ELYTRA FILAMENT PAVILION
ROBOTIC FILAMENT WINDING FOR STRUCTURAL COMPOSITE BUILDING SYSTEMS

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Novel design and fabrication strategies

Ongoing research conducted at the University of Stuttgart is focused on material-efficient construction through the development of novel design and fabrication strategies for fibre composite lightweight construction systems. In a long-term, bottom-up development across multiple demonstrator projects, the underlying structural principles of fibrous lightweight structures in nature have been investigated in interdisciplinary collaboration with biologists, leading to the development of building technological advancements which allow the transfer of biological lightweight construction principles into technical fibre composite structures (Menges, 2015, Dörstelmann, 2015a, Van de Kamp, 2015). A series of prototypical demonstrator projects have showcased a higher degree of material efficiency and functional integration than current building methods.

The presented project continues this line of research in a site-specific installation at the Victoria and Albert Museum in London. The project aims to further develop the previously prototypically tested processes at a larger

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scale, with additional functional capacities being embedded and ultimately constituting a fibrous building system that is suitable for niche applications in architecture. Developments include significant advancements in coreless filament winding techniques, embedding of sensory systems into the fibre composite building parts, integration of construction detailing and interfaces to complementary building systems such as façade and ground anchoring, structural simulation methods, reconfiguration and expansion capacity based on a sensor-informed learning system in combination with a local fabrication set-up. The focus of the presented paper is the advancements in robotic fabrication methods for bespoke fibre composite parts.

Fibrous composites are versatile and structurally performative materials, useful for many architectural applications. They have been utilised in many engineering industries (e.g. aerospace and automotive) for decades, due to their high strength-to-weight ratio and high degree of formability. The use of these materials has not been fully developed with respect to architectural production, although the building sector could largely benefit from the material performance, efficiency and degree of functional integration in fibrous lightweight constructions (LeGault, 2014). Early experiments with fibre-reinforced polymer (FRP) buildings in the 1960s were unsuccessful due to the lack of appropriate design flexibility and construction methods for this group of materials. The fibrous material, which is often a hand-laid fibre-woven textile, creates a sturdy albeit homogeneous material arrangement that only takes limited advantage of the anisotropic nature of the fibres for structural efficiency. Many of the traditional composite fabrication techniques require full-scale surface moulds, which is inefficient in both material usage and cost (Weitao, 2011). This often leads to serialised production of similar parts in order to take advantage of the initial material formwork investment, which is the case in these early architectural explorations. The legacy fabrication techniques, which have not changed much in nearly nine decades, are restrictive from the perspective of both design and material performance.

Filament winding, the most efficient and cost-effective method of composite fabrication, is an alternative to hand-laid fibres that can be automated for speed and efficiency in industrial production (Peters, 2011). Fibre orientation can be controlled, which makes this process more adaptable to the structural requirements and changing boundary conditions of architectural production. Industrial processes often still require surface moulds or mandrels for geometric articulation and composite performance. Precedent work on the use of FRP in architectural construction developed at the Institute for Computational Design (ICD) and the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart was focused on the development of integrated design, engineering and fabrication methods that allow the harnessing of the material characteristics of fibrous materials for building construction while reducing the need for surface moulds (Dörstelmann, 2014, Waimer, 2013, Reichert, 2014). The ICD/ITKE Research Pavilion 2013-14 showcased the ability to make a dual-layered composite structural system from highly differentiated components using a 'coreless filament winding' system and reconfigurable winding frame (Prado, 2014). This project pushed the possibilities for morphological exploration and novel fabrication techniques. Two synced industrial robotic arms fitted with reconfigurable frames created a highly adaptable fabrication set-up, where geometric articulation and morphologic differentiation were key areas of investigation. This project showed high potential in both the developed dual-layered structural system and the coreless winding fabrication process.

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1. Photo of the onsite fabrication core of the Elytra Filament Pavilion. Image: © NAARO.

2. Photo of component production and connection tests. Image: © V&A Museum, London.

While the previously mentioned fabrication process was capable of a high degree of morphologic freedom (useful when creating geometrically specific structures or expanding the design potential of the system), for simpler applications this process could be refined to reduce complexity and increase fabrication efficiency. The Elytra Filament Pavilion proposed an adaptive, reconfigurable construction set with structural components that could be rearranged or grow into various configurations. This resulted in a unified edge condition for each component, making a reconfigurable frame unnecessary while still allowing for unique, individualised geometries and fibre arrangements to be created. More research interest was placed on the refinement of the fabrication scenario and the performative component geometries suitable for this design implementation.

The development of a versatile fibrous building system requires further consideration in several areas beyond that of previous investigations. First, to show its applicability as an architectural system, it must be utilised at a larger architectural scale. More specifically, in the case of the Elytra Filament Pavilion, the scale required longer spans and cantilevers to test the use of the structural system in various scenarios. Furthermore, beyond purely structural considerations, a fibrous building system should be able to integrate, incorporate or interface with other building systems such as the roof enclosure, wall façade construction, floor or foundation, which are important preconditions for wider applications in the building industry.

Fibre composite building system

Small-scale pavilions have historically often served as vehicles for highlighting innovation in design, material or fabrication, while reduced programmatic, spatial and functional requirements allow a focus on specific research questions. Similar past projects, such as the ICD/ITKE Research Pavilions 2012 and 2013-14 (Knippers, 2015, Dörstelmann, 2015b), were scientific demonstrators built on the campus of the University of Stuttgart and thus did not require significant interface with other building systems. In comparison, the Elytra Filament Pavilion is formed from fibrous components interlinked with multiple other material systems. Additionally, being sited in a prominent public space, it was required to pass through the rigorous certification process required for an inhabitable architectural structure.

The key components of the pavilion building system include (from top to bottom): the makrolon cladding panels, coreless wound fibre composite cells, bolted component-to-component joints, integrated lighting and sensor systems, coreless wound fibre composite column halves, bolted component-to-frame joints, steel supporting columns, membrane-support bracketry, core-enclosing membrane, core steel frame, foundation plates and helical ground anchors. Many of these elements are common within the building industry, but as no standard interface details exist for coreless wound fibre composite components, these were developed alongside the fabrication process.

Robotic coreless filament winding allows complex spatial arrangements of filament rovings to structurally connect various points in space. The distribution and spacing of winding points not only influences the component's shape and fibre layout resolution, but is also most suitable to be used as fabrication-inherent connection detailing if equipped with aluminium or stainless steel metal sleeves. Through the nature of the robotic winding process, the fibre composite rovings are bundled around the winding points, so the metal sleeves are embedded and structurally connected to the composite material. Rather than cutting or drilling (operations often used to create mechanical connections in fibre composites), the fibre rovings remain intact and structurally uncompromised. To increase the load transfer capacity of the metal-composite interface, sleeves with structured exterior surface geometry were used. Load transfer from and to these connection points through the composite structure is enhanced as the anisotropic fibres naturally align towards the connection during the winding process.

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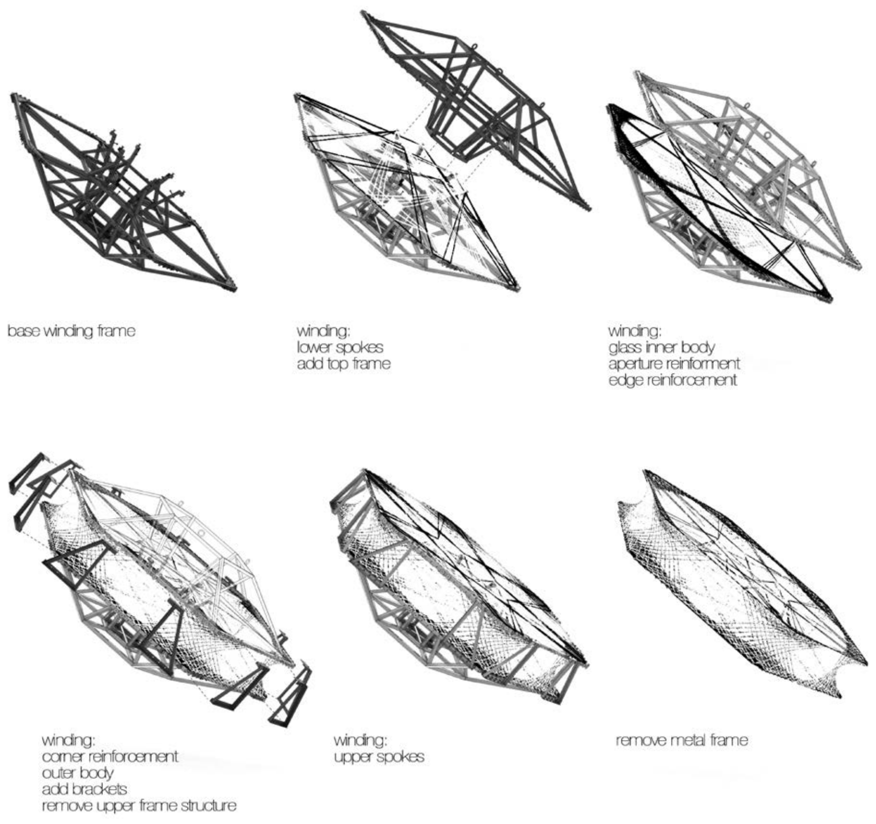
The inside of the metal sleeves can be blank or threaded to enable screw and bolt connections to the various building systems mentioned above. The use and type of connector can be preprogrammed as part of the frame assembly for the specific application required.

Robotic fabrication process for coreless filament winding

The presented fabrication process utilised a refined custom production set-up as well as further developments in the coreless filament winding process. An 8-axis robotic set-up consisting of a 6-axis industrial robotic arm linked to a 2-axis turntable, which carries a multi-part fixed frame, was used for winding (Fig. 3). For offsite production, a custom resin bath and spool holder which could carry up to six carbon fibre spools simultaneously were utilised for higher production speeds, while for onsite production (Fig. 1) pre-impregnated fibre spools were used. A higher degree of integrated construction detailing was enabled by advancements in the robotic coreless filament winding techniques. A multi-stage winding process was developed, which relied on several phases of frame assembly and disassembly throughout the winding process in order to wind fibres in specific configurations (Fig. 4). With this technique, embedded connectors and structural spokes could be created to interface with a transparent shingled roof enclosure system. Through adaptations in the robotic fabrication process, the construction of a wide variety of component geometries with tailored structural performance is possible on a simplified winding frame. The differentiation in system morphology, which would not be possible with standard FRP fabrication techniques, showcases the refinement and control of the coreless winding system. The surface curvature and the size of the aperture could be controlled for each component. Expanding beyond single-surface topologies (emblematic of fabrication techniques requiring a mould) enabled a hierarchical organisation of volumetric form, including a global bilayer structure. This structural system, used in previous research, was refined to create larger diameter components with a thinner structural depth to cover more area with less volume. This made the system highly efficient, requiring less material for a larger structure.

3. Coreless winding fabrication set-up: initial multi-stage frame. Image: © V&A Museum, London, © ICD/ITKE, University of Stuttgart.

4. Diagram of multi-stage winding sequence. Image: © ICD/ITKE, University of Stuttgart.



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Another evolution in the structure was the development of the closed-body reinforcement at the component scale. This created two interconnected hyperbolic surfaces which enclose a complex structural volume. With traditional mould-based fabrication techniques, these geometries would be impossible to manufacture unless the winding core remained in the finished piece or was sacrificed completely. At the material scale, coreless winding techniques were developed to control local fibre density and thus enable increased surface depth. This process, similar to three-dimensional weaving techniques, builds height from alternating dense fibre directions and a low-density, counter-directional stabilisation layer. This refinement was further demonstrated in the variation of fibre resolution, providing more control over the structural filigree.

Improved manufacturing efficiency

The refined fabrication process allowed for highly efficient production of unique roof and column components. Optimised winding times range from 4 to 9 hours per component, which were then cured and tempered overnight before being removed from the reusable winding frame. The process was highly automated and could be performed with a single robotic operator. Material handling, resin mixing and frame assembly are still manual processes in this scenario, though using industrial solutions for these could further improve manufacturing efficiency.

The Elytra Filament Pavilion cells are formed from a mix of unidirectional carbon and glass fibre roving to tailor structural efficiency. The stiffer carbon fibres provide the primary load paths within the cells, while the glass fibre creates the required geometry, distributes load and stabilises the carbon fibres. The flexibility of the fabrication set-up enables variation of the cell aperture size, changing the resulting performance of the structure. A small aperture uses more material in the top and bottom surfaces of the component, resulting in a heavier but stiffer element (Fig. 5). The cell's corners, which include connection points to its neighbours, then receive a variation in carbon material quantity based on the amount of load to be supported, with higher forces requiring greater localised stiffness and strength.

In certain critical parts of the structure, the whole cell is reinforced with a layer of carbon fibre to provide improved load transfer and strength. These strongest cells are capable of supporting a load of up to 500kg in a cantilevering condition. In earlier cellular prototypes, the free edges arising from this base geometry were susceptible to buckling issues, but this was eliminated in the final demonstrator through the closed outer body reinforcement mentioned previously (Fig. 4). The pavilion cells are therefore toroid-like beams that, when joined, create a continuous double-layer shell without free edges and with significant shear connectivity (Figs. 1, 2 and 7). Apart from geometric variation, the additive nature of coreless filament winding allows for a highly efficient use of material, placing fibres of different types only where they may be best used. With the possible variations in cell geometry and reinforcement known, a computational tool was developed to determine material placement, balancing stiffness and load distribution across the structure while achieving deflection limits (Fig. 5).

The project uses the integrative capacity of fibrous building systems to embed a sensor system that monitors visitor movements, microclimatic conditions and structural behaviour (Fig. 6). In combination with an onsite fabrication set-up, the project showcases the potential of fibrous lightweight structures to become responsive learning systems that expand and reconfigure as evolving structure and space.

Fibre optical sensors allowed for the monitoring of internal stress states of the composite structure, while thermal imaging enabled the gathering of anonymous statistics of visitor utilisation of the courtyard. Local weather data and climate simulation processes allowed predictions of local microclimatic conditions. Interpreting these data sets' interrelations allowed for reactive or proactive expansion and reconfiguration behaviours of the canopy and deriving of the respective fibre layout and fabrication data for new components. During the run of the exhibition, new components were produced at specific onsite fabrication events. The onsite fabrication set-up utilised the compactness of industrial robot arms and the fibre composite material spools. After assessing the structural capacity of the global system and local loading conditions, the new components were produced with even less material, continuing to push the boundaries of lightweight construction throughout the ongoing research process. The produced components were added during onsite reconfiguration events, resulting in two cantilevers reaching out by 5.5m and 6m from the next support, highlighting the structural performance of the implemented fibre composite building system.

The Elytra Filament Pavilion was installed in the John Madejski Garden at the Victoria and Albert Museum in London in May 2016. In its starting configuration, the fibrous canopy was constructed from 40 differentiated roof components resting on seven columns. It covered an area of 200m^2, which was extended to 220m^2 during the exhibition run. The fibre composite structure weighs only 9kg/m^2, while the entire canopy weighs 2.5 tonnes. The project showcases the future potential of fibrous building systems and how integrated design, engineering and fabrication strategies allow for simultaneous advancements in building technology and building culture.

Future fabrication scenarios

Future research will focus on the upscaling of building parts while maintaining the level of detail and resolution in differentiation and local adaptation. Preceding projects have shown how fabrication time can be reduced by fabricating fewer components on larger scales. This also reduces the amount of joints required and increases the fibre continuity for higher structural efficiency. Scaling up the existing fabrication scenario would not be possible due to the workspace limitations of an industrial robotic arm and transportability volume, but alternative set-ups may be used which incorporate a robotic linear axis or onsite fabrication methods using small moveable fabrication agents. Industrialisation of the winding process could require further refinement, including sensor-integrated cyber-physical winding strategies for increased automation, error correction and live adaptation of the robotic movements, or material quality control for composite durability and UV and fire resistance. Answering these questions would provide a big step towards developing a fibrous building system for architectural applications.

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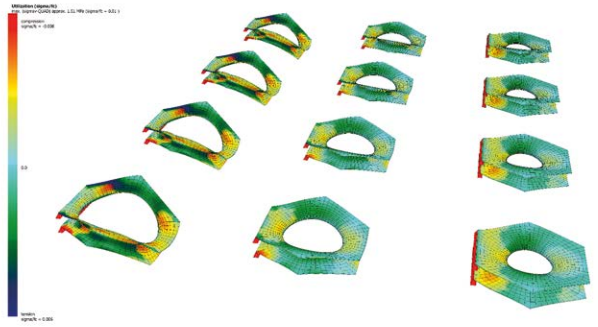

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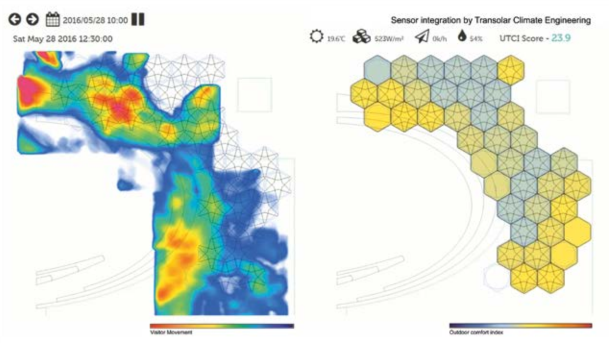

5. Diagram of structural testing of cell aperture variations.
Image: © ICD/ITKE, University of Stuttgart.

6: Diagram of sensor data visualisation:
(a) visitor movements,
(b) microclimatic conditions.
Image: © Transsolar KlimaEngineering.

7. Photo of canopy structure with differentiated cellular arrangement.
Image: © NAARO.

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