Integrative Design Methods for Spatial Winding

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Abstract

A cooperative multi-robot system was developed to leverage the fibre's potential to act as formwork and allows to create wound filament connections which reduce the necessary formwork to a bare minimum. The developed process results in a novel typology of lightweight fibrous space frame structures. This paper contextualizes the presented work and introduces design methods for the developed spatial filament winding process. Syntax logics and rules were informed by geometric dependencies and fabrication-driven constraints. Computational design tools were developed to simulate the interdependent material behaviour and structurally inform the created artefacts. The proposed strategies and fabrication system expand the design possibilities of lightweight fibre structures and demonstrate the potentials of tailoring the fibres in space.

Keywords: Integrative Design, Fibre Composites, Filament Winding, Robotic Fabrication, Space Frame Structures, Lightweight Structures, Spatial Winding.

1 Introduction

1.1 Lightweight Fibre Structures

In recent years, many projects have demonstrated how fibre composites can open up new possibilities in the field of architectural design. Due to the fibres' anisotropic properties, it is possible to program the material's behaviour and generate structurally optimized lightweight structures. Its inherent ability to form complex geometries allows an exploration of new morphologies, materialities, and aesthetics, but requires an integrative design method, which considers material, fabrication, design and structural performance in a single coherent design framework (Prado et al. 2014).

Figure 1: Spatial Winding - Node detail with fibre-fibre interaction.

Introduction of Coreless Filament Winding (CFW) enabled novel applications of fibre composites beyond conventional aerospace and car manufacturing scenarios towards the fabrication of architectural elements. Research conducted in this field (Reichert et al. 2014; Doerstelmann et al. 2015; Vasey et al. 2015; Felbrich et al. 2017; Bodea et al. 2020; Solly 2020; Kayser et al. 2019) relied on the additive deposition of filament layers for fabrication of complex geometries with minimal formwork requirements. The majority of precedent projects deployed simple reconfigurable frames contrary to solid moulds used in conventional industrial applications (Prado et al. 2014)(**fig. 2**). These frames featured pre-installed anchors for winding of the filament around them. Strategic control of fibre tension and filament winding syntaxes allowed to create complex double-curved surfaces that emerged from the interaction of multiple layers of filament pressing against each other (Prado et al. 2014). Although this affords generation of continuous surfaces, a relatively large amount of fibre and winding anchors is necessary and the frame can become overwhelmingly complex.

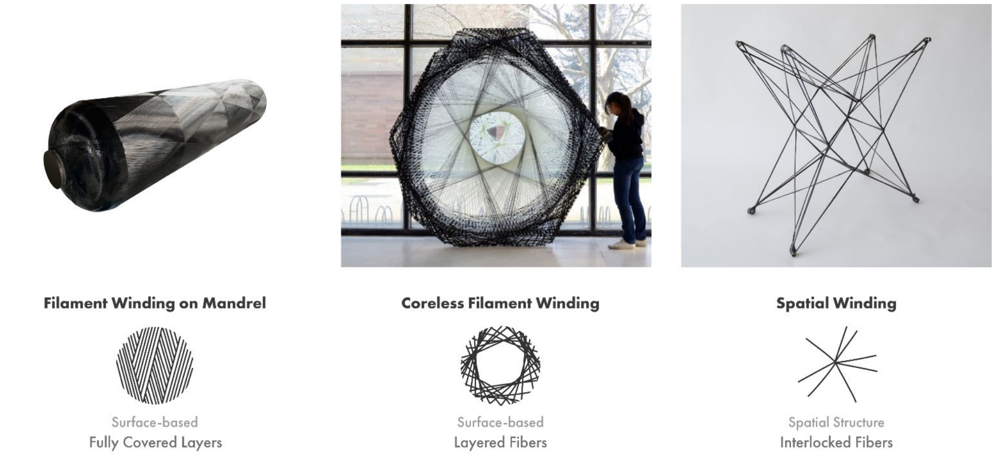


Figure 2: Comparison of methods: Filament Winding on Mandrel (carbowave.com 2020), Coreless Filament Winding and Spatial Winding.

Placed within the context of this ongoing investigation into the reduction of necessary moulds and formwork complexity, the research presented in this paper aims to contribute to the collection of existing material interaction strategies by introducing a new type of fibre-fibre connection. Instead of generating surface-based geometries, the proposed system is designed to create space frame structures, in which fibres act as formwork for other fibres, enabling the use of fewer anchors, and the use of simpler frames.

This paper introduces the design method for the proposed spatial winding system with a focus on the development of the syntax logic and rules that form the fundamentals of the geometrical possibilities. As part of an integrated design framework, computational design tools were developed to simulate the material behaviour and structurally inform design decisions. With the aim to digitally fabricate the proposed system, a cooperative multi-robot system was developed, implemented, and tested Duque Estrada et al. (2020). However, the robotic system lies outside the scope of this publication and thus will not be described in detail.

1.2 Space Frames

Commonly, space frame structures consist of two types of parts: nodes and edges. An edge is a linear element connecting two nodes. A node is an element that joins edges together into a spatial arrangement. Conventional steel space frames rely on standardized parts, as node designs can be highly complex. They usually implicate a fixed amount of connections, resulting in fixed topologies. This implies further constraints on the possible connection angles for each edge. Nodes, in particular, can be very expensive, as they typically represent 30-50% of the total fabrication cost (SCI P358 2014) and require up to 50% of the overall construction material (Narayanan 2006). Konrad Wachsmann is most known for his work on wide-span space frame structures applied to military airline hangars. As an early pioneer of prefabrication, he focused his work on the search for a 'universal joint': combining the reduction and standardization of parts in the most universal possible application (Andrzejewski et al. 2019). Wachsmann's experimental work "Study of a Dynamic Structure" (**fig. 3a**) is one of his most radical proposals, which he developed with his students in Chicago in 1953 (Gramazio et al. 2018). It envisions a structural system that defies any difference between nodes and edges, vertical and horizontal; strands, and intersections. It consists of structural threads twisted together to form an endless fabric. The edges operate as both columns and beams and each of them is only held in place by its distinct relationship to its neighbour. The joint becomes the driver of the system where the edges intertwine at nodes, providing vertical and horizontal contact while distributing the loads in converging diagonal lines (Borden and Meredith 2012).

Previous research demonstrates the potential of filament materials in continuous structures as Wachsmann proposed. Aerial Construction, by (Augugliaro et al. 2015) presents a manufacturing process for tensile structures with unmanned aerial vehicles (UAV). The spool is directly attached to the quadcopters, which allows them to fly through and weave between existing ropes and use previously laid fibres as formwork. Except for the required anchor points at both ends of the structure, the demonstrators' connections and links are entirely realized by the flying machines and solely made with the continuous rope (Mirjan et al. 2013). Conducted at the intersection of precedent work in fibre composite structures and Wachsmann's experimental notion of a "twisted joint", this research proposes a sequentially emerging type of space frame system from continuous fibres which form both nodes and edges. Although there is a certain structural clarity embedded in spatial frames that are wound only from a continuous fibre tow, it is impossible to break down their spatial formation into separately prefabricated components with static geometries. Rather, such a system can only be intentionally articulated when one is able to anticipate the embedded sequential choreographies of dynamic and spatial winding behaviours and their three-dimensional geometric interdependencies. In the following chapters, we discuss tools and methods that augment the designer's perception of spatially wound fibrous space frames and enable their calculated conception and controlled fabrication.

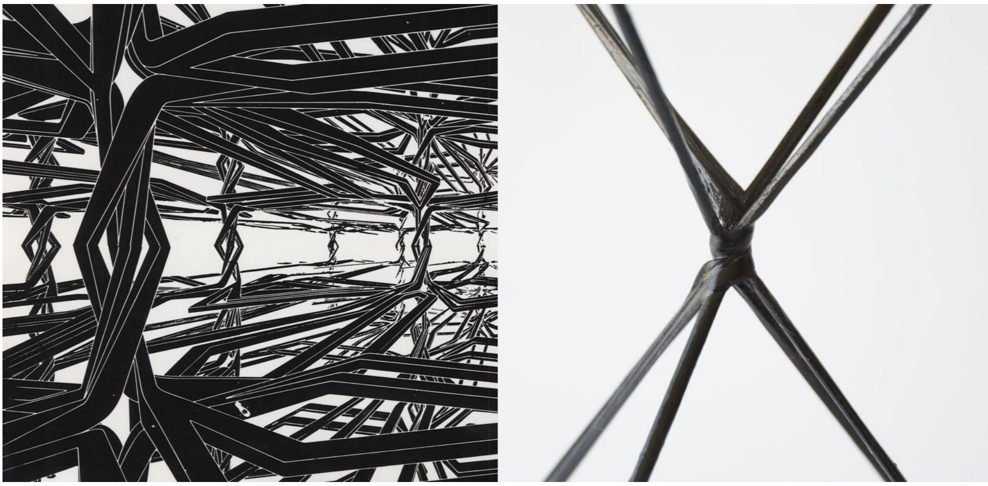


Figure 3: (**a**) Konrad Wachsmann: Study of a Dynamic Structure (Akademie der Künste, Berlin 1953), (**b**) Spatially wound CFRP node.

2 System Explorations

2.1 Fibres as Anchors

With CFW, the composite structure relies on the fibre behaviour resulting from the combination of frame geometry, anchor locations, and winding sequence (Prado et al. 2014). In these cases, the final surface emerges from the tension that each new fibre applies to already wound fibres. The level of differentiation is highly dependent on the amount of winding pins and the complexity of the frame. Aiming to simplify the frame but keep a high level of product complexity and geometrical differentiation, the proposed system needs to allow certain independence of the frame, number of anchors, and final geometry. The proposed system achieves that through a new type of fibre interaction that does not rely on anchoring to the frame but on fibres wrapping around each other, creating nodes in space. These nodes can act as winding anchors minimizing the need for mechanical ones and allowing the creation of numerous geometries within a simplified frame. Unlike in CFW, where the spool is positioned externally and a loop of fibre is manipulated by the robot, wound fibre-fibre connections require robotic manipulation of the whole spool. By removing the spool from its usually stationary condition and allowing it to be moved and handed through the structure, the system achieves interlocked fibre interaction, which is the core concept of the proposed geometrical system.

In order to understand what type of geometries could be generated within this system, a new set of rules and syntax logics were explored and systematized. These rules were informed by the fabrication constraints, such as bobbin size and robotic dexterity, as well as material properties. The principles were established on a minimal set-up, setting the fundamental criteria to form a geometry. Through iterations of physical and digital prototypes, different material behaviours were observed and transformed into syntax logics, creating a set of parameters to be tuned and combined.

The initial syntax logic was conducted with a minimal set-up consisting of a two-dimensional arrangement of four anchors in a square. By connecting these anchors, edges are formed and can be pulled from opposite anchors, transforming the initial edges into two segments. The relation between anchors and edges define the angles of the pulling and pulled fibres and well as the position of the new node (**fig. 4**).

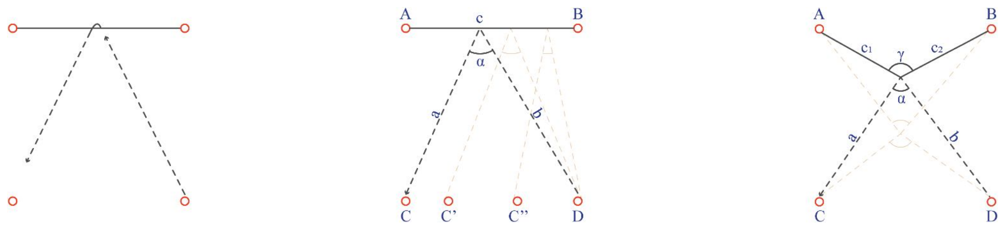


Figure 4: Node placement and dependencies.

By repeating this logic on the four sides of the square, a 4-pointed star is formed creating at least four new nodes in space (**fig. 5**). The new nodes can then be considered as new winding anchors for the next syntax iteration. In order to expand this method towards a three-dimensional topology, a next layer can be fabricated using the same principle but at a different height. The new nodes of both levels, as well as the initial anchors, are connected with vertical or diagonal segments (**fig. 5**).

By varying the position of the initial anchors, different star configurations can be formed and combined to generate unique geometries. At a local level, the number of turns around a fibre will define if the position of the node is fixed or can slide along the pulled edge. The same can be applied to vertical connections. To avoid single unconnected fibres, the material should go over and under each other in a weaving manner, pulling the material together. Research shows that the angle between fibres and frame can have a significant impact on how the loads are transferred, and by changing the orientation of the anchors, the connection's structural capacity between fibre reinforced components can be improved (Gil Pérez et al. 2019). Another important parameter is the direction of the anchoring routines, which will define if and how the fibres will cross each other after being wound on the anchors (**fig. 6**).

This bottom-up exploration with eight winding anchors generates an inner cubic structure. This network of fibres behaves as a space frame where the continuous

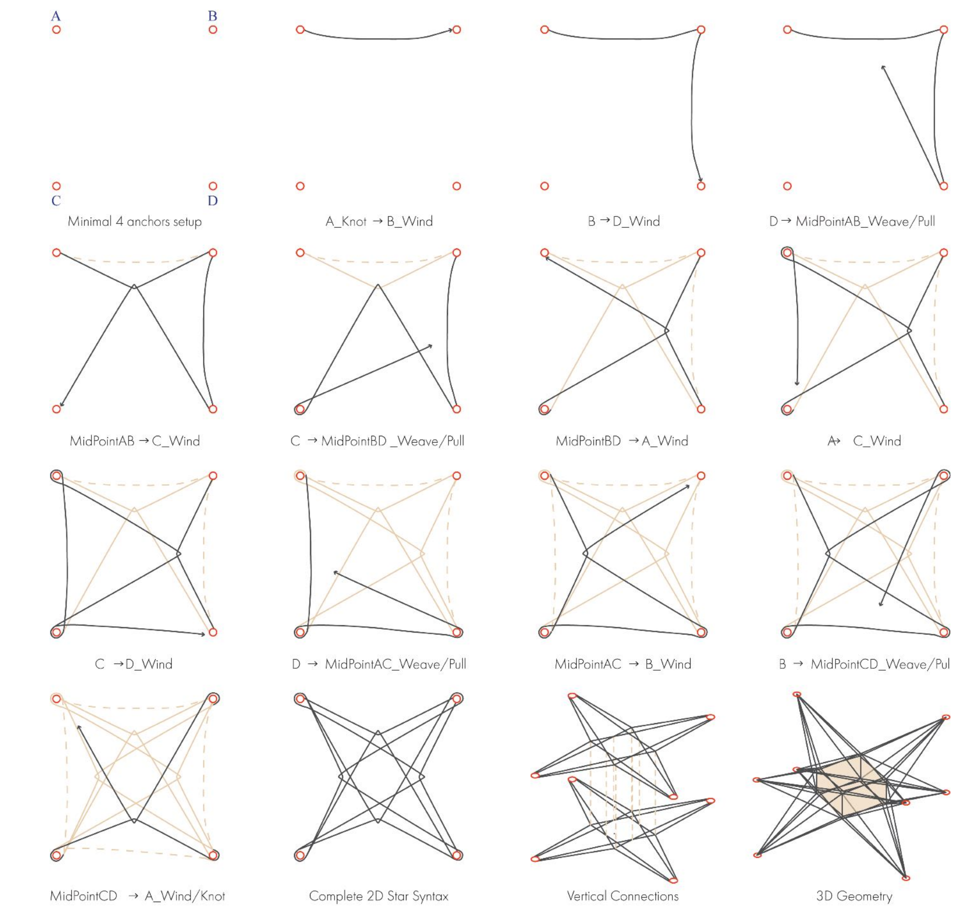


Figure 5: Syntax to form a basic geometry on a minimal setup.

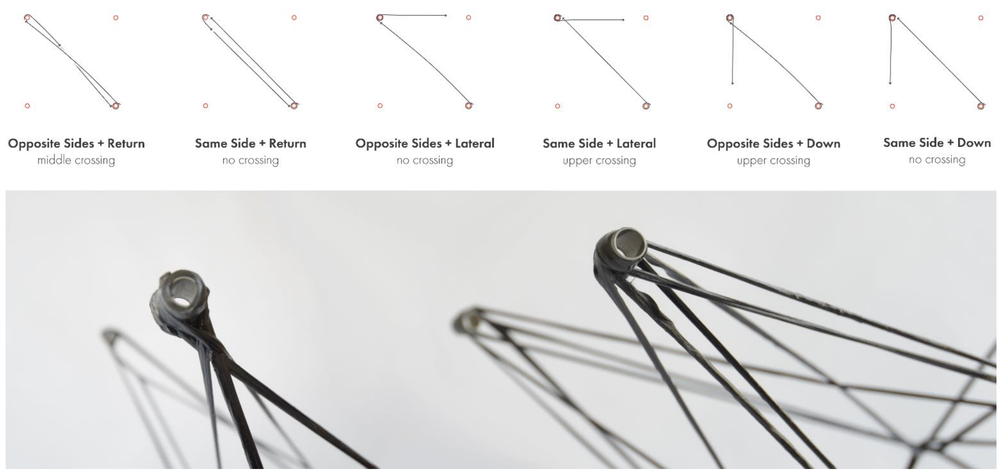


Figure 6: (**a**) Anchoring routines and resulting crossings, (**b**) Details of anchors with different anchoring routines.

fibre forms both the edges and nodes of the system. The nodes emerge at the points where the fibre edges meet and change direction. Contrary to traditional steel space frames, these nodes do not have a fixed amount of connections and pre-defined directions, presenting a vast range of design possibilities.

2.2 Syntax Strategies

Once the initial syntax was defined, a collection of strategies was developed to evaluate the geometric system at various levels of complexity, while maintaining the simplicity of the frame (**fig. 7**). A new set of rules enabled the creation of a diverse catalogue of geometries that do not depend directly on their frame but relate to the positions of newly created nodes in space.

The first strategy shifts the anchor heights (**fig. 7a**), essentially winding the basic star already in 3D. By combining two mirrored stars, a triangular dodecahedron emerges as an inner structure, creating new nodes at different points in space. The second strategy connects two non-parallel planes, enabling an angular final geometry that can be generated with symmetric or asymmetric stars (**fig. 7b**). This strategy allows multiple arrangements of heights and the combination of many elements could generate curved structures. The third strategy focuses on a way to expand the possible areas to create a node in space (**fig. 7c**). By increasing the length of an edge it is possible to offset the position of the created node. Combining four planes of anchors generates an intricate geometry with a dense centre. The final strategy addresses the use of the fibre as formwork, creating a temporary or permanent pre-structure to form a node in space (**fig. 7d**). This strategy brings the possibility to use another material that does not need to present a structural capacity in the main structure, and it could remain or be removed after being cured. Each strategy can be fully used to generate a final structure or can be applied locally to fulfil a specific function.

When connecting the geometries out of a plane, there are two approaches to forming a node. The first one travels from the centre of the geometry until the outer edge, pulling together all the fibre segments in between. This approach creates the main node, connecting many edges together (**fig. 8a**). In the other approach, the bobbin passes through the fibre intersections, pulling directly on the outer edge, leaving the other fibre intersections untouched. These fibre intersections are called sub-nodes since their interaction happens by a simple touch and does not involve wrapping around each other (**fig. 8b**). Both approaches are constrained by the relation of the diameter of the bobbin to the size of apertures resulting from the fibre intersections. If the bobbin can pass through them, the second approach is preferred as it avoids long edges and therefore minimizes the buckling length.

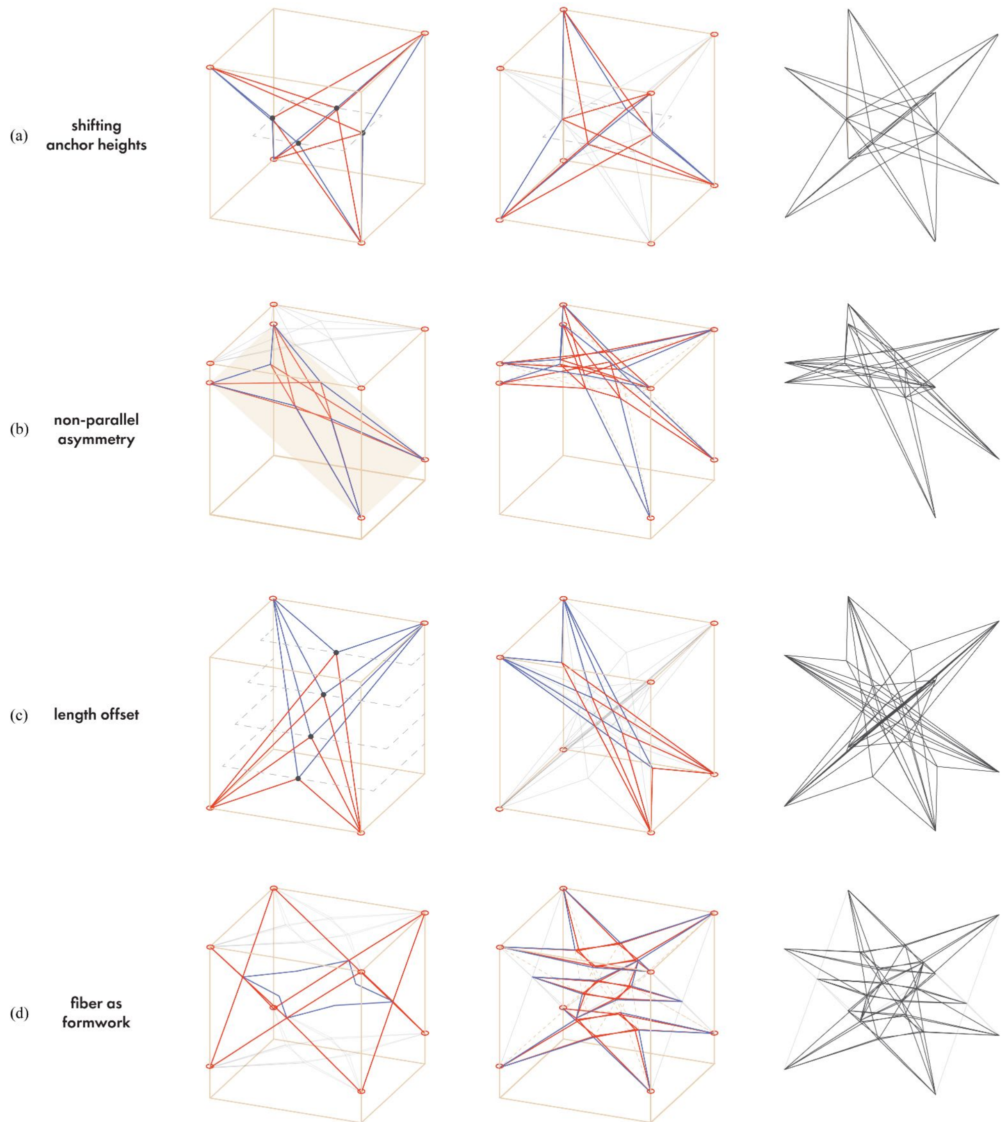


Figure 7: Catalogue of syntax strategies.

2.3 Physical Prototyping

The system was explored and tested through a series of various physical prototypes (**fig. 9**). This informed the syntax strategies and confirmed the feasibility of the fibre connection routines. The manual winding of these prototypes helped to understand important aspects of transferring it to an automated process and build material intuition necessary for further development of the system. It was evident that the tension needs to be consistent throughout the winding process, otherwise previously laid fibres would become loose from subsequent winding steps.

Figure 8: (**a**) Main node with fibres pulled together, (**b**) Sub-nodes resulting from fibre intersections.

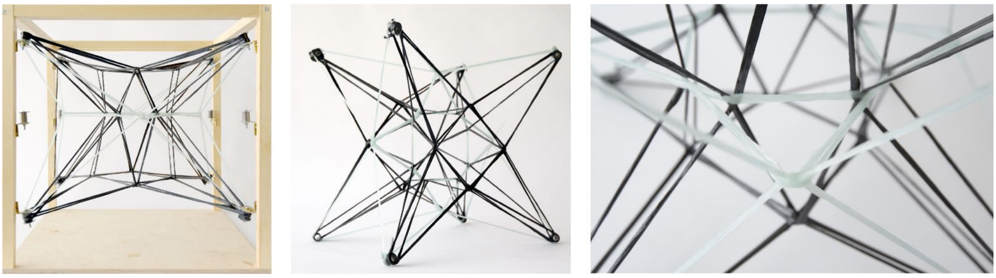


Figure 9: (**a**) Winding frame with 8 anchor points, (**b**) Physical prototype, (**c**) Glass fibre as formwork.

By choosing the filament material according to its properties and specific task within the syntax, further differentiation down to the material level emphasizes the fact that the resulting structure is a direct expression of its performance. For example, glass fibre was used purely as a formwork for the carbon fibres which were later wound onto it (**fig. 9c**).

2.4 Robotic Fabrication

In the development of an automated process for the fabrication of these structures, the required motions and routines were determined. Potential problems of automation were tested in manually-wound physical models, as the process of winding is analogous to a robotic fabrication process (Prado et al. 2014). In contrast to CFW, this process required two hands, outlining the need for two separate robotic agents. For the fabrication process, the agents were placed on opposite ends of the structure. Their routines were categorized into winding, material exchange, and material transport. In between winding steps, the bobbin is handed through the structure from one agent to the other, which allows to wind through and onto previously laid fibres. Constraints such as bobbin size, frame collisions, and the definition of vertical, lateral, and angular exchanges informed both the syntax strategies and the robotic development (**fig. 10**).

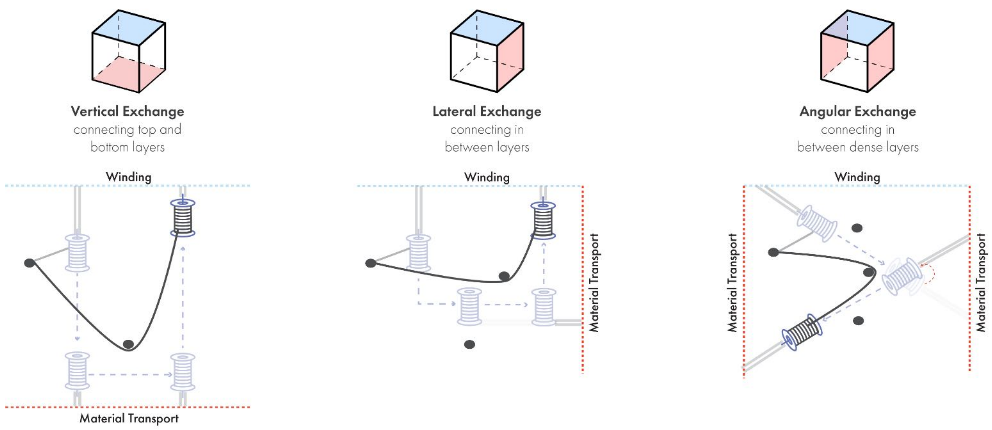


Figure 10: Robotic operation areas and material exchange planes.

A cooperative multi-robot system was developed and built to validate the robotic fabrication of the proposed system (Duque Estrada et al. 2020). It consists of a 6-axis robotic arm and a 2-axis CNC gantry, both equipped with bespoke end-effectors. One agent in the multi-robot system was simplified to a CNC gantry as a proof of concept. Potentially, two robot arms could cooperatively wind in a more elaborate and dexterous system.

3 Integrative Design Processes

Spatial Winding presents a complex interrelated system which requires an integrative co-design approach in which design, structural analysis, material properties, and fabrication constraints are considered in a feedback loop. The following chapter describes the digital tools that embedded material properties into the digital realm and informed design and fabrication development.

3.1 Form-Finding Tool

To simulate the complex reciprocal material behaviour, a digital form-finding tool was developed. It assists the design process and allows it to rapidly iterate through possible geometries. The design tool was created using spring-based relaxation with the live physics engine Kangaroo. A (line-sphere) collision model was used to simulate the fibre intersections under constant tension (fig. 11). However, due to the ambiguous nature of the developed fibre syntax, an initial approach vector and the rest lengths need to be defined. This determines where the fibres will intersect and the new node is created. With a higher amount of intersections, computation speed becomes an issue with this simulation method. Further work needs to be conducted in this regard.

The fibre syntax was defined as straight lines and node subdivisions. By dynamic relaxation of those lines toward target points, different geometries can be explored. The chosen geometry then informs the rest lengths of the individual edges for future fabrication.

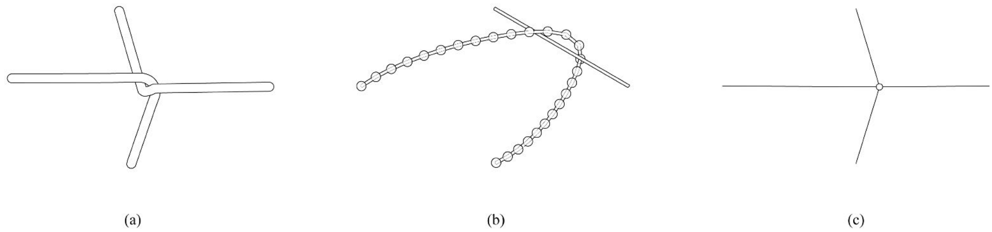


Figure 11: Abstraction of fibre interaction: (**a**) Physical behaviour, (**b**) Line-sphere collision model, (**c**) Converged edges and node.

3.2 Structural Simulation

Taking into account the structural qualities of CFRP, in particular, its high tensile strength, it was possible to approach the material as a minimal layout of intersecting fibres instead of a dense surface. By leveraging the material's affordances, it was possible to keep the material usage at a minimum. Therefore, it was important to evaluate the structural performance by informing the design decisions with material properties.

A simulation workflow was set using Karamba3D: a finite element analysis (FEA) tool. Curves and anchor points from the model were imported into the tool to calculate the structure under a certain load case. The point loads were established on the upper winding anchors. With the results obtained from the FEA component, it was possible to analyse the maximum displacement, minimum and maximum axial forces, and identify which elements were under compression or tension (**fig. 12a**).

A cross-section optimization component was implemented in addition to the FEA, informing the optimal thickness through a list of possible cross-sections (**fig. 12b**). As a result, each fibre segment was assigned an optimal cross-section that could be translated into the material thickness to be used during fabrication. By allowing some small geometrical adjustments, the parametric model and the results obtained from the FEA were used as input for the evolutionary solver (Galapagos), which in turn generated optimal geometric solutions and cross-sections for the chosen fitness criteria.

Although this method fits the expected purpose, the mathematical model should consider the material's varying tensile and compressive strength, the buckling behaviour as well as a more approximated modelling of the cross-sections for a

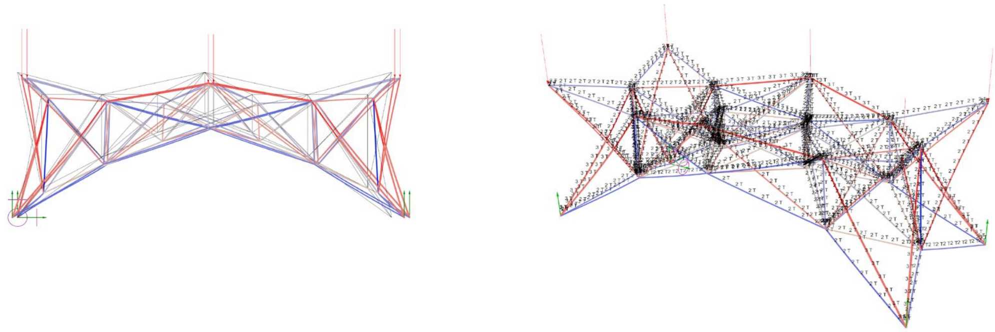


Figure 12: Structural simulation model showing: (**a**) elements under tension (blue) and compression (red) and the final displacement under load, (**b**) cross-section optimization showing the optimal number of tows for each segment.

more realistic result. This latest consideration would help to predict buckling caused by the compression and the high slenderness ratio (relation between cross-section and length) which tends to be the main failure of these types of structural systems. Nevertheless, the tool proved to be very useful during the process of syntax development. By acquiring quick feedback on how syntax strategies would interfere with the distribution of forces, it allows for a better understanding of the relationship between geometry, material, and structural behaviour.

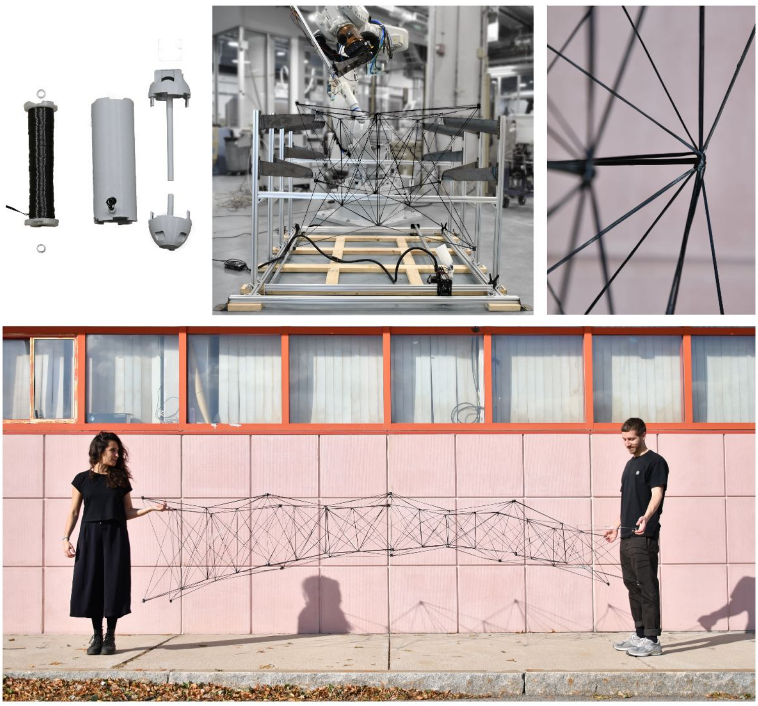
4 Case Studies

As the presented geometrical system relies highly on material interaction, it was important to explore the material system through physical prototypes and case studies. The chosen fibres (and resin system) and their properties have a high impact on the performance of the structure and are integral to the design process.

Two design case studies were chosen to demonstrate the system's potential. A spatially wound table was designed and fabricated to prove the spatial qualities and structural capacity (**fig. 13a**). It measured 800 x 1.600 x 750 mm and weighed only 1.8 kg. Two elements were wound in a frame with 12 winding pins. The table was wound using pre-impregnated fibres (prepregs) produced in-house in wet condition. Specific edges in the structure were reinforced by winding certain paths multiple times, resulting in varying cross-sections of the edges. The final structure was cured in an industrial oven for four hours at 120°C. A transparent polycarbonate plate was chosen as a surface and an evenly distributed load test up to 60 kg showed less than two cm of deformation.

A model of a spatially wound pedestrian bridge served as a feasibility study of the robotic fabrication routines (**fig. 13b**) and the overall material and geometry systems. For this case study, industrial prepregs were chosen. As they are dry to the

(a)



(b)

Figure 13: Case studies (material, fabrication method, node detail, final prototype): (**a**) Spatially wound table, (**b**) Spatially wound pedestrian bridge.

touch, they present a cleaner solution and are much better suited for the robotic application. Material thickness was kept consistent for the whole structure. Using a multi-step curing process and re-attaching already cured elements to the winding frame (interwinding them with the next element), it demonstrated the ability of the system to produce objects far larger than the frame and the work envelope of the robotic system.

5 Discussion

The syntax strategies proposed in this research and explored on a minimal setup could be expanded to different scenarios beyond the cubic frame, opening up design possibilities with new geometries and spatial configurations. Both case studies proved the system's potential for architectural applications, and further research could consider the development of more complex geometries towards the production of typical long-span architectural elements like slabs, roofs, or cantilevers.

Geometric deviations between digital and physical models were observed as many factors influence the materialized outcome. As the digital tool was developed mostly to allow fast iterations of possible outcomes, in-depth realistic fibre-interaction simulation was out of the scope of this research and therefore the final digital model did not fully represent the material behaviour of the physical structure. Further research in this regard would enhance the design process and enable higher precision during robotic fabrication. Material properties such as viscosity can influence how much the fibres will slide when wrapped around each other, but bringing such information to the digital model presents a challenge. Means of fabrication, either manual or robotic will influence how much tension will be applied during winding, which can influence the structural performance of the cured structure.

The structural simulation provides insight on the buckling behaviour but not on buckling failure. A different strategy to reduce the buckling length of the members could be developed in addition to the aforementioned sub-node strategy (**fig. 8b**). The sub-nodes were applied during the fabrication of the table but not considered in the robotic fabrication, as it requires improvements on robotic dexterity and scaling down of the effector and the bobbin, respectively. A higher resolution of fibre interaction requires a smaller bobbin, which therefore needs to be replaced more often.

Changing the directionality of fibre is usually considered to be adverse to their performance (Knippers et al. 2011). Since this is intrinsic to the spatial wound nodes, further research should be conducted by physical structural tests of the fibre-fibre nodes.

The developed multi-step curing process that combined advantages of continuous and component-based systems in a hybrid presents potential for on-site fabrication, in which the continuous structure grows during fabrication instead of being assembled (**fig. 14**).

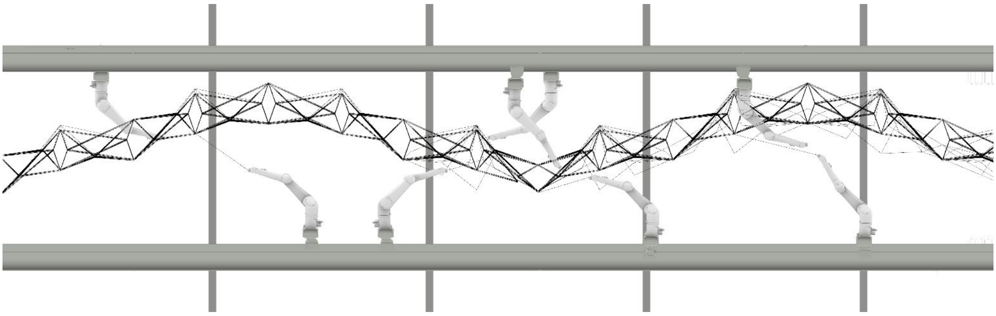


Figure 14: Upscaled fabrication scenario with multi-robot system cooperatively winding a spatial structure.

6 Conclusion

A space frame network, where both edges and nodes are of the same continuous material could be a flexible solution to the usually expensive node fabrication in traditional steel space frame structures. It provides lightweight structural performance with a high degree of customizability. The explored syntax strategies, such as using the fibres as formwork for other fibres, demonstrate how novel methods of fibre manipulation can employ the fibres inherent qualities and therefore simplify certain aspects of fabrication, for instance the frame complexity. Spatial Winding as a material system showcases the potentials of an integrative design methodology and the potential of a process that allows to fully tailor the fibre in space.

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