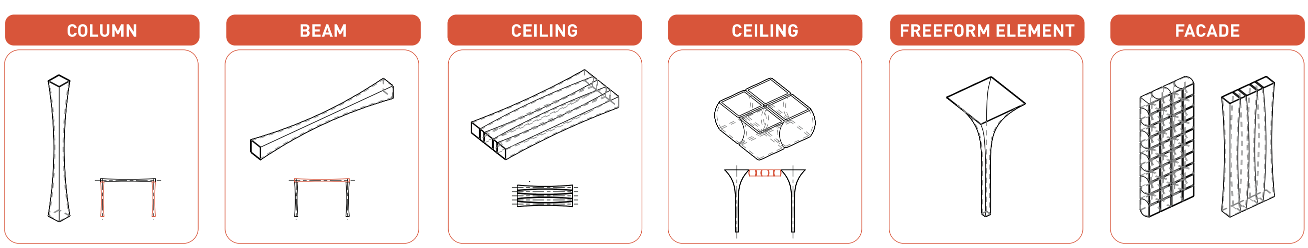


Fig. 17 Geometric shaping possibilities of robotically winded timber components and possible modular architectural application, i.e., as columns, beams, structural slabs, free-form components or façade elements

for temporary structures due to their simple assembly, disassembly and re-assembly (Fig. 17).

4.4.3 Customization

Winding offers unique design and customizing possibilities, such as the control of fiber orientation and material distribution in the elements, as well as the ability of creating geometric shapes with integrated connection details. Through this, components with structural derived forms can be created, e.g., hollow columns optimized for buckling, or patterns with gradual material distribution. In addition, smooth transitions from columns to ceilings can be realized, for an optimal force-flow. Since the components can be fabricated with integrated joining details for form-fit connections or even topological interlocking of whole components can be imagined.

5 Conclusions

Winding technologies are well-known fabrication processes used for the manufacturing of highly resistant lightweight synthetic fiber composites. Existing applications of these components can be found in aviation, shipping, automotive and architecture. Even though lightweight, the employed synthetic fibers have a largely negative CO_2 impact. Therefore, sustainable alternatives are needed. This research, therefore, investigated new potentials for lightweight, material-efficient construction with timber using thin continuous timber strips with intact, continuous, and tensile natural fibers. We described the development of a material system, composed of suitable combinations of locally sourced hard- and softwood-based veneers and certified moisture-curing polyurethane adhesives. We further investigated the computational design, and robotic fabrication methods of three-dimensional winding processes for material-efficient hollow profile lightweight components. We created a flexible, modular, prototyping workflow using our own custom developed open-source software. Through several case studies, we demonstrated that linear and free-form components with varying cross-sections can be designed and precisely manufactured. We also described possible applications as architectural and structural components in construction, as furniture and industrial design objects, columns, beams, floor slab or façade components. Thereby, a minimum bending radius of only 4 mm for thin veneers allows a large range of component geometries. Through computational control of the winding layout, surface geometry and winding sequence, the material can be optimally distributed and customization possibilities as variable patterns with open and closed surfaces and braiding effects can be achieved. Further research in joining, winded-in reinforcement is needed for enabling adapted and material-efficient connection of components. The structural design and characterization of these components is subject to a future research project.

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Declarations

Conflict of interest No competing financial interests exist. All the authors discussed the results and contributed to the final manuscript.

References

Ansari SM, Ghazali CMR, Husin K (2017) Natural fiber filament wound composites: a review. In: MATEC web of conferences, vol 97. EDP Sciences, , p 01018. https://doi.org/10.1051/matecconf/20179701018

Barth M, Carus M (2015) Carbon footprint and sustainability of different natural fibres for biocomposites and insulation material. Hürth: Nova-Institute. http://eiha.org/media/2017/01/15-04-Carbon-Footprint-of-Natural-Fibres-nova1.pdf. Accessed 01 Nov 2021

Beck C, Taranczewski R (2014) LignoTUBES–ein runder Furnierverbundwerkstoff für den ökologischen Leichtbau. ECEMP–European Centre for Emerging Materials and Processes Dresden: 15

Bledzki A, Faruk O, Sperber V (2006) Cars from bio-fibres. Macromol Mater Eng 291(5):449–457. https://doi.org/10.1002/mame.200600113

Braumann J, Brell-Cokcan S (2015) Adaptive robot control—new parametric workflows directly from design to KUKA robots. In: Real time—proceedings of the 33rd eCAADe conference, vol 2. Vienna University of Technology, Vienna, Austria, 16–18 September 2015, p 243–250

Brockmann W, Geiss PL, Klingen J, Schröder B (2005) Klebtechnik: Klebstoffe. Anwendungen und Verfahren. Wiley, Hoboken, p 254. https://doi.org/10.1002/3527605851

Bundesministerium des Innern, für Bau und Heimat (2021) Polyurethan-Klebstoffe. https://www.wecobis.de/bauproduktgruppen/klebstoffe/polyurethan-klebstoffe.html. Accessed 21 Jul 2021

Chen F, Li M, Xin W, Zhou H, Smith LM, Wang G et al (2019) Development of bamboo winding composite pipe (BWCP) and its compression properties. BioResources 14(3):5875–5882

Claypool M, Jimenez Garcia M, Retsin G, Jaschke C, Saey K (2020) Discrete automation. ACADIA 2020: Distributed Proximities / Volume I: Technical Papers. In: Slocum B, Ago V, Doyle S, Marcus A, Yablonina M, del Campo M (eds) Proceedings of the 40th Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA) ISBN 978-0-578-95213-0]. Online and

Global, pp 638–647. http://papers.cumincad.org/cgi-bin/works/Show?acadia20_638

Costalonga Martins V, Cutajar S, van der Hoven C, Baszyński P, Dahy H (2020) FlexFlax stool: validation of moldless fabrication of complex spatial forms of natural fiber-reinforced polymer (NFRP) structures through an integrative approach of tailored fiber placement and coreless filament winding techniques. Appl Sci 10(9):3278. https://doi.org/10.3390/app10093278

Dahmus JB, Gonzalez-Zugasti JP, Otto KN (2000) Modular product architecture. In: International design engineering technical conferences and computers and information in engineering conference, vol 35142. American Society of Mechanical Engineers, p 225–235

Dataholz (2021) Sustainability evaluation of timber construction products. www.dataholz.eu. Accessed 08 Dec 2021

De Beus N, Carus M, Bart M (2019) Carbon footprint and sustainability of different natural fibres for biocomposites and insulation material. Nova Institut. https://renewable-carbon.eu/publications/product/carbon-footprint-and-sustainability-of-different-natural-fibres-for-biocomposites-and-insulation-material-%e2%88%92-full-version-update-2019/. Accessed 29 Apr 2020

Deleuran AH (2014) Mesh analysis. Github repository: https://github.com/AndersDeleuran/MeshAnalysis. Accessed 20 Nov 2021

Dunky M, Niemz P (2002) Holzwerkstoffe und Leime. Technologie und Einflussfaktoren. Springer, Berlin. https://doi.org/10.1007/978-3-642-55938-9

EDEK Uni Kassel (2021) Robot components v0.17.002: intuitive robot programming for ABB robots inside of rhinoceros grasshopper. https://github.com/RobotComponents/RobotComponents

Elashry K, Glynn R (2014) An approach to automated construction using adaptive programing. In: Robotic fabrication in architecture, art and design, Springer, Cham, p 51–66. https://doi.org/10.1007/978-3-319-04663-1_4

Gilbert BP, Dias-da-Costa D, Lebée A, Foret G (2020) Veneer-based timber circular hollow section beams: behaviour, modelling and design. Constr Build Mater 258:120380. https://doi.org/10.1016/j.conbuildmat.2020.120380

Gurit (2022) Guide to composites. www.gurit.com/-/media/Gurit/Datasheets/guide-to-composites.pdf. Accessed 10 Jan 2022

Hata T, Umemura K, Yamauchi H et al (2001) Design and pilot production of a “spiral-winder” for the manufacture of cylindrical laminated veneer lumber. J Wood Sci 47:115–123. https://doi.org/10.1007/BF00780559

Hata T, Umemura KU, Kawai S (1998) Continuous manufacturing of cylindrical-LVL by using "spiral-winding method". Wood research, Kyoto

Inaba D, Morita M, Nakano H, Takenaka AU, Kawai S (2003) Continuous manufacture of cylindrical laminated veneer lumber. Wood research Nr. 90, Kyoto

Jowat SE (2021a) Jowacoll® Five Star 102.49. https://www.jowat.com/additional-data-sheets/832/Deutsch/P007115855-b7b8_deutsch.PDF. Accessed 21 Jul 2021a

Jowat SE (2021b) Tragender Holzleimbau. Zertifizierte Klebstoffe für Keilzinkenklebung und Lamellierung. https://www.jowat.com/de-DE/anwendungen/holzindustrie/massivholzverarbeitung/tragender-holzleimbau/. Accessed 29 Oct 2021b

Kaijima S, Michalatos P (2008) Simplexity, the programming craft and architecture production. In: First international conference on critical digital: what matters(s)?, 18–19 April 2008, Harvard University Graduate School of Design, Cambridge, USA, p 181–194

Kohler M, Gramazio F, Willmann J (2014) The robotic touch: how robots change architecture. Park Books, 2014.

Lamontia MA, Funck SB, Gruber MB, Cope RD, Waibel BJ, Gopez NM, Pratte JF (2003) Manufacturing flat and cylindrical laminates and built up structure using automated thermoplastic tape laying, fiber placement, and filament winding. SAMPE J 39(2):30–43

Lignotube (2022) LignoTUBE—the new semi-finished product for lightweight construction. www.lignotube.com. Accessed 20 Jan 2022

Lundahl M, Klar V, Wang L et al (2017) Spinning of cellulose nanofibrils into filaments: a review. Ind Eng Chem Res 56(1):8–19. https://doi.org/10.1021/acs.iecr.6b04010

Mackey C, Sadeghipour Roudsari M (2018) The tool(s) versus the toolkit. In: De Rycke K et al (eds) Humanizing digital reality. Springer, Singapore. https://doi.org/10.1007/978-981-10-6611-5_9

Van Mele T, Liew A, Mendez T, Rippmann M (2018) COMPAS: a framework for computational research in architecture and structures. 1(09)

Meng F, McKechnie J, Turner T et al (2017) Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Compos A Appl Sci Manuf 100:206–214. https://doi.org/10.1016/j.compositesa.2017.05.008

Minsch N, Herrmann F, Gereke T et al (2017) Analysis of filament winding processes and potential equipment technologies. Procedia CIRP 66:125–130. https://doi.org/10.1016/j.procir.2017.03.284

Misri S, Ishak MR, Sapuan SM, Leman Z (2015) Filament winding process for Kenaf fibre reinforced polymer composites. In: Manufacturing of natural fibre reinforced polymer composites. Springer, Cham, p 369–383. https://doi.org/10.1007/978-3-319-07944-8_18

NaHoPro (2021) Rechteckige Konstruktions-Hohlprofile aus biobasierten Multimaterialsystemen als Substitution von Metallprofilen. https://www.fnr.de/ftp/pdf/berichte/22019018.pdf. Accessed 10 Dec 2021

Paulitz J, Gusovius H-J (2007) Faserernte- und Faseraufschlusstechnologien. In: Regionale Wertschöpfungssysteme von Flachs und Hanf. Verlag Metropolis

Piao C (2003) Wood laminated composite poles. Louisiana State University, Baton Rouge

Pickering K, Efendy M, Le T (2016) A review of recent developments in natural fibre composites and their mechanical performance. Compos A Appl Sci Manuf 83:98–112. https://doi.org/10.1016/j.compositesa.2015.08.038

Prado M, Doerstelmann M, Solly J et al (2017) Elytra filament pavilion: robotic filament winding for structural composite building systems. In: Fabricate 2017: rethinking design and construction. UCL Press. London, p 224–231. https://doi.org/10.2307/j.ctt1n7qkg7.35

Quanjin M, Rejab M, Idris M et al (2018) Robotic filament winding technique (RFWT) in industrial application: a review of state of the art and future perspectives. Int Res J Eng Technol 5:1668–1676

Quigley M, Conley K, Gerkey B, Faust J, Foote T, Leibs J, Wheeler R, Ng AY (2009) ROS: an open-source robot operating system. In: ICRA workshop on open source software, vol. 3, no 3.2, p 5

Rossi A (2021) Wasp—a combinatorial toolkit for discrete design. https://www.food4rhino.com/en/app/wasp. Accessed 29 Oct.2021

Rust R, Casas G, Parascho S, Jenny D, Dörfler K, Helmreich M, Gandia A, Ma Z, Ariza I, Pacher M, Lytle B (2018) COMPAS FAB: Robotic fabrication package for the COMPAS Framework. Gramazio Kohler Research, ETH Zurich. https://github.com/compas-dev/compas_fab

Sagat M, Remesıkova M (2017), Discrete Lagrangian algorithm for finding geodesics and its comparisons with the fast marching method. In: Advances in architectural, civil and environmental engineering: 27th annual PhD student conference on applied mathematics, applied mechanics, geodesy and cartography, landscaping, building technology, theory and structures of buildings, theory and structures of civil engineering works, theory and environmental technology of buildings, water resources engineering, 25 October 2017, Bratislava, Slovakia, 1.vyd. Spektrum STU, Bratislava, s. 54–6

Schwartz T (2013) Hal. In: Robl Arch 2012. Springer, Vienna, p 92–101

Soler V (2016) Robots: grasshopper plugin for programming ABB, KUKA, UR and Staubli robots. https://github.com/visose/Robots

Solly J, Knippers J, Dörstelmann M (2020) Coreless filament winding: from academia to practice. In: Design transactions: rethinking information modelling for a new material age. UCL Press, London. https://www.jstor.org/stable/j.ctv13xprf6.21

Sorrentino L, Marchetti M, Bellini C et al (2017) Manufacture of high performance isogrid structure by robotic filament winding. Compos Struct 164:43–50. https://doi.org/10.1016/j.compstruct.2016.12.061

Stefas A, Rossi A, Tessmann O (2018) Funken—serial protocol toolkit for interactive prototyping. In: Computing for a better tomorrow—proceedings of the 36th eCAADe conference, vol 2. Lodz University of Technology, Lodz, 19–21, September 2018), p 177–186

Surazhsky S, Surazhsky T, Kirsanov D, Gortler SJ, Hoppe H (2005) Fast exact and approximate geodesics on meshes. ACM Trans Graph 24(3):553–560. https://doi.org/10.1145/1073204.1073228

Tessmann O, Rossi A (2019) Geometry as interface: parametric and combinatorial topological interlocking assemblies. J Appl Mech. DOI 10(1115/1):4044606

Wehsener J, Werner T-E, Hartig JU, Haller, P (2014) Advancements for structural application of fiber-reinforced moulded wooden tubes. Materials and joints in timber structures. Recent developments of technology. vol. 9. RILEM bookseries. Springer, Dordrecht, p 99–108. https://doi.org/10.1007/978-94-007-7811-5_9

Weizmann M (2021) Starfish. https://www.food4rhino.com/en/app/starfish. Accessed 29 Oct 2021

Willmann J, Block P, Hutter M, Byrne K, Schork T (eds) (2018) Robotic fabrication in architecture, art and design. Springer, Cham. https://doi.org/10.1515/9783035609844-017