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ICD/ITKE Research Pavilion 2016/2017: Integrative Design of a Composite Lattice Cantilever

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Abstract

This paper describes the design and fabrication of the ICD/ITKE Research Pavilion 2016/2017, the most recent in the series of experimental installations developed as an outcome of the design-and-build studio of the ITECH Masters Programme. The completed structure is a 12m long cantilevering lattice-composite shell that was wound in one piece by a multi-machine fabrication system using coreless filament winding. To realise such a structure through this fabrication process involved a negotiation between architectural design, structural requirements and fabrication constraints, details of which are found in this paper. Technical details of the multi-machine fabrication system were previously described in Felbrich et al. [1].

Keywords: Fibre-Reinforced Composite, CFRP, GFRP, Shell Structure, Robotic Fabrication, Additive Fabrication

Figure 1: ICD/ITKE research pavilion 2016/2017 at the opening event in March 2017 in Stuttgart

1. Introduction

The ICD/ITKE Research Pavilion 2016-17 is the latest in an ongoing series of collaborative studies at the named institutes on the generation of lattice composite structures through the process of robotic coreless filament winding. While the previous pavilions have investigated and then demonstrated fabrication strategies possible within the limited-reach of an industrial robot, the presented work considers a major expansion of the fabrication space for winding. The extension of this volume within which a monocoque structure may be created offers both new structural possibilities and challenges, defined by limits of the selected fabrication strategy, that are outlined within this paper.

The project was realised in a collaboration between researchers of both institutes and students on the ITECH International Masters Programme and resulted in the creation of a 12m long monocoque cantilever formed from a fibre-reinforced composite lattice and fabricated through the coreless filament winding process by a novel multi-machine system that incorporated both UAVs and Industrial Robots. The structure was installed on the Stadtmitte Campus of the University of Stuttgart in April 2017 and was later moved to the Zentrum für Kunst und Medien in Karlsruhe, where it currently resides.

2. Background and context

2.1 Lightweight structures and composite materials

J.Schlaich and M.Schlaich (of Schlaich Bergermann and Partners) wrote in 2000 that *any structure designed intelligently and responsibly aspires to be "as light as possible"* [2] and they note that a structure can be considered as "lighter" if the ratio between dead load and live load is reduced. Thus the use of modern high-tech materials with superior strength to weight ratios can immediately be considered as a step towards achieving this definition.

Fibre Reinforced Polymers (FRP) are one such type of modern material. CFRP has a specific strength of ~780kNm/kgm, over 10 times higher than structural steel at ~45kNm/kg and they have already been deployed on several projects where this benefit has used to great advantage (for example see Part F "Case Studies" of Knippers et al. [3]). In addition, the fabrication of FRP from fibres and resin (highly flexible before curing) offers the opportunity for designed material placement at a local level and the creation of freeform geometries.

Shell structures are known to reduce the quantity of material required to support a load if the correct form can be found to enable loads to be primarily carried by in-plane forces, as described by Adriaenssens et al. [4] for example. Discrete lattices can offer savings compared to continuous shells. By utilising carefully-oriented bar-type elements, material can be directly aligned with the carried load and in situations where little material is required for the stress constraint, the amount needed may be gathered into bundles with greater local section heights, improving buckling resistance compared with a thin sheet. This is well researched in aerospace where an example is the carbon fibre lattice tube by IsoTruss Industries that requires only 56% of the material of an equivalent continuous CFRP cylinder [5] to carry a load.

Considering all of the above, FRP placed in a lattice arrangement over a global shell-type form can be considered as a highly suitable system for the creation of lightweight structures. The wider benefits of lightness in structures have been covered in many papers, i.e. Schlaich and Schlaich [2]. In this research pavilion, one highly beneficial property of lightness was in the ability to transport the completed pavilion by road without significant cost or complication.

2.2 Coreless filament winding

2.2.1 Coreless filament winding method

Coreless Filament Winding (CFW) is a fabrication method for the creation of fibre-reinforced polymer (FRP) parts that has been actively developed at the ITKE and ICD since 2011 for the creation of composite building systems. Details of the process were first described in La. Magna et al. [6]. CFW is based on the FRP fabrication process of Filament Winding that involves the wrapping of fibre bundles around a rotating mandril, a process well-used in industry due to the speed of material placement.

As outlined in [6], the use of a core-based fabricated method has significant limitations for use in architecture (and the wider AEC industry), primarily because each required geometry must have its own core and therefore a unique part must have a unique core.

CFW involves the winding of resin-impregnated fibre-bundles in a programmed sequence around winding points that are (typically) located at the boundary of the element being produced. Each arrangement of winding points enables multiple geometries through variation in the placement sequence of fibres. In previous projects these points have been mounted to minimal skeletal frames that can be demoulded once the composite has cured. The first fibres form a pseudo-mould for all later placements and final fibre locations depend on fibre-fibre interactions in space. Both of these points highlight the criticality of using the correct winding sequence.

The material deposition concept of CFW is therefore extremely simple, with fibre bundles pulled from a spool and wrapped around winding points and one other. As fibres must be under tension during winding, the formed geometries are examples of tensile anticlastic surfaces. Thus the fabrication process is a type of form finding similar to that described in Adriaenssens et al. [4] and wound geometries are often efficient shell forms by default.

The described limitations on fibre placement and form creation and were a critical input to the engineering design of the Research Pavilion 2016/2017.

2.2.2 Coreless filament winding previous projects

The development of CFW by the ITKE and ICD has been widely disseminated to the public, AEC industry and the academic community through the presentation of a series of architectural installations. The ICD/ITKE Research Pavilions of 2012 and 2013-2014 developed within the ITECH Master Program initiated investigations that were then progressed through projects within the institutes.

Figure 2: ICD/ITKE research pavilions made from coreless-wound fibre-reinforced polymers

The Research Pavilion 2012 [8] was a monocoque structure fabricated by mounting the skeletal winding frame onto a rotary axis then placing fibres using an industrial robot. This pavilion effectively demonstrates the largest scale easily achievable with a single industrial robot mounted in a static location.

The Research Pavilion 2013-2014 [9], the University of Stuttgart Fair Stand [10] and the Elytra Filament Pavilion [7] all demonstrate the use of CFW for the creation of components that are then assembled into a larger structure. These modular elements enabled the creation of larger structures without increasing the size of the fabrication setup but added complexity in the necessity for joints.

The Research Pavilion 2016-2017 studio took its starting point from the intention to create a jointless structure, considered in the 2012 demonstrator, but with the greatly improved CFW system knowledge developed through the, more recently completed, modular projects.

3. Research Pavilion 2016/2017

3.1 Integrative design

The research aim of the ICD/ITKE Research Pavilion 2016/2017 was to build a fibre-reinforced polymer structure that extended beyond the reach of a single industrial robot.

The underlying ITECH approach is to identify the coupled implications of design constraints on form, function and fabrication of the structure. Due to a fully model-based process, the impact of various options could be iteratively simulated and visualised in order to progress towards an optimal solution within the range of available possibilities. This process included physical prototypes as well as virtual ones in order to understand the influence of winding sequence on the geometry of the pavilion. The final sequence was derived from virtual models using combinatorial algorithms then tested on physical models that provided information to be fed back into the algorithms for later iterations.

An unmanned aerial vehicle (UAV) was chosen to pass material between two independent fabrication environments that each contained a fixed-position industrial robot. The use of a UAV showcases the potential for this fabrication system to be scaled. In combination with precise control over the pretension of fibres during fabrication, the completed setup would allow an easy extension of the length of the structure along the axis between the stations. The details of the multi-machine fabrication system are explained in [1].

3.2 Structural design methodology

The thin structural surface of the CFW cantilever was designed to support external loads (wind, snow etc.) and the structural form-finding and design to achieve this was divided into two phases. In the first phase, a parametric model of the pavilion surface was meshed into shell elements and evaluated as a normal structural shell for stress concentrations and buckling performance. The highly anisotropic constituent materials were characterised for this phase by the creation of representative sample lattices that were tested in the lab to generate pseudo-isotropic material properties for the shell elements.

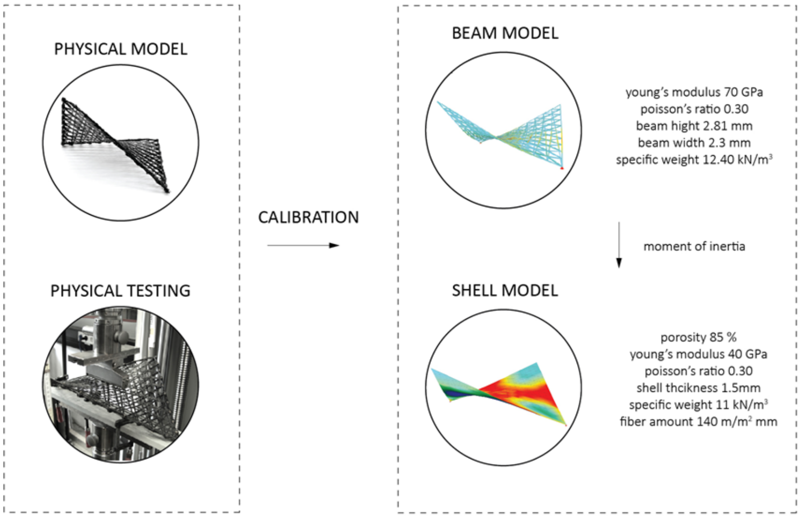

Figure 3: Calibration process for defining pseudo-isotropic material properties of a carbon and glass fibre composite lattice structure

The geometry of the surface was generated through a membrane-relaxation between the two boundaries to give an approximation of the tensile wound form which could be converted into a structural model and the relative performance measured. With this as an output metric, the boundary geometry and membrane form-finding parameters were handed to an optimisation algorithm in order to determine the most performative possible form. The controllable parameter ranges were limited to ensure that any output geometry would be fabricatable using CFW.

Early in the design process it was noted that the edges of the shell were in compression and susceptible to lateral buckling. The "folded" edges where therefore added to generate a semi-closed profile formed through wrapping carbon fibres from outside to inside around the initially-laid sheet geometry. Both arrangement of anchor points and fibre winding syntax were tailored towards enabling this essential and final step.

The results of this first shell-analysis phase was a shell model of the most optimal structural geometry within the boundary conditions selected. The results from this model were used to determine critical buckling regions and areas of high and low stresses, generating a "criticality map" of the surface.

In the second phase of analysis, this criticality map was combined with a map of windable fibre paths (determined, as mentioned earlier through a combination of algorithmic design and physical prototyping) to select candidate fibres for inclusion in the final design and discard those that would cover non-critical regions along their length. These candidate fibres were used as inputs to a beam element model of the structure, which was then run through a size-optimisation algorithm that could select from a series of possible fibre-beam cross-sections. This iterative process was repeated for each of the layers of carbon fibre strands to achieve a stable, optimal fibre arrangement that could then be queried to determine the number and sequence of fibre-roving placements needed.

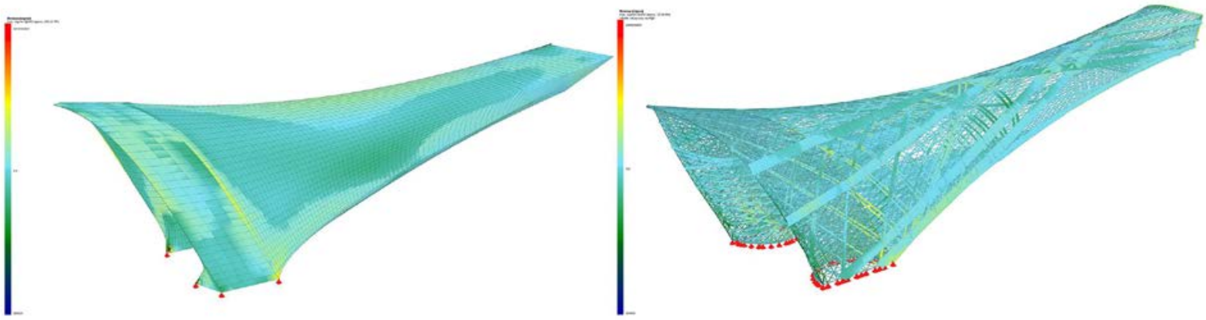

Figure 4: FEA models (left to right): initial model with shell elements for geometry evaluation, refined model using beam elements for final analysis

3.3 Fabrication

Following several design iterations the pavilion consisted of four key elements: (i) initial bent flat sheet of the portal, (ii) volumetric portal, (iii) cantilever shell, (iv) folded edge.

The initial GFRP sheet of the portal was produced flat on a timber frame with embedded sleeves for winding later fibre layers and to allow connection to the steel foundations (feet).

Once cured this was elastically bent into shape over the foundations then reinforced using carbon fibre bundles. The fibre rovings were pre-impregnated through a resin infusion process (tow-preg) developed by the Institute of Aircraft Design**,** University of Stuttgart. Glass fibres were wound within this bent sheet to generate the inner surface of an arch with a “D”-shape cross-section. This was later reinforced, again using carbon fibre, to complete the volumetric portal, the first complete part of the final structure. This was loaded to confirm its stiffness and strength and scanned to compare as-built and design geometry. Three configurations of load test (1-5 kN) were performed: (i) centric horizontal load, (ii) eccentric horizontal load left, (iii) eccentric horizontal load right. The maximum deformation recorded was just 10 mm and geometry deviation was within 5-70mm of the digital design. These results were used to update the central model, something crucial for the form finding and structural analysis of the cantilever.

The cantilever shell started with a glass fibre layer serving as a supportive mould for the primary load-carrying CFRP ribs. During winding the as-built geometry of the strands was surveyed to ensure the digital model reflected reality so the structural model could be updated if required and the correct amounts of reinforcement placed. While deviations were observed during fabrication, the model did not vary so significantly during fabrication that extra material was required.

The folded edge was constructed in a similar manner, with a glass-fibre guiding layer placed before carbon fibre reinforcement was added.

Figure 5: Glass fibre body of the cantilever with initial carbon fiber strands

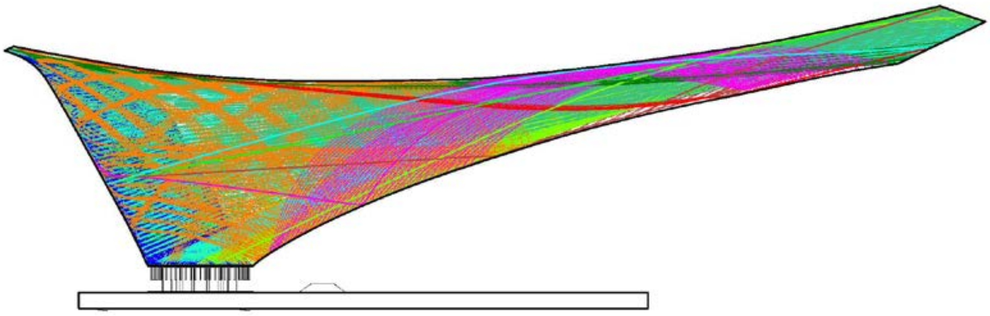

Figure 6: Pavilion fibre trajectories with different fibre path-types shown in different colours

3.4 Support systems

Aside from the high-tech fabrication system, the pavilion required temporary supports that could bear the relatively high tension forces and resulting bending moments during winding.

The portal rests on project-specific steel foundations (feet), to which the 184 km of resin impregnated fibres were anchored. The shape of the feet defined the possible winding geometry for both the portal and the cantilever.

Figure 7: Shape defining, project specific foundation components anchored to the formwork system

The beams below the portal are a permanent part of the structure, resisting winding forces during fabrication and also preventing overturning when installed. The workshop had rail systems embedded in the floor allowing the formwork to be connected to the foundation of the building. On site the space in between the beams was filled with gravel (20 kN) to prevent the cantilever from lifting and tipping.

The tip of the cantilever was held up by push-pull props and support beams, designed to withstand winding forces. The necessary arrangement of anchor points for the tip was provided by a custom steel extension that could be disassembled so only the anchor points remained embedded in the composite.

A component based steel system, typically used for concrete formwork, was used for the major beams and props. All of the parts belonging to this system were returned following project completion.

Figure 8: Formwork system of the cantilever (left to right): portal frame and permanent part of the structure, temporary tip frame with push-pull props and steel extension

4. Conclusion and Outlook

The project demonstrates that CFW lattice composite systems can be used to create performative, lightweight, monocoque shell structures. While using industrial robots as fabrication tools, the dimensional limitations of a single unit were expanded. The final structure currently retains its integrity after being moved twice, experiencing significant weather conditions through winter and being climbed upon by many adventurous interlopers (not a recommended activity).

The project furthered the two institute's research on design and simulation of windable geometries, structural modelling of CFW structures, the technical process of robotic winding and recorded some additional constraints for the process. For example, to achieve the specified fibre directions and quantity at the root of the cantilever resulted in more material than required at the tip due to many fibre paths needing to travel to this winding frame.

Future CFW structures could utilise multiple winding frames to avoid this problem, the winding process could be automated or manual (depending on project requirement) and components could be prefabricated and later assembled or fully wound on site. The combination of high strength-to-weight ratio, longevity of the material and the compact format of fibres and resin before winding and curing makes these structures suitable for use in remote or inaccessible areas.

Below we present a concept for a CFW bridge that stems from the completed Research Pavilion. The two sides could be considered as separate components but there is also the possibility for the central form to be a integrated winding frame, supported in space by a few initial fibres to provide an intermediate deviation point for all remaining fibres. This helps to overcome the issues noted above in expanding a fibre-wound tensile surface over longer distances.

Figure 9: CFW Future Bridge Concept

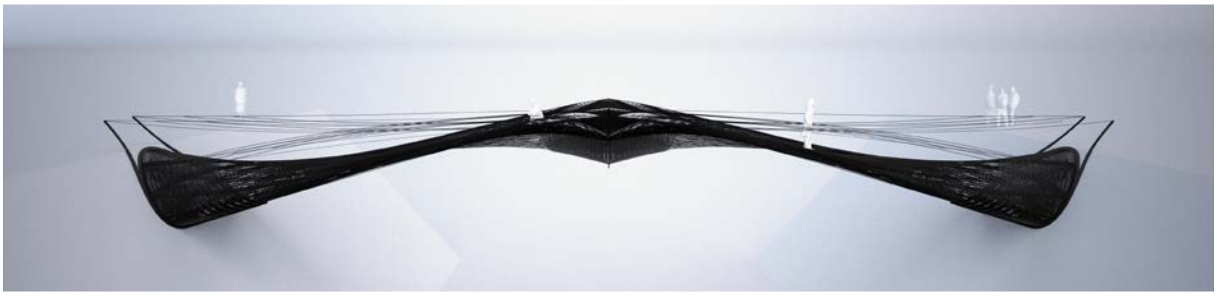

Figure 10: CFW Future Bridge Concept

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