MODULAR CORELESS FILAMENT WINDING FOR LIGHTWEIGHT SYSTEMS IN ARCHITECTURE

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ABSTRACT

The paper describes novel strategies towards coreless filament winding of geometrically complex fibre reinforced building components. The research focuses on winding processes that reduce the need for formwork, allowing for the fabrication of individual one-off components made of glass and carbon fibre rovings. The component geometry and layout of the rovings is adapted to the structural loading of the system. Through the development of a modular system, the dimension of the resulting structure is not limited by the robotic fabrication set-up, which demonstrates how the coreless winding method is applicable in large scale building implementations.

The paper presents two prototypes produced by modular coreless winding: First, the *ICD/ITKE Research Pavilion 2013-14* investigated and demonstrated the geometric variability of the system. Second, the *Elytra Filament Pavilion* at the Victoria and Albert Museum in London in 2016 extended this approach towards a fully functioning roof system of significant scale. The *Elytra Filament Pavilion* is additionally equipped with a fibre optic monitoring system, allowing for on-line sensing of strain and temperature and illustrating the potential of multi-functional fibre systems.

KEYWORDS

FRP, RC beams, strengthening, interfacial stresses, analytical solution.

INTRODUCTION

Filament winding represents a cost effective and often-used fabrication method for synclastic composite components such as pipes, vessels or aircraft fuselages. Typical filament winding techniques require the production of a positive mould onto which the fibres are later laid. The fabrication of this mould is an elaborate process and causes waste material. In addition, the size of the core is usually limited by fabrication constraints. Thus, filament winding is often used for repetitive synclastic components of limited size and diameter. To overcome these drawbacks, a *Coreless Winding* process was conceived to avoid the production of a large positive core.

CORELESS WINDING FOR MODULAR STRUCTURES – ICD/ITKE RESEARCH PAVILION 13-14

Initially, the coreless winding process was used for large scale monocoque structures (La Magna *et al.* 2014, Reichert *et al*. 2014). In a second step the process is adapted to smaller individual components (Parascho *et al* 2015). The aim was the development of a winding technique for modular, double layered fibre composite structures, which reduces the required formwork to a minimum while maintaining a large degree of geometric freedom and leading to a strong and robust structural system. Through the development of computational design and simulation tools, both the robotic fabrication characteristics and the structural requirements could be simultaneously integrated in the design process. A fabrication method was developed, which uses two collaborating 6-axis industrial robots to wind fibres between two custom-made steel frame effectors held by the robots. While the effectors define the edges of each component, the final geometry emerges through the interaction of the subsequently laid fibres. The fibres are at first linearly tensioned between the two effector frames. The subsequently wound fibres both lie upon and tension each other resulting in a reciprocal deformation. This fibre–fibre interaction generates synclastic surfaces from the initially straight deposited fibre connections. The order in which the resin impregnated fibre rovings are wound onto the effectors is decisive for this process and is described through the winding syntax. The specific sequence of fibre winding allows control over the layout of every individual fibre, leading to a material driven design process. These reciprocities between material, form, structure and fabrication are defined through the winding syntax, which therefore becomes an integral part of the computational design tool.

Figure 1 ICD/ITKE Research Pavilion 2013–14 (photo: ICD/ITKE University of Stuttgart)

The effectors are adjustable to various component geometries, thus only one reconfigurable tool setup is required. Coreless filament winding not only saves substantial resources through the lack of individual moulds, but in itself is a very material efficient fabrication process since there is no waste or cut-off of fibre mats.

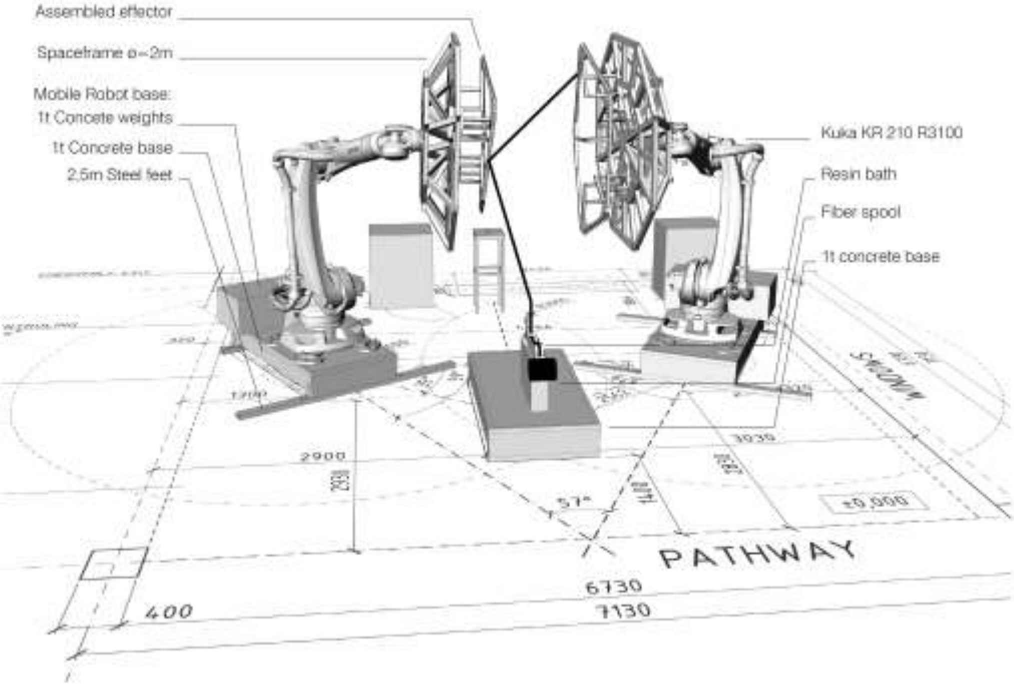

Figure 2 Fabrication Set-up for ICD/ITKE Research Pavilion 2013-14

The specific robotic fabrication process includes the winding of 6 individual layers of glass and carbon fibres plus an optional layer for enclosure (Fig 4). A first glass fibre layer defines the element geometry and serves as formwork for the subsequent carbon fibre layers. These carbon fibre layers act as structural reinforcement and are individually varied through the fibres anisotropic arrangement. A simplified FE Analysis, in which the global structure is approximated as a continuous shell, gives the orientation of the stress tensors. They are transferred into fibre orientations which are finally corrected according to the constraints of fabrication (Fig 3). The generated winding syntax allows the automatic winding of the 6 fibre layers (Fig 4) including the structurally differentiated fibre layer 3.

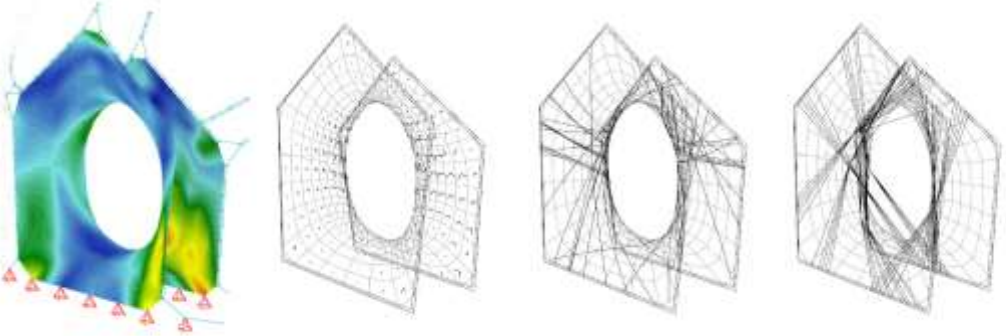

Figure 3 FE Analysis of global force flows and their transfer into structural carbon fibre reinforcements

The woven components are joined using aluminium sleeves that are integrated into the edge of the fibrous structure. These sleeves are mounted onto the winding frame before the process begins. As the fibres are placed by the robot they are wrapped around the aluminium sleeves, becoming permanently bonded to them as the epoxy resin cures. The accurate location of the aluminium sleeves allows adjacent components to be linked by steel bolts passed through pairs of the sleeves and tightened simply by hand. Due to the depth of the components the bending in the structure is converted into a push/pull tensile and compressive load. The bolts therefore carry tension and some limited shear.

In total 36 individual elements were fabricated. Each of them has an individual fibre layout which results in a material efficient load-bearing system. The biggest element has a 2.6 m diameter with a weight of only 24.1 kg. The research pavilion covers a total area of 50 m² and a volume of 122 m³ with a weight of 593 kg.

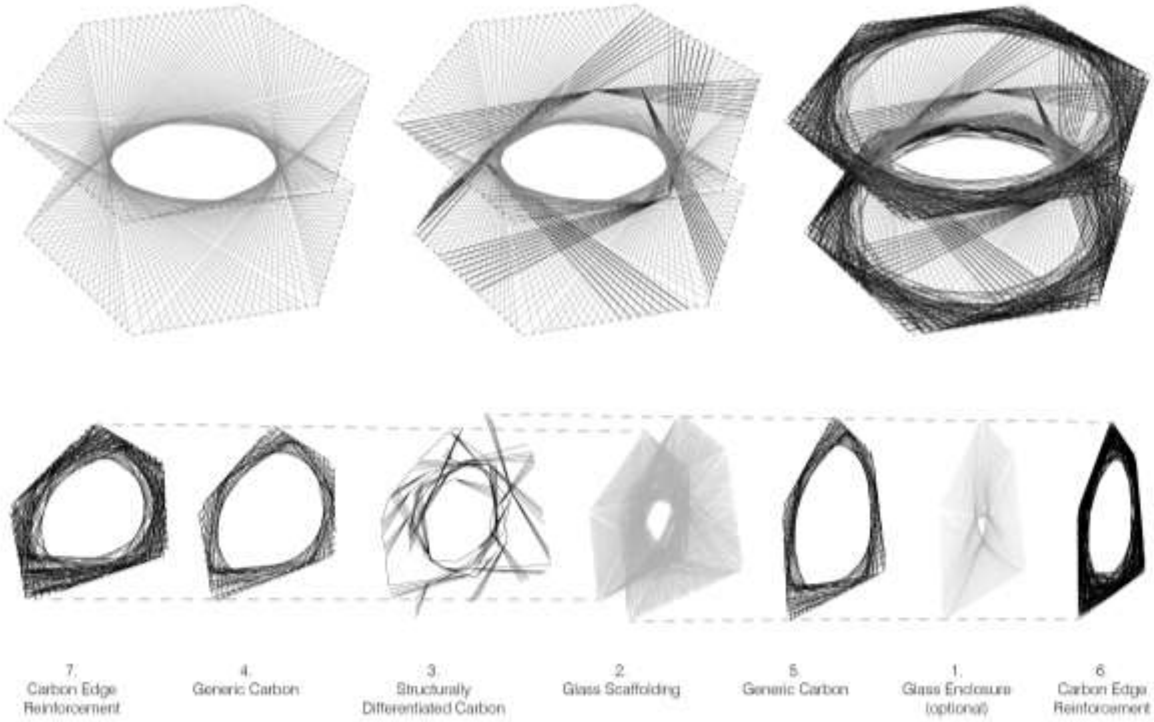

Figure 4 Winding Syntax for individual components

MODULAR FIBROUS SYSTEMS FOR ROOF STRUCTURES – ELYTRA FILAMENT PAVILION

While the aim of the *ICD/ITKE Research Pavilion 2013-14* was to demonstrate the geometric and structural potential of the developed fabrication method, the aim of the *Elytra Filament Pavilion* is to showcase how this approach could be used in a typical architectural application. The pavilion was installed in the John Madejski garden of the Victoria and Albert Museum, London, during summer 2016. It is based on the same modular concepts as described above but the fabrication process was further simplified for the use of a single robot.

Figure 5 The *Elytra Filament Pavilion* at the Victoria and Albert Museum in London, 2016 (photo: NAARO)

Figure 6 Structural differentiation of fibre layout for columns and roof components (photo: NAARO)

The roof was configured as a planar, slightly inclined canopy supported by seven columns. The canopy was a modular structure made up of initially 37 and finally 40 hexagonal roof components. 3 components were produced on site at specific public events. The components were covered by a polycarbonate sheet to provide rain coverage and drainage. The outer dimensions of each component are identical: the depth is 40 cm and the diameter 2.40 m. After winding each component is tempered in an oven for about six hours at 80 C°.
In this project the diameter of the central aperture as well as the reinforcement with carbon fibres along the edges and on the hyperbolic surface was differentiated according to the specific loading of the respective

component. For analysis a simplified model was used as in *ICD/ITKE Research Pavilion 2013-14*: the woven mesh is represented as a surface and the woven edge connectors are idealised to lines (Fig 6). From material testing, the characteristic capacities of the wound fibre composites were determined (Tensile Capacity $f_{t,k}$ = 4000MPa, Bending Capacity $f_{b,k}$= 1330MPa). From these tests a design strength of $f_{t,d}$ = 445MPa was chosen.

Wind loading has been considered in accordance with EN1991-1-4 General Actions – Wind Actions and the UK National Annex. The site in the central courtyard is generally sheltered as a central well within a larger bluff building structure. The wind loads applied were: Maximum uplift 0.72 kN/m^2 along the edge, uplift on the remainder 0.46 kN/m^2, max downforce 0.142 kN/m^2.

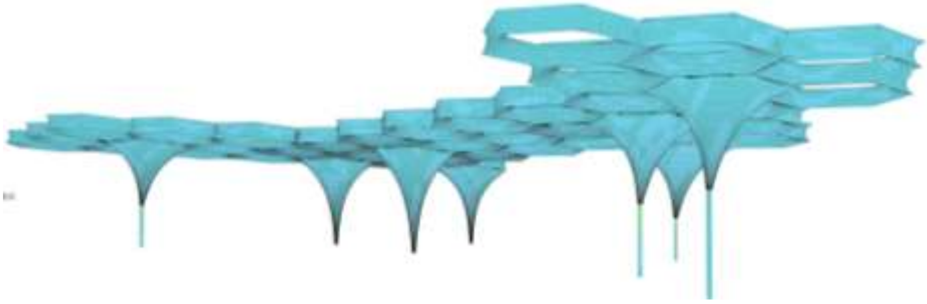

Figure 7 Finite Element Model of the Canopy with all Columns

Two differently sized fibre composite columns were used to support the canopy. The three larger column heads around the fabrication core took majority of the horizontal wind loads (see Fig 6), while the smaller ones were connected to 10cm diameter steel tube and carried vertical forces mainly. The maximum tensile loading applied to any column is found to be 7kN. This requires an anchor to prevent uplift. A Spirafix helical anchor, common for temporary and semi-permanent structures in the UK, is used.

The maximum expected deflection of the structure under SLS loading combinations is found to be in the uplift case with maximum of 16mm uplift and 30mm downwards movement. Given the scale of the structure and the fact that these deformations will occur only in the worst case 1 in 50 year storm, this is considered to be acceptable. The structure is generally under a very low state of stress even in the most onerous loading condition due to the comparably small loads and large surface of structure across which these are distributed. At the junctions between elements and the support points for the polycarbonate covering some stress concentrations are developed. The peak value is seen as 152MPa therefore this is still acceptable compared to the 445MPa limit.

In addition to structural analysis a variety of components and columns were tested (Fig 8). The horizontal loading was increased until a bending moment as in FE Analysis of the global structure (Fig 7) was reached. In testing, as well as in analysis, buckling of the compression loaded edges proved to be the decisive failure mode. Deformation and stiffness properties were also measured. The results were used to adjust the stiffness properties of the global FE model shown in Fig 7.

Fig 8 Testing of components

The structural monitoring was achieved through optical fibre sensors that are integrated into the composite material (Gabler and Knippers 2014). This technology requires a light emitter and a reading station to be located close to the installation and permanently supplied with energy. The structural sensor fibres are equipped with

BRAGG gratings that serve as elongation sensors. If the sensors are mounted to a structurally active surface strain is measured and the stress state in the material will be computed. If the sensor is detached from the load bearing structure, e.g. placed in a tube, it measures temperature. Six components were equipped with strain and temperature sensors in Stuttgart prior to installation. The sensing chains of the components will be connected via very small so-called FP/APC plugs. Each instrumented component has four fibre chains, each with 3 strain and 1 temperature sensor. The latter is needed for the temperature monitoring and to separate the measured elongations from thermal and mechanical loading.

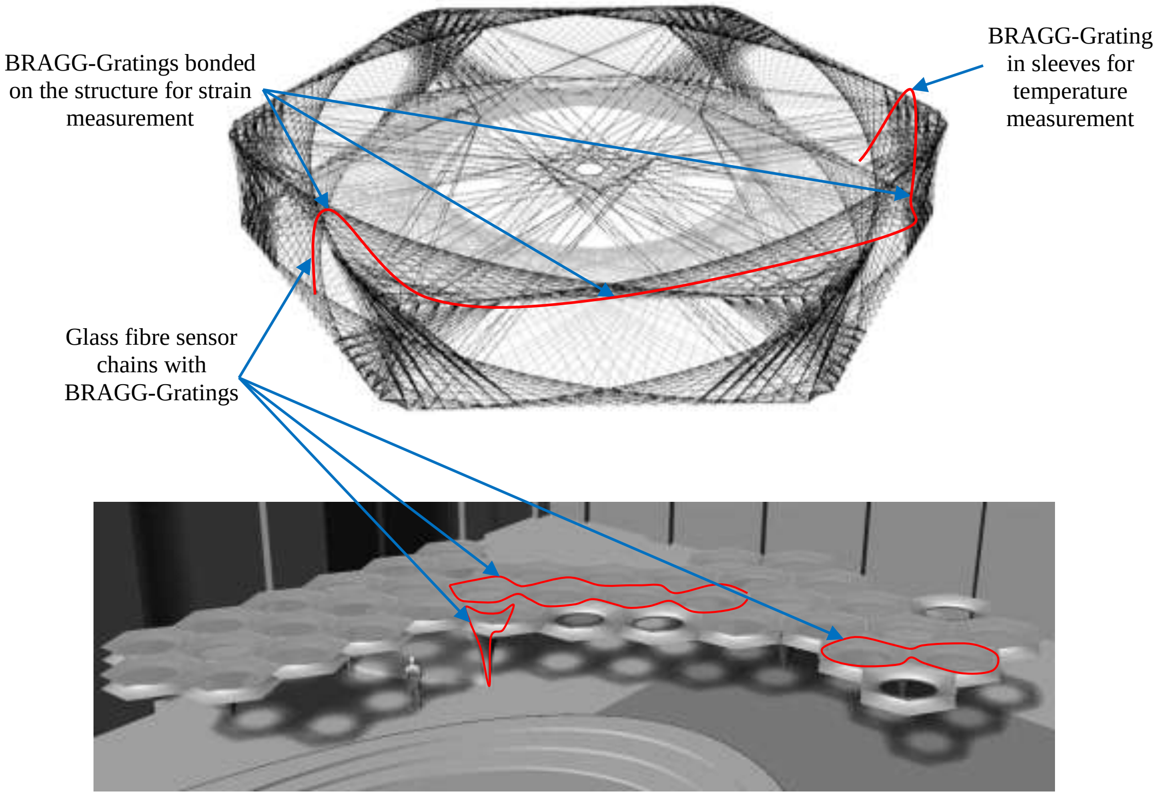

Figure 9 Fibre Optical Sensor Arrangement in one component (top) and Fibre Optical Sensing Chains (bottom)

ACKNOWLEDGMENTS

Both projects are joint efforts of the ICD Institute for Computational Design (Prof. Achim Menges, Moritz Dörstelmann, Marshall Prado) and the ITKE Institute for Building Structures and Structural Design (Prof. Jan Knippers, Valentin Koslowski, James Solly, Stefana Parascho, Thiemo Fildhuth) at the University of Stuttgart. We want to thank many students, collaborators at the Universities of Stuttgart and Tübingen and sponsors who contributed to the projects and made them possible.

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