Serban Bodea

UPSCALED, ROBOTIC CORELESS FILAMENT WINDING METHODS FOR LIGHTWEIGHT BUILDING ELEMENTS FOR ARCHITECTURE

RESEARCH REPORTS
Institute for Computational Design and Construction

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Edited by Prof. Achim Menges

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Foreword

Serban Bodea’s dissertation investigates the production of fiber composite elements made of glass or carbon-reinforced plastics for the construction industry. His research focuses on the further development of the manufacturing method of coreless robotic winding developed at the University of Stuttgart by the institutes ICD and ITKE. The work makes a valuable contribution towards the goal of further component scaling and increased process automation, in particular sensor-based quality control. Serban Bodea has successfully pursued this through the development of appropriate digital fabrication methods, which he also prototypically tested and evaluated through prototypes and full-scale component demonstrators.
Prof. Achim Menges

Die Dissertation von Serban Bodea beschäftigt sich mit der Fertigung von Faserverbundelementen aus Glas- bzw. Kohlenstoffverstärkten Kunststoffen für das Bauwesen. Der Schwerpunkt seiner Forschung liegt dabei auf der Weiterentwicklung der an der Universität Stuttgart von den Instituten ICD und ITKE entwickelten Fertigungsmethode des robotischen Wickelns ohne Kern. Die Arbeit leistet einen wertvollen Beitrag hinsichtlich des Ziels einer weiteren Bauteilskalierung und einer gesteigerten Prozessautomatisierung, im Besonderen der sensorgestützten Qualitätskontrolle. Serban Bodea hat dies durch die Entwicklung entsprechender, digitaler Fertigungsmethoden erfolgreich verfolgt und anhand vollmaßstäblicher Bauteildemonstratoren auch prototypisch getestet und evaluiert hat.

Prof. Achim Menges

UPSCALED, ROBOTIC CORELESS FILAMENT WINDING METHODS FOR LIGHTWEIGHT BUILDING ELEMENTS FOR ARCHITECTURE

A dissertation approved
by the Faculty of Architecture and Urban Planning of the
University of Stuttgart
for the conferral of the title of
Doctor of Engineering (Dr.-Ing.)

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First of all, I would like to thank Prof. Achim Menges for his supervision and guidance. The interdisciplinary research environment he created at the ICD, his vision, and his trust are the elements that shaped me as a researcher and allowed me to define my own contribution to technology and architecture.

Furthermore, I would like to thank my ICD colleague Niccolo Dambrosio for his support during the research and development work for the BUGA Fibre Pavilion, and for contributing his talent to find synergies between our larger research projects. Similarly, I would like to thank my ICD colleague Christoph Zechmeister for his constructive attitude and the collaborative mindset he contributed this research. I would also like to thank my former ICD colleague Moritz Doerstelmann for the stimulating exchanges on the architectural, theoretical, and practical aspects of

Fibrous Morphology and for hosting me at FibR during the BUGA Fibre Pavilion prefabrication process. I would also like to thank my former ICD colleague Lauren Vasey for generously sharing insights and best practices for automation and cyber-physical production systems for computational fabrication in construction.

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Serban Bodea

Contents

List of Abbreviations

AEC	Architecture, Engineering, and Construction
AM	Additive Manufacturing
CF	Carbon Fiber
C/GFRP	Glass and Carbon Fiber Reinforced Polymers
CFW	Coreless Filament Winding
CLT	Cross-Laminated Timber
CNC	Computerized Numerical Control
CPPS	Cyber-Physical Production System
CPRCFW	Cyber-Physical Robotic Coreless Filament Winding
CPS	Cyber-Physical System
FDM	Fused Deposition Modelling
FEM	Finite Element Method
FPT	Fiber Pre-Tensioning
FVR	Fiber-Volume Ratio
FW	Filament Winding
GF	Glass Fiber
IT	Information Technology
OOP	Object Oriented Programming
RCFW	Robotic Coreless Filament Winding
RGB	Red, Green, and Blue
RPM	Rotations Per Minute
SO	Strategic Objectives
TCP	Tool Center Point
TRIZ	Teoriya Resheniya Izobretatelskikh Zadatch
WM	Work Modules

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Abstract

Starting in the 1940s, advances in the chemical industry and composite materials such as Fiber Reinforced Polymers have revolutionized manufacturing enabling new lightweight - high strength applications in the aerospace, automotive, and consumer goods industries. However, composites failed to significantly impact the building industry due to its poor digitalization and low integration of design and engineering methods. Nevertheless, these shortcomings can be mitigated through construction-specific design, fabrication methods, and building regulations for composite structures.

Especially, lightweight construction has yet to capitalize on the high strength-to-weight ratio afforded by composite materials such as Glass or Carbon Fiber Reinforced Polymers and thus shape its contribution to contemporary high-performance, lightweight architecture. However, 21st Century advances in digital design methods in conjunction with newly-available hardware and control systems allow for automated fabrication approaches to re-imagine established fabrication methods such as Filament Winding(FW).

This thesis presents novel upscaling and automation strategies for Coreless Filament Winding(CFW), which is an adaptation of FW to construction applications. CFW is a fabrication method that relies on the anisotropic mechanical properties of free-spanning fibers wound around supports in space to create efficient load bearing structures without requiring molds or dies. These strategies are supported by a state-of-the-art review focused on the technological requirements for robotic coreless filament winding in construction applications.

The investigation identified fabrication method scalability and insufficient process automation as research gaps in academic investigation for construction composites. The thesis demonstrates that existing prefabrication methods of Robotic Coreless Filament Winding (RCFW) can be successfully upscaled and utilized for large-scale, long-span loadbearing structures. Furthermore, the thesis presents an approach to advance existing process-monitoring and quality-control methods, named Cyber-Physical RCFW (CPRCFW).

The two objectives are investigated through two representative tasks: (1) verifying the RCFW method's scalability and its industrialization potential, and (2) the development of a CPRCFW method for quality control, integrating winding process automation, process monitoring, data acquisition, and analysis. Each objective is demonstrated through the research and development of hardware, consisting of fabrication setups and tooling and software, comprising CAD-implemented industrial robot motion planning and control algorithms. The objectives are verified through large-scale demonstrators at component and building scale, illustrating how the research findings are conducive to RCFW becoming a valid alternative to industry-verified technologies in composite construction applications.

Zusammenfassung

Seit den 1940er Jahren haben Fortschritte in der chemischen Industrie und Verbundwerkstoffe wie faserverstärkte Polymere die Fertigungsverfahren revolutioniert und neue Anwendungen mit geringem Gewicht und hoher Festigkeit in der Luft- und Raumfahrt, der Automobilindustrie und der Konsumgüterindustrie ermöglicht. In der Bauindustrie haben sich Verbundwerkstoffe jedoch aufgrund der unzureichenden Digitalisierung und der geringen Integration von Design- und Konstruktionsmethoden nicht wesentlich durchgesetzt. Diese Deizite können jedoch durch konstruktionsspezifisches Design, Fertigungsmethoden und Bauvorschriften für Verbundwerkstoffstrukturen beseitigt werden.

Insbesondere der Leichtbau muss sich noch das hohe Festigkeit-Gewicht-Verhältnis von Verbundwerkstoffen wie Glas- oder kohlenstofffaserverstärkten Kunststoffen zunutze machen und so seinen Beitrag zu einer zeitgemäßen Hochleistungs-Leichtbau-Architektur leisten. Die Fortschritte des 21. Jahrhunderts bezüglich digitalen Designmethoden in Verbindung mit neu verfügbarer Hardware und Kontrollsystemen ermöglichen jedoch automatisierte Fertigungsansätze, um etablierte Fertigungsmethoden wie Filament Winding (FW) neu zu definieren.

In dieser Doktorarbeit werden neuartige Hochskalierungs- und Automatisierungsstrategien für das Coreless Filament Winding (CFW) vorgestellt, das eine Anpassung von FW an Bauanwendungen darstellt. CFW ist eine Herstellungsmethode, die sich die anisotropen mechanischen Eigenschaften von frei im Raum um Stützen gewickelten Fasern zunutze macht, um effiziente tragende Strukturen zu schaffen, ohne Bedarf für Formen oder Werkzeuge. Diese Strategien werden durch eine Überprüfung des Stands der Technik unterstützt, die sich auf die technologischen Anforderungen für die robotergestützte kernlose Faserwicklung in Bauanwendungen konzentriert. Die Untersuchung ergab, dass die Skalierbarkeit der Herstellungsmethode und die unzureichende Prozessautomatisierung, unzureichend erforschente Aspekte in der akademischen Forschung für Verbundwerkstoffe im Bauwesen darstellen. Die Arbeit zeigt, dass bestehende Vorfertigungsmethoden des Robotic Coreless Filament Winding (RCFW) erfolgreich hochskaliert und für großflächige, weit gespannte Tragwerke eingesetzt werden können. Darüber hinaus stellt die Arbeit einen Ansatz zur Weiterentwicklung bestehender Prozessüberwachungs- und Qualitätskontrollmethoden vor, bezeichnet als Cyber-Physical RCFW (CPRCFW).

Die beiden Ziele werden anhand von zwei repräsentativen Aufgabenstellungen untersucht: (1) die Überprüfung der Skalierbarkeit der RCFW-Methode und desen Industrialisierungspotenzials und (2) die Entwicklung einer CPRCFW-Methode zur Qualitätskontrolle, die die Automatisierung des Förderprozesses, die Prozessüberwachung, die Datenerfassung und -analyse integriert. Jedes Ziel wird durch die Erforschung und Entwicklung von Hardware, bestehend aus Fertigungseinrichtungen und Werkzeugen, und Software, bestehend aus CAD-implementierten Bewegungsplanungs- und Steuerungsalgorithmen für Industrieroboter, demonstriert.

Die Ziele werden durch groß angelegte Demonstrationen im Komponenten- und Gebäudemaßstab verifiziert, um zu zeigen, dass RCFW eine echte Alternative zu industrieerprobten Technologien im Verbundwerkstoffbau darstellt.

1

Introduction

Since the First Industrial Revolution, building construction and the manufacturing industries have engaged in knowledge transfer driven by the market economy. The industry has supplied the technology to meet an ever-increasing need for efficiency and productivity. Construction has created design-engineering knowledge to shape a diversifying built-environment, fueling a continuously expanding demand.

However, in the context of the Fourth Industrial Revolution [128], characterized by accelerated digitalization and automation, a linear supply-demand relationship no longer represents the only feasible development model nor the only source of innovation, wealth, or knowledge creation.

The advanced materials industry provides excellent examples of design opportunities and business models adapting to international markets in the highly-diversified global economy. Academia and industry have perceived this challenge as an opportunity for technological innovation and a catalyst for new design and engineering opportunities.

In Architecture Engineering and Construction (AEC), interdisciplinary research has created an effervescent environment for architects and engineers to explore new design spaces, novel design methods, or develop novel fabrication technologies. Rather than relying on the industry standard, driven by incremental innovation, an increasing number of design and engineering research streams have seized the opportunity to reimagine the construction process through digitalization and automation. One of the most promising applications in architectural engineering, only possible because of recent advances in computation, simulation, and automation, is lightweight composite construction.

Owing to their high strength, stiffness, and lightweight, composite materials such as glass and carbon fiber-reinforced polymers(G/CFRP) are widely used in civil engineering applications such as bridges, roof structures [99] , domes [9], piers, retaining walls, airport facilities, and storage structures [104].

From a manufacturing point of view, G/CFRPs are highly workable [51], moldable and have low post-processing and finishing requirements. They exhibit excellent specific strength [11], even compared to more widely used materials such as steel [121]. A linear elastic stress-strain behavior characterizes composites such as CFRP before brittle failure by rupture. This brittleness under stress-strain has come to define the use of FRP composites in structural, civil engineering applications.

Nevertheless, FRP composites exhibit several advantages compared to steel which is more ductile but heavier and more prone to corrosion. Additional advantages of composite materials are their non-magnetic properties, high energy absorption capacity, and high durability (fatigue resistance). Furthermore, the lightweight of composites means inexpensive handling, transport, and installation. These qualities give composite components a distinct advantage compared to metallic, concrete-based, or natural composite-based alternatives and present potential opportunities for the development of hybrid materials. Most civil engineering applications require materials that perform well in tension and compression. Hence, the high strength of FRP materials has been utilized to maximum beneficial effect in combination with concrete. Concrete has excellent compressive strength but relatively low tensile capacity. Therefore, FRP reinforced concrete has gained significant attention in existing research [56; 57; 120]. Typical fiber-reinforced concrete applications are external bounding of concrete elements, concrete structures internally reinforced or prestressed with FRP, or simply concrete-filled FRP columns and other hybrid building components such as beams or decks.

In addition, the material and processing cost (load capacity per unit weight [104]) of composites has become increasingly competitive, owing to automation and the decreasing cost of customization. These advantages spanning material properties, economics, and logistics are essential for lightweight construction revitalized by recent developments in fabrication-informed, design-engineering automation. Aiming to contribute to this emergent field, this Dissertation identifies its core scientific contributions in building technology research and development for composite lightweight construction.

1.1 Dissertation aim

This Dissertation aims to improve the scalability and automation of existing Coreless Filament Winding (CFW) fabrication methods in construction. A correlated aim is for the technology to reach the capacity to produce G/CFRP building elements, at a scale and level of complexity matching building industry requirements. CFW allows precise tailoring of production methods to the specifications of civil engineering structures. The work presented in this Dissertation is grounded in interdisciplinary research at the University of Stuttgart and benefits from recent advances in architectural design, engineering, and material science research. Furthermore, the investigations are contextualized within the computational design paradigm of Object-Oriented Programming (OOP) and implements building construction automation principles common to the industrial robotics domain.

The scope of the presented research is lightweight construction for load-bearing applications. Such methodologies are essential to adequately inform design scenarios utilizing load-adapted structures in large-scale construction applications of domes and roofs. A design-driven response to these challenges led to industrial robotic fabrication technology appropriation and adaptation to anisotropic material systems primarily consisting of G/CFRP. Thus, the research investigates the tailoring of materials and geometry to structural purpose in applications spanning the research laboratory towards the factory floor.

The research presented here led to a body of scientific work included cumulatively as a peer-reviewed conference publication hereafter referred to as Article A [9] and two scientific journal publications, subsequently referred to as Article B [8] and Article C [7]. The author of this Dissertation is also first author of the publications introduced above.

Complementary to this work, the scientific literature in the field was reviewed, and the conclusions were synthesized in Section 1.3.4. This review informed the specific research objectives which organized the work program presented in Chapter 2.

1.2 Context and motivation

Construction is one of the leading industrial sectors essential to a sustainable societal development. However, construction is also a significant resource-consumer and waste-producer[13,14]. Thus, the imperative to develop a more sustainable building environment while increasing the productivity and efficiency of the industry have positioned fabrication-aware design-engineering at the forefront of applied scientific research in AEC. Examples of research initiatives that advance this design and economic agenda with potentially profound positive social and political implications are the NCCR DFAB[21] at ETH Zürich and the IntCDC at the University of Stuttgart[126]. Both institutions recognize the importance of digitalization and automation in construction. Both engage in wide-ranging interdisciplinary research fusing architectural design, engineering, material science, applied information technology, and building construction automation.

1.2.1 Lightweight construction

Lightweight construction is an essential component of building culture [64]. But what makes a structural system lightweight? Jörg Schlaich defines ’lightweight’ as the ratio between the ’dead load’ of a structure and the ’live loads’ incurred by its use. The smaller the ratio, the lighter and more materially efficient the structure[111].

The presented Dissertation focuses on lightweight construction under pressure to reduce its ecological impact [92]. Lightweight structures promise material efficiency provided they include the judicious use of resources and the reduction of construction waste. Furthermore, lightweight construction favors modularity and ease of assembly and disassembly. Hence, its adoption may facilitate a cultural shift, within the AEC disciplines, towards design intelligence and the celebration of engineering advances [64]. This trend is already visible in manufacturing and is catalyzed by the ecological imperative and enabled by recent technological advances such as additive manufacturing[64]. This paradigm shift for the AEC sector allows a transition from a heavy, resource and energy-intensive industry towards one where leaner, smarter, and more sustainable construction practices are the norm, not the exception [64]. Excellent examples of lightweight construction almost exclusively stem from interdisciplinary work involving structural engineering, architectural research, and visionary practice.

Lightweight construction contributes to engineering and design history through the work of architects and engineers, amongst which Buckminster Fuller, Frei Otto, Jörg Schlaich, Heinz Isler, and Norman Foster. The modern history of lightweight architecture has some exceptional built examples. Fuller combined geometry and structural design in The Montreal Biosphere geodesic dome[10]. Frei Otto and Jörg Sclaich’s pioneering work on bending-active structures and minimal surfaces led to the Mannheim Multihalle and the Roof of the Munich Olympic Stadium [124].

Heinz Isler developed the building system for thin concrete shells[62; 63]. Norman Foster [98] utilized geometric optimization and digital design to revolutionize the seel and glass grid-shell proposing lightweight designs solutions such as the Great Court Roof at the British Museum. It is impossible to understate the extent to which these works stimulated the industry, inspired generations of architects and engineers, and advanced applied scientific research.

Moreover, the history of lightweight architecture interweaves the invention and development of more durable and tougher building materials with the development of compatible design and engineering methods. Since the 1950s and 1960s, the introduction of new materials and automated means of production has accelerated the development of novel architectural forms, structural systems, and building details.

Fuller's Dymaxion House (1945) [137], for example, was conceived with one material in mind: aluminum, an engineered material that required no periodic maintenance [137]. Thus re-tooled aviation production lines found a new application in building components[137].

Similarly ambitious, the Monsanto House of the Future, designed at the Massachusetts Institute of Technology, was built in 1956 on the Disneyland grounds in Anaheim. In Europe, the FUTURO[123], designed by Matti Suuronen in 1968, still enjoys an architectural following. Both examples utilized the emerging plastics and FRP industry to propose a domestic space under constant evolution. They also exemplify engineering solutions based on monocoque structures and minimal surfaces, reflecting the new materials' capacity to be molded into virtually any shape [122]. However, while the manufacturing and automotive industries have fully embraced FRPs, in AEC there are few applications utilizing these new materials.

Notable contemporary examples of composite materials used in construction were only recently proposed. The Steve Jobs Amphitheatre (AC2) by Foster + Partners (2016) and the composite earthquake-resistant Komatsu Seiren building by Kengo Kuma (2015) showcase these materials' aesthetic and structural qualities. The AC2 roof structure, for example, needed to be extraordinarily lightweight yet stiff enough not to buckle when supported exclusively by the thin structural glass panels of its façade. The AC2 roof is a circular disc with a diameter of 47 meters. It comprises 44 identical components with a maximum length of 21 meters and a full structural depth of 1.5 meters. Premier Composite Technologies produced the foam-core sandwich construction roof components in Dubai which were shipped to the United States of America and dry-assembled on-site [54]. The completed load-bearing 72.5-tonne structure was finally lifted in place and rested on the glass façade with a crane. The Komatsu Seiren building curtain, on the other hand, utilizes a technique for twisting ropes out of composite materials, common to the region of Ishikawa, Japan, to add flexibility to the CFRP composite strands. The resulting façade curtain is part of the renovation of the building, providing additional resistance to lateral dynamic loads characteristic to earthquakes in the region [54].

While the three historical examples offer an accurate glimpse into the building culture of their time. They sought to imagine and build a vision of the future, integrating structure, technology, and utility. Whereas the Dymaxion utilized engineered materials and proposed building systems that utilized the building industry's postbellum overcapacity, the Monsanto House of the Future and FUTURO designs relied on new plastics and composite materials for which they sought to create a niche in construction. The two contemporary examples utilize composites for their structural and aesthetic qualities: the former embodying transparency and a progressive corporate image, the latter standing for functionality and safety and minimal interventions on existing built environment through high-tech applications. Yet, both represent a functionally and economically prohibitive use of composite materials and can thus be categorized as one-offs. The first one serves as the headquarters of one of the world's most valuable companies, while the second utilizes experimental technology developed by its client. Furthermore, these applications slow incremental innovation is still the preferred path for rethinking space and material in the architectural profession.

This Dissertation investigates whether the currently-available technologies and design-production methods available in the AEC are suitable for sustainable growth and increased productivity. When attempting to re-imagine the application of composite materials in construction, some designers and engineers have looked elsewhere than the industrial standard. They drew inspiration from biology and their tools from technology. This Dissertation aims to be one example where technology, bio-inspired design, and engineering considerations merge to open new opportunities for lightweight building construction.

1.2.2 Towards a biomimetics-informed methodology for the design of fibrous morphologies

In a 2006 publication entitled "Biomimetics: its practice and theory," Julian Vincent illustrates the applicability of the problem-solving system "TRIZ" [133; 131], developed to facilitate knowledge transfer between different engineering disciplines [131], to knowledge transfer between biology and engineering.

"Biomimetics" [132] is a term coined by Otto Schmitt in 1969 [133] in the research paper titled: "Some interesting and useful biomimetic transforms". He aimed to describe the transfer of ideas from biology to technology.

Why is biomimetics important in the context of this Dissertation? After all, as Vincent explains: "The benefits to be gained from biomimetics are not yet totally obvious, other than to deepen the human race's box of technical tricks" [133].

More importantly: why is it essential to investigate biology, as potential inspiration for technology and, in extension, for design-engineering? Researchers, including Vincent [133] and Fratzl [40], have suggested a possible answer. They argued that biology could provide less energy-intensive solutions to everyday engineering problems. But to do this, both academia and industry must overcome compartmentalization and a self-referential "incremental research culture," which stifles innovation. Moreover, "Biomimetics: its practice and theory" also illustrates that when tasked with solving similar problems, researchers have identified a mere 12 percent similarity between strategies employed in biology versus those familiar to engineering practice. According to the authors, this methodological difference suggests a significant untapped potential for engineering to benefit from developing a systematic framework for knowledge transfer from biology[133].

Nevertheless, the application of biological solutions to engineering proves non-trivial. Its success requires the systematic development of investigation methods, enhanced to answer engineering questions adapted and ready to be reformulated in biological terms and vice versa [132]. As Vincent points out, the mechanisms for finding solutions in biology versus engineering are very different, stemming from the organization of the fields and their research output. On the one hand, biology is descriptive, relying on observations of evolution and natural selection, methods by which nature solves problems under the pressures of environmental interactions and the need of organisms to survive. Consequently, as a scientific field, biology generates classifications.

On the other hand, technology is prescriptive, utilizing top-down decision-making to create rules and methodologies. However, the crucial similarity is that biology and technology rely on resolving technical conflict as a driver for change [133]. This compatibility is essential for biomimetics because it suggests a methodology for connecting the two fields. Blurring the boundaries between biology and engineering can generate innovation in both. The benefit for technology is evident. However, Vincent also points out that systematization might benefit biology itself. That is because it would allow a novel path of scientific investigation: "the verification of biological mechanisms by manufacture. This would lead to positive feedback between biology and engineering" [131]. Vincent suggests multiple feedback loops between research and application, with technology integrated as verification methodology in biology's fundamental research.

A caveat, however, is that direct transfer of technical solutions from biology to engineering is not always possible. Biological solutions answer highly complex optimization problems whereby many traits, although obsolete, are still inherited[68] and passed on to next generations. The inheritance aspect makes it challenging to select single biological characteristics to model engineering solutions. Simply put, it isn't easy to know what biology has optimized for by merely studying phenotype[40].

Achim Menges pointed out the importance of inheritance and inertia in technology. When discussing the applicability of novel composite materials in construction, the Menges remarks that many composite manufacturing industries utilize production techniques developed initially to process other materials such as metals. He concludes that this form of inheritance is inappropriate if prior critical assessment is missing. Menges argues that when tasked with shaping glass and carbon fiber composites, one should first study fibrous morphologies in nature and then develop design engineering and fabrication methods that match the materials' morphogenetic potential[79].

In many cases in building construction , technological solutions and design methods are adopted by virtue of inertia because of the conservative nature of the industry and the prevalence of complex supply and demand chains ensure short-term competitiveness. However, incremental innovation is not a guarantee for long-term success. Inheritance represents a valuable evolutionary trait common to biology and technology, which can even stifle innovation if improperly leveraged. As adequately inquired by Rik Huikes: "if bone is the answer, then what is the question?"[58].

Moreover, Vincent argues that the main conceptual difference between biology and engineering is that, while biologists are presented with the solution trying to find a question, engineers and designers are given a problem and try to find the best solution. Of course, the constraints in biology and technology are very different. Fratzl, therefore, suggests that an in-depth morpho-functional investigation of biological systems within a given set of biological and physical constraints is a meaningful way forward in biomimetic research [40].

This account of the debate involving biomimetics, design, and technology underlines this research field's important role in developing new design-engineering methodologies.

Currently, building operation can achieve a dramatic reduction in energy consumption. Therefore, embodied energy in materials and structures remains the primary area where significant reductions can still be made [92] towards a less energy intensive built environment. The realm of biological research provides role models interesting for architects and engineers. Nature utilizes inexpensive, readily available materials as fundamental building blocks that are not energy-intensive, instead prioritizing form [40], structure, and morphological differentiation. This is manifested at different levels of hierarchy and across different scales of magnitude and degree of sophistication [131; 133; 134; 40; 68; 132]. Thus, it becomes possible to open up new avenues of research into knowledge transfer between biology, engineering, and architecture.

In a 2005 study [132], Vincent showed that only 20 percent of engineering approaches match the biological ones when attempting to solve seemingly contradictory design challenges such as simultaneously achieving stiffness and lightness - with lightweight materials. The author highlights this research domain as particularly significant for technology and engineering to learn from biological role models[132] and make signoficant contributions to societal challenges. The methodology for "Inventive problem-solving - TRIZ," as illustrated by Vincent, has exciting structural design applications that prioritize adequately utilizing composite materials. For example, the challenge of achieving high-strength-to-weight ratios is the subject of a case study on the arthropod cuticle. Here a composite material of chitin fibers and protein-matrix is shown to perform many integrated mechanical and sensory functions through morphological differentiation over the small dimensions of the animal.

However, illustrating the similar goals of resolving technical conflict in the respective disciplines is not sufficient for effective knowledge transfer. The way biomimetics addresses fabrication processes must be nuanced. While biology utilizes growth processes [40] to transform the genotype into varied phenotype manifestations, technology relies on prescriptive processes of fabrication of exact designs. On the one hand, biology acts through morphogenetic and environmental forces. On the other hand, technology relies on detailed explicit plans, a paradigm currently questioned by computational design and the advent of artificial intelligence applications in construction. Therefore, innovative fabrication becomes an essential tool and enabler for biomimetic design.

Moreover, smart manufacturing constitutes an indispensable field for the implementation of complex architectural designs. In terms of the fabrication process, this

Dissertation is inspired by the close integration of materials and fabrication methods already achieved in nature and revealed by biomimetic research. In biology, structures and skins are grown based on instructions encoded in the materials themselves. As Jan Knippers and Thomas Speck explain: in biology, morphology and structure are interchangeable concepts. The fact that biology and architecture are nondeterministic opens up many opportunities to explore structural solutions previously considered sub-optimal by classical structural engineering but successfully utilized in biology [68].

Vincent's contribution is essential for biomimetic research in AEC; it is one of the influential quantitative assessments of the similarities and differences between biology and technology. Thus, many designers and engineers amongst which Menges and Knippers understood that the study of biological role models may help advance the scientific understanding of technological problems through biomimetic design.

A particularly effervescent research with foundations in biomimetic research is conducted at the University of Stuttgart by the aforementioned researchers through their institutes and in collaborating with Prof. Thomas Speck from the Plant Biomechanics Group at the University of Freiburg and others. Their research utilizes computational design and automated fabrication, leading to a unique body of interdisciplinary work in architecture, engineering, and building construction. Their early investigations, which contextualise the architectural and engineering results of this Dissertation, have been fundamental for a reinvention of design and fabrication methods for lightweight architecture. The chosen material systems are natural composite building materials, such as timber, or technical building materials, such as G/CFRPs [79]. According to Menges, Knippers [79], and Hansel [27], the investigations into novel forms of lightweight construction utilizing composite materials first sought to illustrate how new design-engineering and fabrication processes enable a novel approach to biomimetics applied to the AEC field. Secondly, the research stream into construction composites sought to develop automated fabrication processes that take advantage of insights from biology, singling out lightweight structures as an exciting area of application for fibrous composites in construction [90]. Thus, the present Dissertation, chose material and geometry-informed computational fabrication as its area of interest, using the author's previous architectural training to identify and research in detail the fibrous morphologies most suitable for numerically-controlled fabrication.

In previous research, state-of-the-art industrial robotic technology and the materials' morphogenetic design potential were newly examined and evaluated. This reorientation triggered a redevelopment of the industrial fabrication processes of Filament Winding (FW). Of particular interest for the presented research is the technological variation utilized at the University of Stuttgart. Coreless Filament winding(CFW), is a process designed to minimize the utilization of molds and scaffolds. The interrelated research into the reciprocal deformation of free-spanning fibers under controlled pretension [8] enabled advanced CFW methods. The need for advanced simulations of fiber interaction and the emergence of novel design-engineering methods currently form a well-defined research field. This research interest towards digitalization, automation, and knowledge transfer from fields such as biology, fiber technology and industrial robotics becomes an instigator for developing Robotic Coreless Filament Winding (RCFW) methods for construction composites.

1.2.3 Incremental innovation in industrial composite filament winding

Composite manufacturing utilizes multiple Additive Manufacturing (AM) processes amongst which automated tape layup, automated fiber placement, and Filament Winding(FW). The latter is an industrial manufacturing process where continuous strands of fiber filaments are consolidated around a supporting negative form, or mandrel, by an automated additive process of continuous material deposition. FW is material agnostic and compatible with any fiber supplied as continuous filaments, bundled into rovings, yarns, or tapes [8]. The composite material consists of a mixture of fibers and a matrix system [7]. The most common matrices utilized in composite filament winding are thermoplastic or thermoset polymers, utilized in admixtures with various other materials such as hardeners or plastifiers. The principal tooling used in the industry are mandrels or stay-in-place liners constructed out of various insoluble or soluble materials. The industrial process is, in principle, very simple: the matrix first impregnates the fiber filaments and then binds them, an automated tool then winds(deposits) the fibers around a mould in successive passes. The process encompasses several ancillary operations, such as controlled curing, tempering, mold removal and machining to create finally arrive at the finished durable, stiff, and lightweight FRP product[114].

Composite filament winding is an industrial process with a rich history characterized by an extensively documented scientific and industrial development [83; 86; 94]. From the onset, it is essential to note that the development of the filament winding technology has been defined by the aim of achieving structurally-tailored fiber layups, usually through discrete winding steps, based on the repetition of "winding-circuits". In FW, a winding circuit represents the fiber path between multiple extremities of the mandrel.

Motivated by the material's anisotropic properties, including its lightness and high rigidity, the first industrial applications were aircraft engine casings. Later on, due to the materials' capacity to withstand tension forces, filament-wound composites were used in pressure vessels where the uniform internal pressure of the liquids or gasses within, represented the primary loading condition. These structures are usually radially symmetrical, i.e., isotensoid or toroidal [94]. Here, the winding pattern or syntax is composed of predominantly identical fiber circuits that repeat and interweave into a precise layup according to a predefined design. We will next review several innovations related to the design and control of the wound fiber patterns and the milestones that underpin the modern applications' high level of automation, performance, and precision.

The first modern application of the process was developed in the United States of America in the early 1940s by Richard E. Young. It consisted of a simple mechanical winder that laid fiberglass on a rotational wooden mandrel. The machine operator adjusted gearboxes and chains of variable length to control the winding pattern. Variations of this system remained in use well into the 1980s [94]. The next advancement involved the ability to wind different patterns. The 'photo-eye winder' technical milestone allowed the new machines to follow printed patterns to achieve different winding angles. Computer control of industrial production systems was introduced in the early 1980s. It represents the third major technological innovation. Through pattern-generation software, the operator could program the winder directly. Image recognition was an early form of 'teaching' for the machine, very effective when dealing with highly repeatable winding patterns[83; 94].

At this point of development, it is essential to distinguish between the automation of the winding process and that of the entire manufacturing process for FW composite parts. Process automation includes all associated ancillary operations associated with FW. Automation of the winding process means machine control over the structural and functional design of the components. Automation of the production process relies on integrating several steps, from winding to cutting, curing, tempering, and eventually post-processing the wound part. Up to this point, winding machines integrated a single delivery eye per spindle.

The 1970s witnessed significant developments in the extractive industries for oil natural gas and the chemical field, in general. This created rising demand for serialized production of elongated tubular parts. The 360° delivery eye winder [83; 94] was developed for producing "endless" tubular structures. In contrast to the single-eye devices, the newly developed, highly efficient system system could lay a complete layer of fibers at every machine pass around the mandrel.

The fifth technological milestone occurred in the 1980s and consisted of multiple winding spindles controlled by the same computer and operated simultaneously by few staff. This development addressed the increasing demand triggered by the sporting goods market. While this technical feature addressed the rising demand for identical elements, the next advancement involved the introduction of additional motion axes about which the winder could orient its delivery eye. Thus, in addition to spindle rotation and carriage translation, the 1990s saw two additional degrees of freedom added: radial motion around the mandrel and 360° rotation of the delivery eye. This development was synonymous with a significant extension of the design space and was only made possible by the enhanced capacity of the numerical control system [83; 94]. The winding process integrated two ancillary operations: automatic fiber tie-on and cut-off which improved labor efficiency by eliminating most human intervention. At the same time, the industry made significant advancements for the integrated fabrication of the inner surfaces of parts such as propane tank liners: an initial liner was rotation-molded, it would act as a 'lost mold' for the composite layers that followed [94].

This historical account finds that innovation in FW was always closely linked to automation and the economy of scale. However, the market, which was initially driven by serialization is currently being increasingly defined by customization. FW technology is a good example of incremental innovation towards the development of a robust manufacturing technology. However, to adequately serve emerging fields such as composite building construction, FW need to allow its design and fabrication method to evolve beyond the reliance on moulds and single-purpose machines, be upscaled and integrated into existing construction processes, adopt new standards, new performance and novel aesthetics. This Dissertation charts one approach towards the collosal task of developing novel technologies, performance, and aesthetics in composite building construction for lightweight architecture.

1.3 State of the art

As we have already discussed, incremental innovation is a feature characteristic to industrial technology and FW is no exception. However, this trend has been accelerated in recent years by an appropriation of industrial robotics and computational design and fabrication into the manufacturing industries and architecture and building construction are no exception.

Next, this Dissertation focuses on the composite manufacturing industry, since much of the progress in composite manufacturing currently stems from the private sector. This phenomenon is described at length in Article B [8], which lays out the particularities of the technology-transfer process applied to composite construction.

1.3.1 Mature technologies in the composite manufacturing industry

The most dominant technologies in composite manufacturing are filament winding and tape-laying [53]. Their most significant technological developments result from an increasingly diversified demand and advanced research and development (R&D) reflected in the high number of publications and patents in the field. Amongst these, we publications that holistically describe composite manufacturing methods [83; 86; 94; 70], examine current trends in composite material science [67], and focus on the materials' mechanical properties [5; 109; 127; 52; 66]. An additional category of reviewed publications includes works on the manufacturing process, with emphasis on process automation [116; 20; 42; 76; 101] and crucial technology turning points [114; 12]. However, architects and engineers must consider new challenges specific to their applications' size scale and functionality for the AEC domain. These challenges include specific design methods, scalability constraints, design space for building component typologies and cross-section design [42], suitability for assembly[1], and end-of-life and sustainability aspects[6].

Some industrial developments address the need to increase production speed through the automation and optimization of all ancillary operations: commercial companies like Mikrosam [82; 43] offer integrated solutions that include automating design analysis and fabrication. Furthermore, Murata Machinery Ltd. [89] has reduced cycle times by developing the multi-filament winding system that simultaneously winds 48 to 180 fiber tows, a technology in prototypical use at the RWTH Aachen [60]. The technology can significantly speed up conventional FW processes because one complete composite layer is applied in one machine pass. Cikoni [16], MF Tech [80], and Cygnet [17] addressed the complexity of composite components in terms of layup, cross-sectional form, and structural performance. The aerospace industry, in particular, has been demanding a shorter, in-situ curing cycle that requires no autoclave, a technology that is now close to being commercially deployed[45].

Hybridization of manufacturing technology is another area of industrial investigation. Companies like MF Tech[80] and Mikrosam [81] offer robotic cells for combinations of FW and automated fiber placement. At the same time, Cikoni has developed a technology for winding CF tows on 3D-printed plastic on metal cores. The symposium Future Composite Manufacturing – AFP & AM(2020)[14] specifically focused on the compatibility between automated fiber placement and AM. The application of localized heat, the layer-based 2D and 3D paths, orthotropic material properties, and thermal activation between layers are currently being utilized across many manufacturing processes, increasing the potential for technological hybridization [44] an blurring the boundaries between applications. An application developed by CEAD, the FlexBot [13], combines AM of composite materials at 0-45° angles and milling on the same robotic fabrication platform.

The appropriation of industrial robotics from the automotive industry has revolutionized and democratized the composite industry enabling applications unconstrained by specialized winding equipment. One industrial company that introduced robotized winding from its entry on the market was MF Tech [80]. The company first provided robotized solutions to match the capabilities of the traditional composite manufacturing industry but soon moved to automate all ancillary operations using industrial robots.

A highly consequential area of research is fabrication data acquisition. MF Tech equips its winding machinery with the ability to acquire data on resin temperature, tracks the fiber and resin batches, winding tension, and operator ID and associates them digitally to the manufactured product. The industry aims to explore further technological innovation through interdisciplinary research.

1.3.2 Emergent technologies in the composite manufacturing industry

Nevertheless, the technologies most interesting for this Dissertation aim to maximize design and solution space, integrate structural evaluation and form-finding, address the need to cut production costs, and reduce offcuts. The reviewed publications offer a holistic account of the recent advances in the field in terms of matrix systems [22; 23], post-processing techniques[69], and the current degree of automation [41; 71]. In general, the technology aims to reduce formwork, mandrels, and dies and utilize the industrial robot’s speed, precision, and repeatability for more effective and economically competitive fabrication processes.

The following industrial developments are also closely dependent on structural optimization of fiber paths that result in a loadbearing composite structure once wound. The first industrial developer of such a technology, named "FiberTEC3D", was Daimler [87] in cooperation with the Institute of Textile Machinery and High Performance Materials at the TU Dresden [125] who provided the software solutions to control the robotic fabrication process. The proposed design methods are based on evaluations of robotic gripper tools for the automotive industry, including dimensioning, simulations of structural loads, strength, stiffness, deflection requirements winding time, and cost. A similar manufacturing technology called "3D winding" developed by the Cikoni [16] was also applied to Daimler's engineering challenge.

In the "FiberTEC3D" application, the fiber tows are impregnated in an open resin bath and wound by two robots. One holds the fiber payout tool, and the other manipulates the winding tool. The structural performance of the parts relies on fiber continuity achieved by deviating the fiber path around "deviation pins". The current application of the technology, also in Daimler's robotic automotive grippers, is discussed in Article B [87]. Published work on the technology found that the strength of wound parts is comparable to that of standard aluminum grippers but with a 50% reduction in weight. The authors point out that the curing process for their technology does not utilize an autoclave. Applying heat and pressure in the curing process would increase performance by up to 15% but incur higher manufacturing costs related to specialized tooling, pressure, and vacuum.

Another technology utilizing 3D winding, called "xFK in 3D", was developed by Automotive Management Consulting [4] and Peter Fassbaender [118; 135] in partnership with SGL Carbon[112]. The technology involves winding single resin-impregnated fiber tows around plastic or metal positioning fixtures that stay embedded in the final product as connectors. As a demonstrator of effectiveness, the weight of a bicycle chainring was reduced by 30% compared to an aluminum equivalent. The developers envisage that their technology could be applied in the automotive sector, citing a favorable balance of customizability, specialization, and a need for lightweight structures.

For FW around a core, the "3D winding" technology by Cikoni [118] utilizes an initial polymer or metal print and applies filament winding on top. Cikoni also proposed an application of 3D winding that utilizes composites as joining structures for modular 3D printed polymer components for the automotive industry utilized as lightweight robot bodies. Finite Element Method(FEM) was used to identify tension and compression areas, which informed material distribution.

In all these examples, a redeveloped FW enables the economical production of small series of highly optimized parts with applications in tooling and automotive parts. The three approaches rely on simulation methods that generate data utilized to design the components. These data sets include information that generates fiber paths and locations for additional materials to embed in the composite piece. These 3D winding applications utilize incremental technological, and functional integration usually embodied through multi-functional robotic fabrication environments.

While the industry heavily invests in research, development, and innovation, this review finds a prevalence of incremental innovation. Research and development are compartmentalized and seldom interdisciplinary, leading to standardization and top-down decisions. Nevertheless, the preoccupation towards material savings and eliminating material offcuts is undoubtedly a path towards higher degrees of automation and individualization, leading to expanding design spaces. As we have seen, continuous, accelerated development, and higher integration between technology and design-engineering are already achieved within the industrial sector. They still remain major challenges for composite construction.

1.3.3 Emergent technologies in composite construction

Composite construction is a relatively young deign-research field [47], enabled by interdisciplinary research in AEC. Cross-disciplinary knowledge transfer from Information Technology (IT), industrial automation and material science contribute to a dynamic research field [47] reflected in the high number of publications and full-scale projects in the last decade and even earlier. This Dissertation aims to provide an overview on the development of the construction composites field under the of larger paradigms in AEC such as digitalization [115], biomimetics [26; 38; 50], and the maker and open-source movements [2; 55; 97]. Here, computational design and structural simulation tools have extended the design spaces for construction composites [88; 78] previously limited by a prohibitive reliance on formwork or molds. Some emerging composite manufacturing technologies covered in the technology overview rely on embedding formwork, which becomes a substrate for composite materials. Others strive to reduce it significantly with the ultimate goal of eliminating it.

The technology transfer between the composite manufacturing industry and construction is also presented in Article B [8]. Knowledge transfer is not unique to composite or lightweight construction. Similar processes can be identified in research streams influenced by digitalization and automation, such as the research on cross-laminated timber building components at the University of Stuttgart [136] or AM research applied to concrete construction at the ETH Zürich [3].

In general, the applications of composite materials in construction have been linked to specific building system requirements either as integrated formwork or as main construction components. Article B [8] reviews the emerging technology of knitting composite materials in research at the ETH Zürich as formwork for concrete ribbed shell structures [96] or as standalone structural membranes at the KTH Copenhagen [119].

Research on coreless filament winding applications in construction is contextualized within the larger field of AM in Article C [7], with technological and design benchmarks in existing composite Fused Deposition Modelling (FDM) applications developed at ETH Zürich [75] and in the industry. While composite FDM printing enjoys a limitless design and solution space, its scalability to construction requirements is still a challenge for research and development. Convincing technology demonstrators have been proposed at the ETH Zürich [75] and by Branch Technology, through the One City Pavilion[91; 113]. However, these applications are either expensive one-offs [91; 113] or limited in scale [75].

In contrast, CFW has proven scalable, robust, and compatible with automated applications [36; 93; 129] and interdisciplinary design, engineering, material science, and robotics [93; 117; 85; 39; 130]. Figure 1.1 illustrates several examples of coreless-wound building structures developed at the University of Stuttgart, also reviewed by Articles B [8] and C [7]. Additional advances in structurally informed design methods are presented in Christie et al. [15], which focuses on lightweight slab applications for multistory construction.

The expertise to design and build composite buildings using CFW has been systematically developed over the last decade of research and development at the University of Stuttgart. In particular, the spinoff FibR GmbH [37] recently demonstrated competence in fabricating small-scale commercial projects. In 2017 it became industry partner for an interdisciplinary building project with the ambition to design, engineer, and build long-span public building using coreless wound G/CFRP exclusively. The research and development work is presented in Articles A [9] and B [8] included in this Dissertation.

1.3.4 Problem identification and research gap

Knowledge and standards in FW and CFW are heterogeneously shared between academia and industry. Thus, the current state of technology was narrowed down

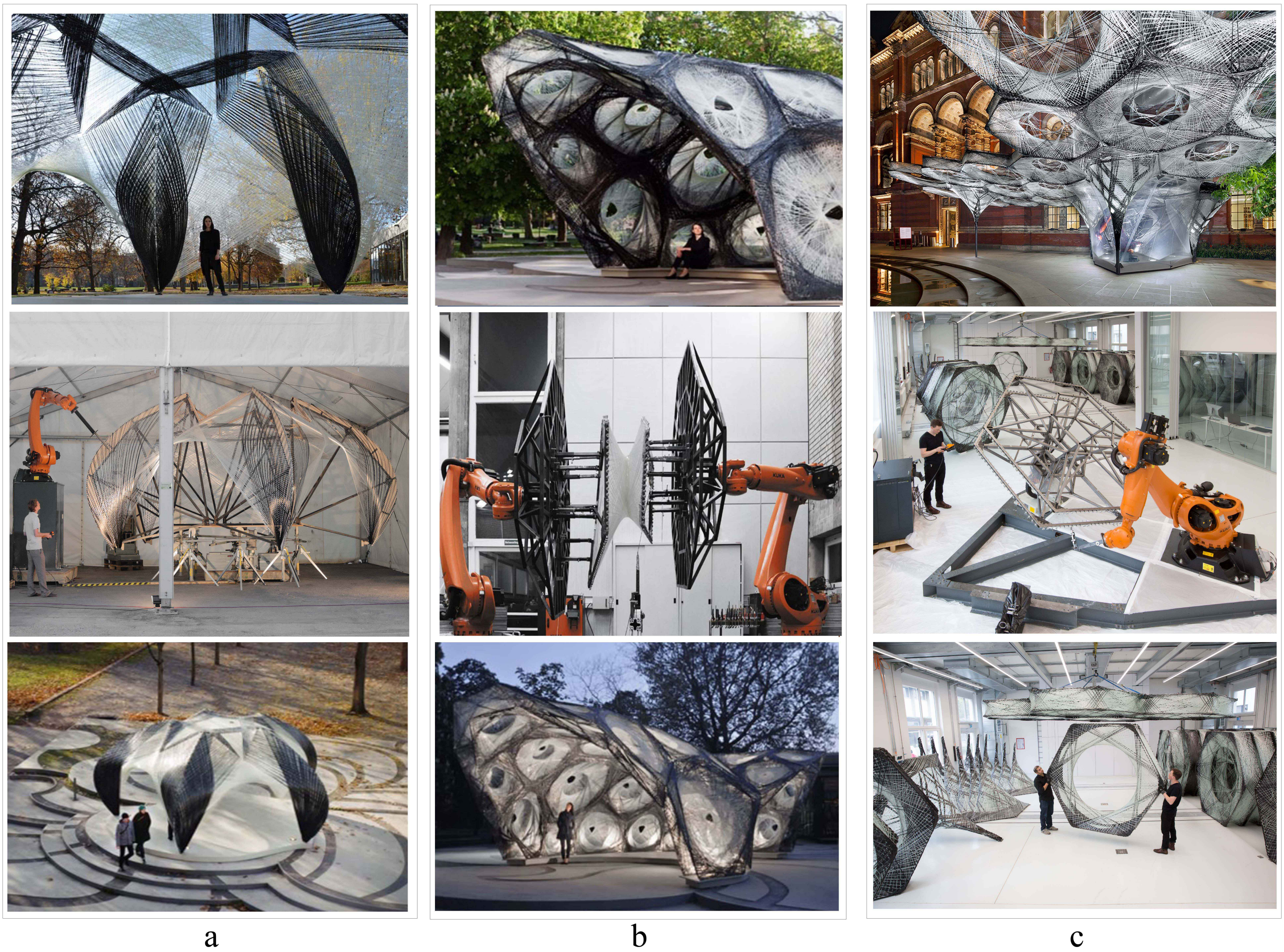


Figure 1.1: Coreless Filament Winding in construction: a. ICD/ITKE Research Pavilion 2012 : Top - Completed pavilion, detail; Middle - RCFW setup, Bottom - Completed pavilion, © ICD/ITKE, University of Stuttgart [105]; b. ICD/ITKE Research Pavilion 2013 - 14: Top - Completed pavilion, detail; Middle - RCFW setup, Bottom - Completed pavilion, © ICD/ITKE, University of Stuttgart [25]; c. Elytra Filament Pavilion (2017): Top - Completed Pavilion, detail; Middle - RCFW setup, Bottom - Components, © ICD/ITKE, University of Stuttgart [99].

and contextualized to construction applications. The State of the art review chapters in this Dissertation and in Articles A [9], B [8], and C [7] yielded two significant research gaps for construction composites.

Firstly, we evaluated the scalability of the coreless-wound composite construction components through the prefabrication of bespoke elements. Although experimentally implemented in the ICD/ITKE Research Pavilion 2013-2014 [99; 93; 25; 24], variation of boundary conditions for plate-like elements is unfeasible for construction beyond pavilion scale. Consequently, the Elytra Filament Pavilion [99] utilized identical components, varying the fiber syntaxes to achieve the intended structural capacity. Moreover, a segmented shell structural typology seems unsuitable for large-scale composite construction because polygonal components therein need to be connected along their entire perimeter for effective load induction. Hence, further research could be extended to additional structural typologies, such as grid shells or domes and the exploration of alternative discretisation and connection methods.

Moreover, a prefabrication methodology for scalable composite construction components that approximate the grid-shell members is missing. Essential requirements for such a system are variable length, variable boundary conditions, and the ability to interface with other components and building subsystems such as self-supporting façades and foundations. Consequently, Research Gap 1 is formulated around developing a prefabrication setup for RCFW. This new setup is required to deliver large-scale building components that embody the significant, still unrealized customization potential.

Secondly, the surveyed RCFW composite construction precedents, while highly attuned to the mechanical properties of the G/CFRP material system, integrate process monitoring and quality control only at an empirical, intuitive level through experimental means such as visual inspection and manual checks. Lack of automation of process monitoring and quality control represents Research Gap 2. Improving the RCFW method's integration of material system properties is essential to scalability and quality control. Our research thus postulates that a higher degree of automation of the RCFW method, combined with automated process monitoring and quality control, could address the identified gaps improving the quality and economic competitiveness of RCFW components.

As stated previously, because RCFW in construction is still an experimental technology, to date the most advanced applications are research pavilion [105; 100] or site-specific installations [99]. Consequently, the prefabrication of the composite elements was conducted in a research laboratory setting, under experimental conditions, and with in-house developed experimental fabrication equipment (See Fig. 1.1). Thus, as part of research Gap 1, this thesis aims to investigate and verify to which extent the RCFW technology applies to lightweight construction in full-scale building applications. Furthermore, the thesis evaluates the implications of industrializing the technology directly related to customization and efficiency.

Research Gap 1 also investigates scalability at computational method, robotic setup, and physical component levels. Moreover, the analysis of existing examples, proposed in Articles A [9], B [8], and C [7], suggests the need to verify any new methods at a large-scale architectural application. This is required to verify the robustness of existing planning methods for the application of composite materials in construction. Article A [9] extensively addresses the need for interdisciplinary research in RCFW, which can only be contextualized by a large-scale architectural application in AEC. The publication identifies the need for large-scale and structurally tailored fibrous morphologies. The solutions for meeting these demands are a scalable fabrication method utilizing robotized industrial FW technology. Article B [8] interrogates whether the updated fabrication method is customizable enough for the demands of building construction.

Incremental innovation is the industry's manner of working, given its profitability targets and the requirement to balance investment with medium and long term returns. However, this development model is currently being challenged in the composite building industry by novel approaches that include automation and computational design. In this context, academia is uniquely positioned to instigate disruptive innovation. Therefore, researchers in architecture and construction can make more considerable strides to bypass established pathways towards innovation.

As Article B [8] points out, even though our RCFW method enables scalability, the monitoring and quality control process is still human-labor-intensive, making it strenuous, costly, and prone to error. The current lack of a methodology for automated process monitoring and control in RCFW constitutes Research Gap 2. Article C [7] postulates the need to develop novel automated material-aware fabrication methods to enhance existing fabrication applications. We also postulate that automated process monitoring and control may utilize bespoke sensor systems, thus positioning the research in the realm of cyber-physical production systems.

2

Methods

In this Dissertation, Work Modules (WM) organize Strategic Objectives (SO) and Tasks(T). This chapter is complementary to the respective sections of Chapters 5, 6, and 7 (Articles A, B, and C). The research aim is to improve the fabricability and quality of construction composites at a scale and level of complexity matching the building industry standards. Hence, the identified strategic objectives are:

- SO1: Integration of design, fabrication, and upscale of coreless filament winding methods for construction composites;
- SO2: Development of upscaled computational design and robotic fabrication methods for large-scale tubular building components;
- SO3: Development of a cyber-physical robotic coreless filament winding method for fabrication, process monitoring, automated fabrication, data acquisition, quality control, and process performance evaluation;
- SO4: Advancement and upscale of the RCFW physical infrastructure.

Four interrelated work modules (WM 1 – 4) and a dissemination module (WM 5) organize the research work. The strategic objectives interrelate domain-specific work modules: systems, methods, and processes, as visualized in Figure 2.1.

Composite construction must develop design-engineering and adaptive fabrication methods to answer the need for lightweight, high-performance, and economically competitive composite structures. Concerning fabrication, Chapter 1 has identified scalability and automation as essential requirements for the advancement of composite construction through automatic coreless filament winding. These are the areas where the current state of the art presents research opportunities. Chapter 2 describes the methodology developed for the investigation of these requirements.

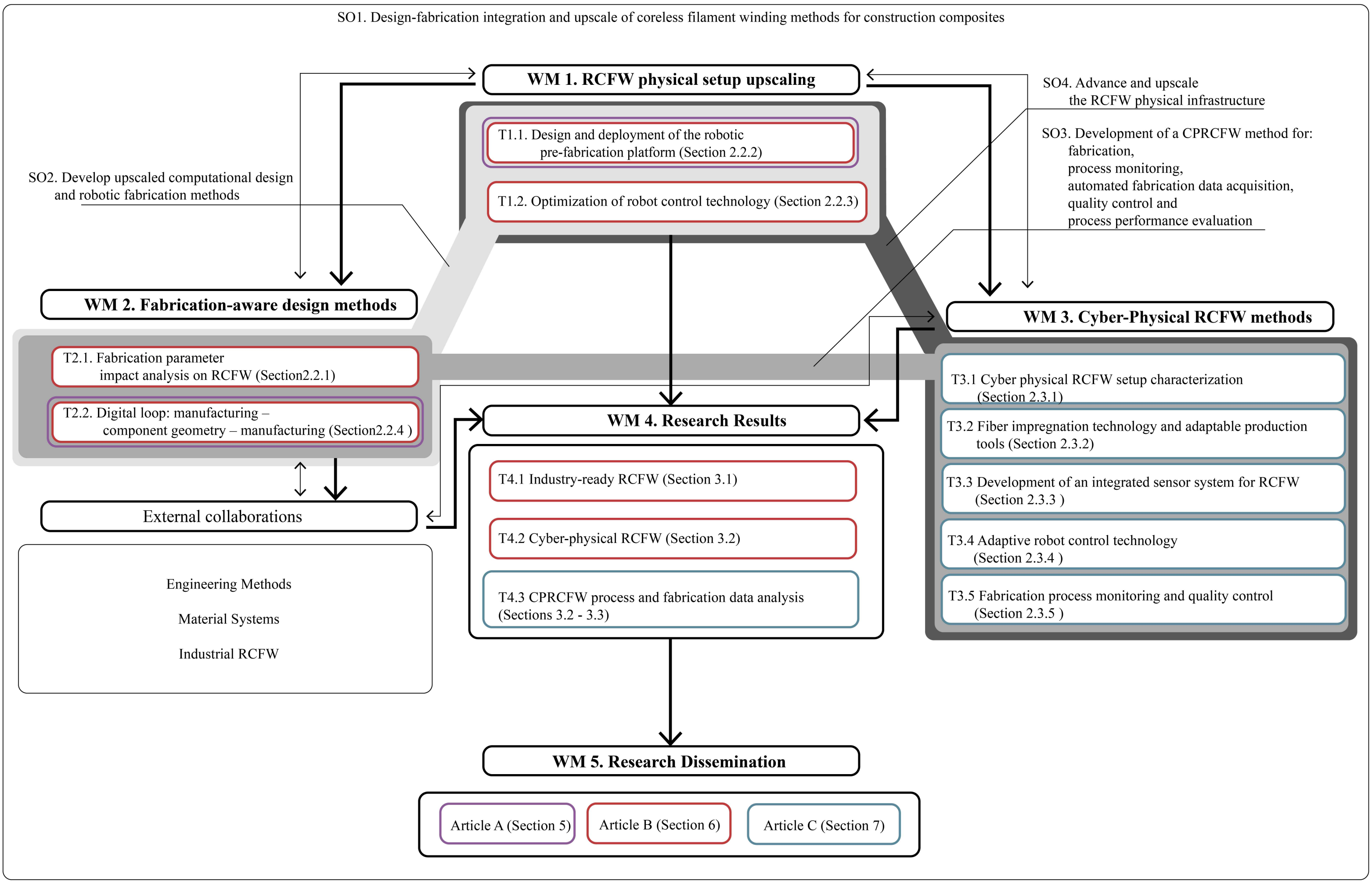


Figure 2.1: Research Plan: Interrelated Work Methods (WM), Tasks(T) and overarching strategic objectives (SO). ©Serban Bodea.

2.1 Research plan: research objectives and research tasks

The WM1 and WM3 develop the upscaled setup and the cyber-physical setup for RCFW, WM2 focuses on integrating design and fabrication.

All WMs contribute to the characterization of experimental work through demonstrators at component scale and the prefabrication of a building-scale demonstrator through industrial RCFW (WM 4). Figure 2.1 illustrates the interrelations between WM and their contribution to the practical implementation step - and subsequently to the dissemination of the research results (Articles A [9], B [8], and C [7]).

SO1 is the overarching objective advanced by the synergy of all WMs.

SO2 interrelates WM1 with WM2 by addressing the specific requirements introduced by the elongated tubular component typology:

- From design to RCFW: high component length results in ample, efficient robotic winding motions;
- From design-engineering to RCFW: higher structural loads demand efficient load induction;
- From fabrication to design: winding fiber circuits along the component circumference requires updated fabrication methods and the introduction of traveling points lying in-between winding points.

SO3 interrelates WM2 with WM3 to realize material system-aware RCFW towards automated online process monitoring and quality control:

- From design to Cyber-Physical Robotic Coreless Filament Winding (CPRCFW): high component length requires ample, efficient robotic winding motions. Specifically, component lengths exceeding 9 meters demanded the introduction of an additional linear robotic motion track and separate control of the two additional robot axes;
- From CPRCFW to design: fully automated CPRCFW demanded a reevaluation of material quantities, fabrication duration leading to major design adjustments.

RCFW is a fabrication technology tailored to construction requirements. Therefore, SO4 interrelates WM1 and WM3 to advance and upscale the RCFW physical infrastructure. The corresponding research tasks are:

- Online process-monitoring;
- Online and offline quality-control;
- Fabrication data acquisition and analysis.

2.1.1 Research Tasks

Research in computational design-engineering and digital building systems supports the interdisciplinary research methods and collaborations at the University of Stuttgart and the private sector, highlighted in Figure 2.1.

The first task of the research is to develop material and design-method aware fabrication technology. This task led to the formulation of the problematic presented in Article A [9]: which investigates the integration of design-engineering and automated fabrication through architecture-led interdisciplinary research.

Additional research tasks address geometric variability of a structural system composed of beam elements of variable length into the specifications of the fabrication setup (WM1 and WM2).

SO3 tackles the development of the material-aware fabrication method; it comprises tasks concerned with the characterization and implementation of online process monitoring and quality control for RCFW. Advances on these topics are addressed by Article B [8] and Article C [7].

An essential aim of this research is to contextualize RCFW within the larger industry and develop suitable, upscaled computational and robotic fabrication methods (SO2). The fabrication methodology is verified by prefabricating a modular composite loadbearing structure for a segmented dome. This Dissertation characterizes the RCFW fabrication method developed for manufacturing the hyperboloid tubular composite elements for the dome's loadbearing structure. Article B presents methodology on the application's industrial and technical characterizations[8]. Here, the producible array of morphological typologies is practically verified. These typologies are proven able to satisfy the requirements derived from digital design and generative building systems. The aim is to make these methods applicable to a broad spectrum of long-span civil engineering structures.

Another objective of the research is to advance and upscale the physical infrastructure and automation of RCFW (SO4). The sets of tasks in WM3 aimed to develop novel miniaturized fiber-impregnation and guidance technology. Another aim was adaptive production tools incorporable into a compact winding device composed of a sensor system to monitor and control Fiber Pre-Tension (FPT) and Fiber-Volume Ratio (FVR) through CNC fiber impregnation. These parameters are essential for process monitoring and quality control in composite manufacturing and have already been fully integrated in conventional FW. The corresponding investigations are detailed in Section 2.3 and contextualized through a cyber-physical application for large-scale RCFW, in Article C [7].

CPRCFW, is described through SO3 and SO4. A proof-of-concept composite element for long-span building applications was designed to assess the proposed computer numerical control(CNC) fabrication method. Verifying the complete design-to-fabrication methodology at 1:1 scale, included:

- Characterization of a suitable fiber layup;
- Force-feedback based fiber pre-tension control;
- CNC epoxy matrix dosing impregnation;
- CNC fabrication data acquisition;
- Quantitative numerical analysis of the acquired data sets.

This methodology represents a step towards the complete automation of ancillary operations in RCFW and is designed for:

- Downstream control: from design to fabrication;
- Upstream control: from fabrication to design.

Correspondingly, the included Article C[7] presents the methodology followed in the technical implementation and verification of the feedback-controlled fabrication method.

2.2 RCFW fabrication methods

2.2.1 Impact analysis of the fabrication parameters

The development of scalable RCFW methods includes scalable fabrication methods and upscaled prefabrication platform and tooling.

WM1 links with WM2 through the related research tasks 1.1 and 2.2. During research and development, task 2.1 was concomitant with task 1.1 (See 2.2).

Articles A [9] and B [8] elaborate on the integrative approach to computational design and fabrication methods and analyze the impact fabrication parameters have on the design space for RCFW. The component and building level at which research and analysis are conducted provide insights into the research and development process. In particular, Article B [8] outlines the selection process for a suitable morphology. This enables the construction architectural spaces out of a CFW composite building system the characteristics of which are mapped to a RCFW solution space. RCFW relies on the reciprocal deformation of free-spanning fibers [8; 138] to form-find a loadbearing fiber lattice.

2.2.2 Design and deployment of the robotic prefabrication platform

The parameters identified as crucial for upscaling and control of the production technology were:

- Enlarging the robotic work-envelope – defining the design and solution space (Fig. 2.2 and Fig. 2.3);
- Monitoring and control of FPT;
- Monitoring and control of FVR.

The Methods chapter of Article C [7] elaborates on the process monitoring and control concept and its specific implementation.

2.2.2.1 Seven-axis kinematic system

RCFW in construction utilize kinematic systems with multiple degrees of freedom(DOF). Usually, a 6-axis robotic manipulator is kinematically coupled with external positioners. The research of existing RCFW systems concluded that a new fabrication setup is needed to enable the prefabrication tubular building components at the scale and complexity required by an all-composite construction system. The methods sections of Article B [8] present the development process that led to the chosen morphological candidates and the RCFW setup. This setup is horizontally organized along the axis of the selected morphology and includes seven degrees of freedom (Fig. 2.2):

- 6-axis robotic manipulator with maximum robot-reach along the horizontal axis of 5 meters;
- Horizontal axis: 1-axis positioner and mechanically coupled counter bearing.

2.2.2.2 Tooling

Tooling for RCFW is composed of end-effectors mounted on different axes of the kinematic system. While the tool dispensing the fiber and the tool receiving the fiber can be interchangeably mounted on different axes, in this research the fiber delivery tool is mounted on the sixth axis of the robotic manipulator and the tool receiving the fiber is mounted on axes belonging to the external kinematic system. This research has adopted the following terminology to describe different types of RCFW tooling:

- Winding eye, for the tool dispensing the fiber (Fig. 2.11, 2.12);
- Winding scaffold, for the tool receiving the fiber (Fig. 2.4, 2.5);

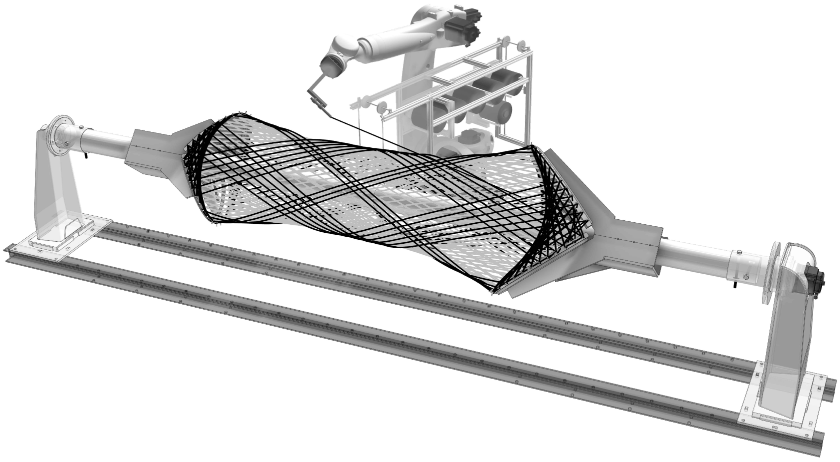


Figure 2.2: RCFW Digital simulation (in the Rhinoceros CAD software) of the implemented seven-axis kinematic system. © Serban Bodea.

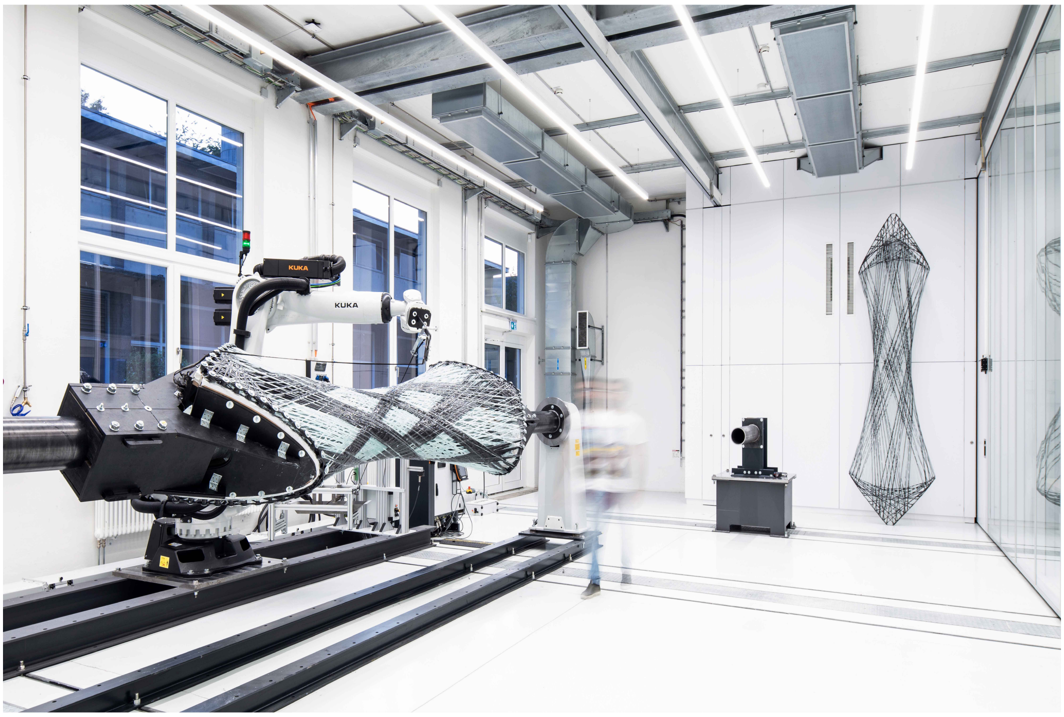


Figure 2.3: Physically-implemented RCFW system: seven-axis kinematic system with fully coreless-wound G/CFRP building component. ©ICD, University of Stuttgart.

Figure 2.4: Timber winding scaffolds for research and development. ©ICD, University of Stuttgart.

- Winding pins, for the modular elements mounted on the winding scaffolds that secure the fibers during RCFW (Fig. 2.7).

Nevertheless, we acknowledge that different authors in the available literature utilize different terminology to characterize similar tooling, reflecting the heterogeneous nature of research on RCFW [105; 100; 99; 77].

For example, articles A [9] and B [8] describe the development of winding scaffolds, first experimentally constructed in timber and subsequently re-designed in metal at FibR GmbH(Fig.2.5).

Generally, tooling that interacts with the composite layup avoids any sharp edges. Moreover, the winding eye was designed to guide the resin-impregnated fiber rovings around modular, metallic winding pins. The winding eye incorporated measures for quality control of the fabrication process: specially coated eyelets and rollers to protect the fibers from excessive friction. Additionally, the winding eye enables manual adjustment of its orientation according to prevailing fiber direction through rotational mounting system. Article B [8] elaborates on the mechanical construction, highlighting measures taken to control angles between the fiber bundle and the Tool Center Point (TCP), thus further reducing the risk of fibers being damages through friction.

The robot control technology was developed concomitant to the winding eye and

Figure 2.5: Steel winding scaffolds for industrial fabrication of the BUGA Fibre Pavilion by FibR GmbH. ©ICD, University of Stuttgart.

validated through kinematic simulations. The newly-developed control technology for RCFW is presented next.

2.2.3 Optimization of robot control technology: programming methods for adaptive RCFW

State of the art in offline robot programming for RCFW in construction are the methods developed for the prefabrication of the Elytra Filament Pavilion [99]. For the presented application, the industrial robot was programmed offline.

The robot control algorithm is organized as a modular 'Winding' class and programmed in Python, following an Object-Oriented Programming (OOP) procedure, inside the CAD Rhinoceros [107] and visual scripting tool Grasshopper [106; 19]. First, winding pin positions are input from a 3D design model. In the Winding class: each winding pin position is initialized as a class instance object. The reviewed state of the art presents this approach in the context of the ICD/ITKE Research Pavilion 2012 [105]. The presented research has adapted and extended the functionality of the existing computational design pipeline. Article B [8] and the section below describe the changes and improvements.

At initialization, the winding script assigns default positions and orientations

Component	Functionality
Winding class	Initialize winding pins
Winding frame	Assign winding pins to winding frames (geometric proximity checks)
Wrapping motion (catalogue)	Assign and adjust wrapping motions
Spanning motion	Interpolate spanning motion targets
External axis control	Compute and attribute external axis position to winding pins

Table 2.1: Robot control technology: custom scripts and algorithms developed for the implementation of the RCFW technology in construction (©Serban Bodea)

to every class instance in the motion planning process. The Winding class first initializes an ordered, hierarchical data structure containing all the coordinates of the winding pins. Subsequently, several algorithms modify the data structure2.6. The position and orientation of local target coordinate systems, representing the individual winding pins are procedurally assigned and evaluated. Table 2.1 presents the functionality of the bespoke components developed to fulfill different tasks in the RCFW algorithm.

Typically, the RCFW process with calibration of the physical setup and continues with data acquisition from the physical RCFW setup. At data acquisition, the 3D positions of the winding pins are manually surveyed by moving the TCP of the robot to a pin reference point and using the robot as a measuring instrument. Next, 3D orientations specific to the positions on the winding scaffolds are defined(Winding Scaffold Definition - Fig. 2.6). In a subsequent step, the pin data structure is either appended with fiber wrapping motion sequences (Wrapping Motion Assignment) or passed on to Spanning Motion Assignment (See Fig. 2.6 and 2.7). In the Spanning Motion Assignment step, the simulated fiber path extracted from the design model is split into discrete "fiber spanning positions". Article B [8] elaborates on the discretization motion control programming. The TCP reaches these positions without executing a fiber wrapping motion. The data structure containing the wrapping and spanning robotic targets is mapped to the working envelope industrial robot.

The External Axis Control stage calculates the rotation angle for the external axis(See Fig. 2.8). Here, a data structure for external axis control is created, and the two data structures are passed to the Winding Process Simulation node that correlates the target positions with the external axis rotations. The winding process is simulated using tools from "ICD Virtual Robot", a plugin for Inverse Kinematic and Forward Kinematic simulations and robot control developed at the ICD. At

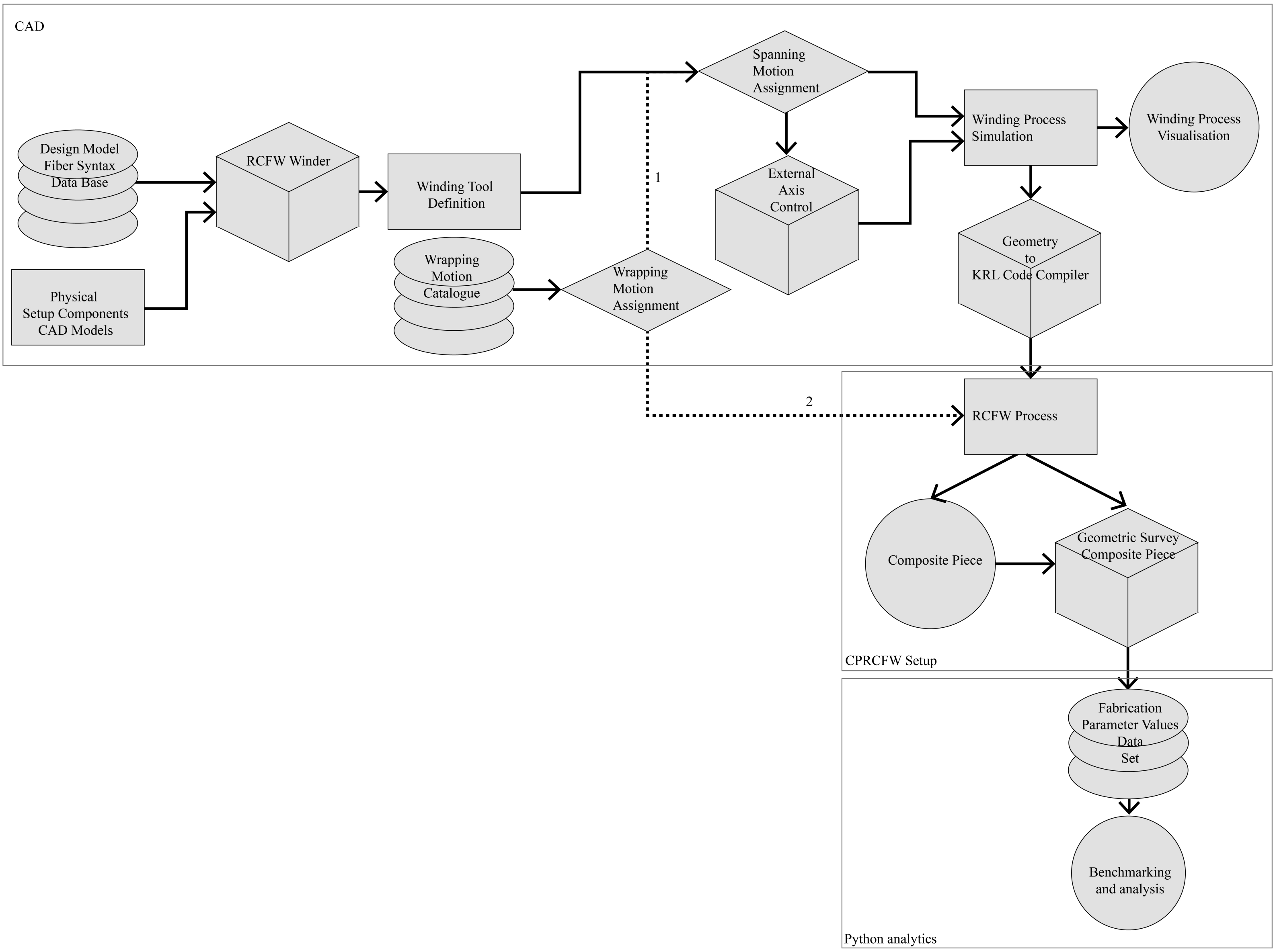


Figure 2.6: Robot control technology: logical scheme for motion planning, from input: geometry/design to output: fabrication data set and physical composite building component. ©Serban Bodea.

the External Axis Control stage (Fig. 2.8), both visual and quantitative checks are utilized to troubleshoot the robotic motion. These checks are individual axis monitoring for out-of-range and singularity situations. The complete data structure is compiled into a KUKA Robot Language module. In a recent development assigning the wrapping behavior has been added at the run-time step. If the wrapping behavior is assigned at this stage, a Wrapping motion function is invoked at run-time, and the fiber wrapping routine is executed.

After the winding is complete and the composite cured, a geometric benchmarking is performed: the composite piece is measured, utilizing the robot as a precision surveying tool. The acquired data is stored in a data structure and used to construct a 3D point cloud of the actual wound geometry. Article B describes [8] this effective benchmarking procedure in detail.

As mentioned above, newly-developed functionality enhances the motion planning algorithm; this additional functionality is presented next:

- Newly-developed winding and spanning sequences make robot control code more modular through:
  - o Dedicated, individually programmable fiber spanning sequences based on the simulated fiber trajectory;
  - o Adaptive wrapping sequences;
- An adaptive winding process allows fiber wrapping around pins positioned in normal orientation to the fiber lattice surface;
- Robot pose adaptability to the 3D fiber direction achieved automatically through geometric checks on the fiber direction.

Pin positions are first matched to inputs from the design models of individual geometries to wind. Orientations of the winding pin instances are procedurally assigned based on functional criteria derived from the fiber morphology.

Robot code modularity allows more flexibility for programming, faster troubleshooting, and reduced downtime. The need to wind highly complex elongated lattices is due to the design-engineering specifications of longspan construction of linear tubular elements joined in multi-planar nodes. Hence, a dedicated fiber spanning sequence was developed and adapted to GFRP and CFRP material specifications. Separately programmed winding sequences allow faster adjustment of the parameters that can be changed on the fly - Article B [8] and Chapter 3. The orientation of the winding pins is critical to achieving efficient load induction [49; 48]. Hence, the orientation of the pins was changed from tangent to normal to the fiber lattice. In turn, this required the development of winding

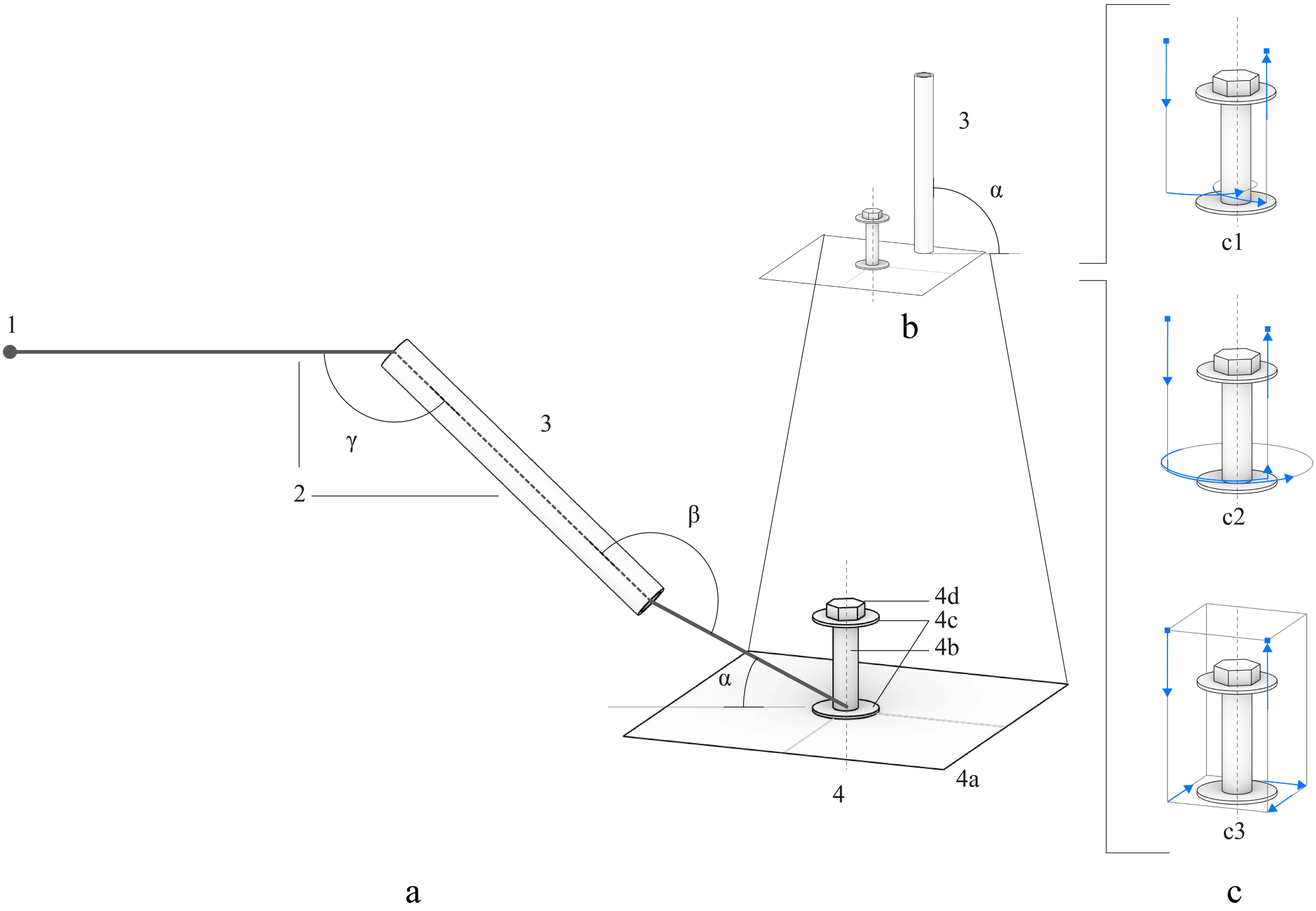


Figure 2.7: Adaptive RCFW: a. Position of the winding eye during fiber spanning motions, elements: 1. Fiber source, 2. Fiber bundle, 3. Winding eye direction, 4. Winding pin assemblage: 4a. winding pin infrastructure (winding scaffold), 4b. metallic spacer – will house the fiber bundle, 4c. metallic sleeves -holding the metallic spacer in place, 4d. metric bolt – fixing the winding pin on the winding scaffold; critical angles programmed: α – angle between fiber bundle and morphology to wind, value tends to 180°, β – angle between the winding eye direction and TCP-winding pin direction, γ – angle between the winding eye direction and the fiber source – winding eye direction; b. Position of the winding eye during fiber wrapping motions, critical angles programmed: α – angle between fiber bundle and morphology to wind, value tends to 90°; c. Fiber wrapping behavior catalogue: c1 – 'α wrapping motion': locks the fiber bundle around pin and prevents most slippage, c2 – circular motion: executes α wrapping motion twice, locking the fiber bundle and prevents all slippage, c3 – U wrapping motion: executes the simplest anchoring without locking the fiber bundle around the winding pin, thereby allowing slippage. ©Serban Bodea.

sequences that incorporate changes in orientation. An additional feature of the robot control technology is the adaptability of the robot pose in response to geometric input of the fiber orientations. As shown in the previous section and detailed in Article B [8] and Chapter 4, the robot pose is procedurally coordinated with the 3D orientation of the fiber bundle currently being wound. Figures 2.7 and 2.8 illustrate the parameters utilized in the winding eye direction control.

Winding eye orientation represents an essential link between design and manufacturing. It is incorporated in a computational method to program an adaptive tool path based on a simulation of the fiber deformation and trajectory during the winding process.

2.2.4 Digital loop: manufacturing – design – manufacturing

A prerequisite for competitive lightweight construction through RCFW is the seamless communication between the involved design-to-production disciplines. This section which focuses on fabrication and design integration lays the basis for adaptive online control of the production process directly from an enhanced design model.

The computational design space was constructed around physical parameters derived from the prefabrication platform to enable online control of the adaptive manufacturing process. Furthermore, geometric data from simulated fiber paths are used for robot-path generation. Figure 2.8 illustrates the parameters utilized to control both geometric and fabrication specifications.

2.2.4.1 Process monitoring and quality control

The upscaling of the additive manufacturing process incorporates scaling effects and material properties into process control. Article B [8] presents the results of the upscaling at building component scale and subsequently in the context of an industrial fabrication process[8].

2.2.5 Industrial fabrication method

The transition from an experimental fabrication process to an industrial process meant developing a modular fabrication environment that has the flexibility to produce series of identical components that rationalize a larger structure, with the ultimate intention to reach "series 0" production capability. Article B [8] describes the transition from a lab-based experimental process to the factory floor, the process timeframes, and the practical steps involved. As shown therein, the the integration

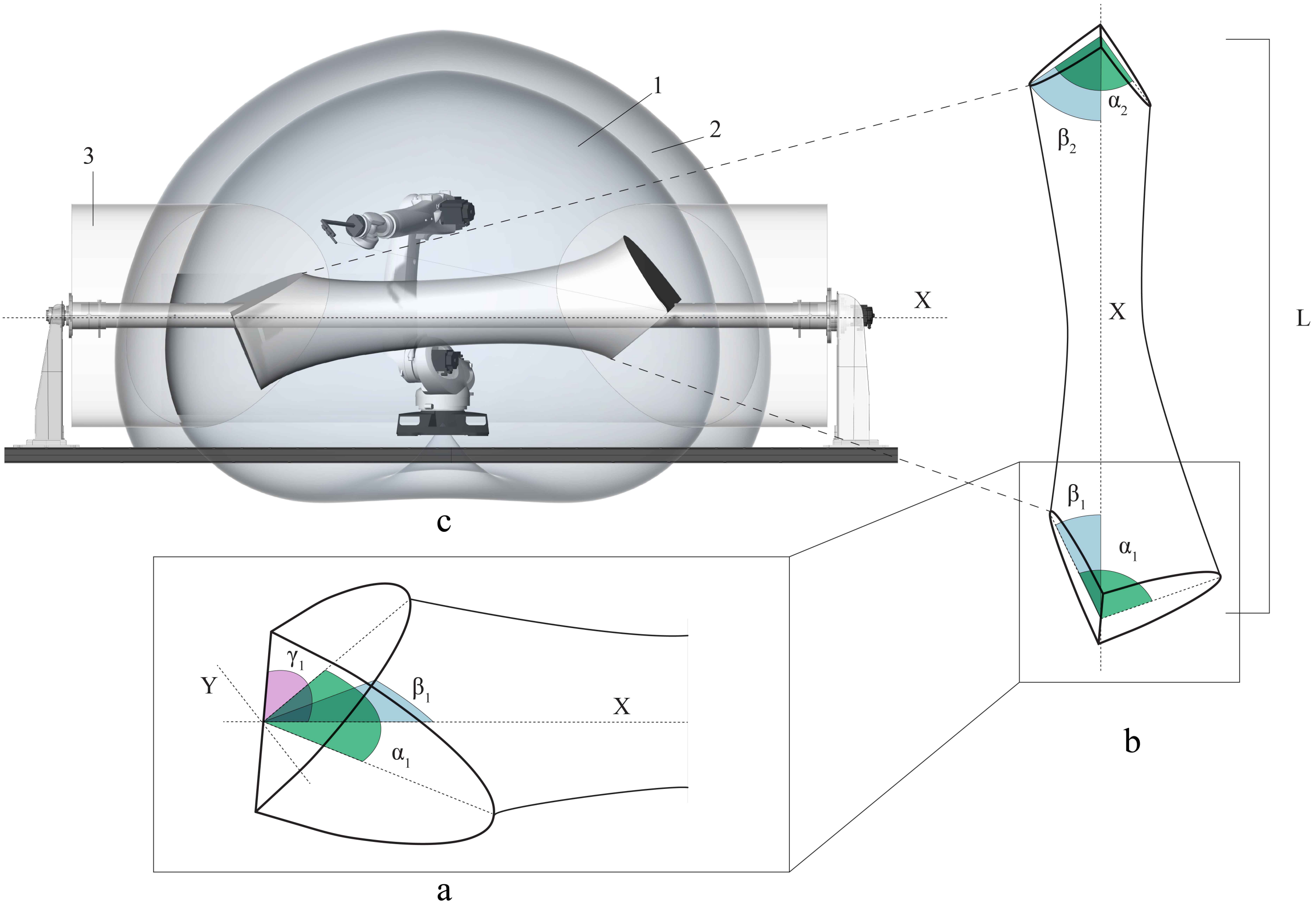


Figure 2.8: Parametric model showing the interrelation manufacturing – morphology to wind – manufacturing: the parameters of an initial design space are converted into a fabrication solution space and leading to the development of modular tooling and adaptable robot motion planning; a. fabrication solution space configuration: 1. Industrial robot motion range without winding eye, 2. Industrial robot motion range with winding eye, 3. Rotational positioner motion range; b. c. design parameters mapped to robot solution space through winding scaffold design: X - rotational axis of the RCFW setup, Y- transversal axis Y of one winding scaffold, α – angles of the winding scaffold, β – angles between axis X and one winding scaffold component, γ – angle between axis Y of one winding scaffold and axis X, L – length of morphology to RCFW. ©Serban Bodea.

of the computational design method and the procedural fabrication method was key to an efficient, seamless data transfer [138] to the industrial partner. As introduced in the tooling section of this chapter , modular generic and robust designs were preferred to ensure robustness and reuse of the equipment. Its functionality was geared towards robustness, reuse, and geometric adaptability to produce the maximum morphological variation using the minimum, reusable tool-set.

Practically, the technology transfer was carried out in a series of tests aimed at validating the research and development of the RCFW through full-scale demonstrators of all the component typologies required by the design. These tests embodied building components' complete structural morphological and aesthetic characterization, individually adapted inside a newly developed long-span composite building system.

Articles A [9] and B [8] explain the extent to which the proposed industrial application achieved analogue process monitoring and quality control.

2.3 Cyber-physical production system for CFW

Essential for an efficient and scalable AM method is a higher degree of automation. As previously shown in Sections 1.3 and 2.2, the motion planning methods for RCFW enable quasi-complete automation of the robot motion. However, the existing methods hardly address the challenges of an adaptive fabrication process, one that can operate automatically with minimal human interference. Importantly, automated fabrication data acquisition is missing, limiting the application range of RCFW. Such a fabrication method requires automation beyond that of file-to-factory applications. Hence, the scope of the presented research was extended to automate online control and monitoring of essential fabrication parameters identified as FPT control and FVR for the G/CFRP material system. Article C [7] illustrates the technological features that enabled automatic data acquisition and analysis.

2.3.1 Cyber-physical RCFW setup characterization

This Dissertation synthetically presented the RCFW methods experimentally developed at the University of Stuttgart. Subsequently these methods were adapted and deployed into an industrial fabrication process (Section 3.1). Nevertheless, the research and development on RCFW continued in a subsequent research phase of cyber-physical system development (Figure 2.2 , WM 3). Within the scope of this dissertation WM 3 and WM 1 are interrelated by research tasks 3.1 and task 1.2.

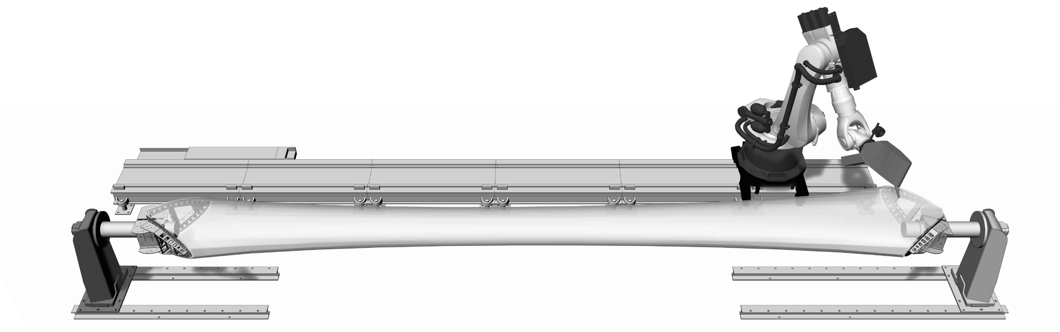


Figure 2.9: CPRCFW Digital simulation: nine-axis kinematic system. ©Serban Bodea.

2.3.1.1 Nine-axis kinematic system

The first aims of the research were to identify the upper upscaling limit for an RCFW fabrication setup and further automate the process. The first working assumption was that a nine-axis kinematic system would be sufficient for automatically winding composite elements double in length compared to those achieved by the previously introduced industrial application. Thus, the necessary degrees of freedom necessary ware defined as a summation of the kinematic capacity of an industrial robot arm and two additional essential solution-space requirements:

- A work envelope of 10 meters in length;
- The need to precisely manipulate two winding scaffolds spaced 10 meters apart.

The corresponding setup (Fig. 2.9 and Fig. 2.10) was developed at the University of Stuttgart's ICD Computation and Construction Laboratory and was equipped with:

- A 6-axis robotic manipulator;
- A 1-axis, 12-meter linear track.

Additional tooling was acquired and integrated:

- The horizontal axis positioners, kinematically-coupled:
  o 1-axis primary positioner;
  o 1-axis secondary positioner;

The maximum robot-reach along the horizontal axis, 15 meters, serves the key geometric characteristic of the composite elements under study, their scalabilty along one axis.

2.3.2 Fiber impregnation technology and adaptable production tools

Developing adaptable fiber-volume ratio methods demanded close coordination between several subsystems:

Figure 2.10: CPRCFW nine-axis kinematic system with 9-meter long component. ©ICD, University of Stuttgart.

- The fiber source subsystems for GF and CF;
- The resin dispenser subsystem;
- The fiber-impregnation subsystem.

A larger kinematic solution space demands updated solutions for storing the fiber material and the epoxy resin system on and around a track-mounted industrial robot.

The task of selecting and designing suitable mechanical components was entrusted to a partner Institute on the University of Stuttgart. However, the coordination of the implemented sub-systems, their integration into the robotic manipulator, as well as the design, integration, and programming of the sensor systems were developed by the author within the scope of this thesis.

2.3.3 Development of an integrated sensor system for RCFW

As we have seen, RCFW is an AM process by which resin-impregnated fiber rovings are wrapped around winding pins. Moreover, the technology relies on minimal support structures and near-total elimination of moulds. Consequently, the fiber rovings span freely and are guided in position to create fiber layups that can withstand structural loads once cured. The structural and aesthetic tailoring of the fibers is the object of computational winding syntax design based on the definition of geodesics on target surfaces. The computational procedure that stands at the basis of the designs was first described by Zechmeister et al. [138].

The RCFW process revolves around the precise deposition of fiber bundles. The development was organized in two development iterations:

- A single-function fiber-winding eye (Fig. 2.11);
- A multipurpose fiber winding eye (Fig. 2.12).

The main advantage of the RCFW approach is that fibrous material can theoretically be continuously spanned between winding pins until the necessary material amount is reached. This advantage ensures fiber continuity without the need for offcuts or interruptions. Consequently, the mechanical devices that execute the correct guiding and deposition of the fibrous material must be compactly organized around and onto the industrial robot. The arm then pulls the fiber roving to the winding pins of the winding scaffold.

Articles B [8] and C [7] elaborate on the compact nature of the newly developed fabrication setup. Article B [8] describes a file-to factory automation approach that relies on the automation of the winding operation only. Article C [7] the assumption that a more efficient RCFW is only possible through the implementation of an automated strategy for process monitoring and quality control implemented through

Figure 2.11: Single-purpose winding eye: fiber guiding. ©ICD, University of Stuttgart.

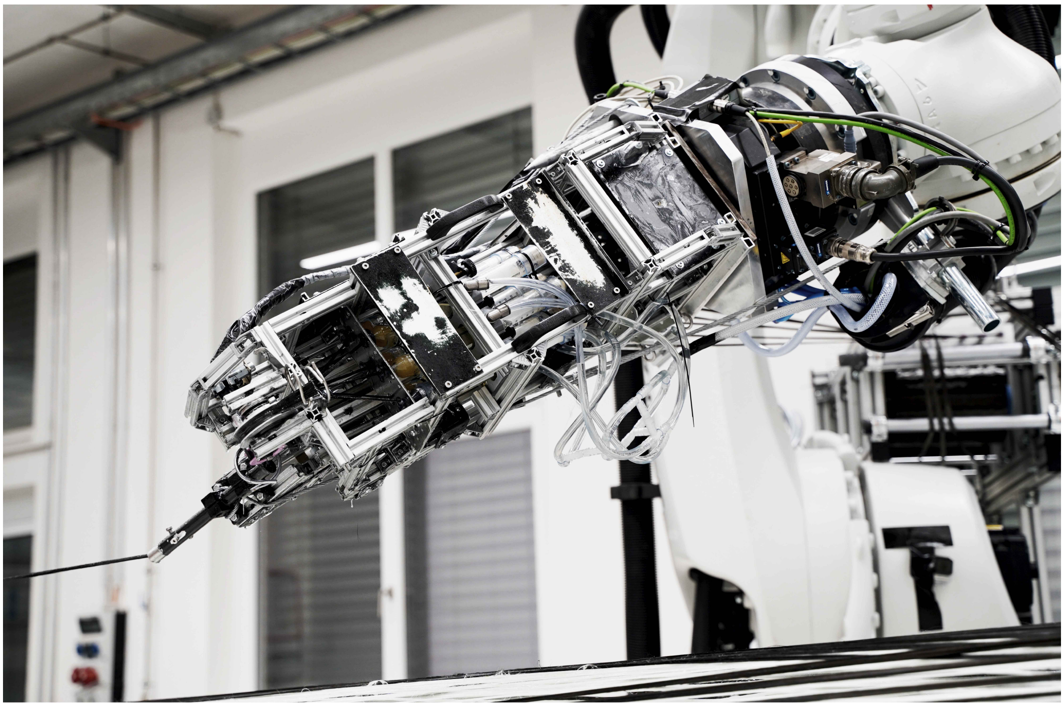


Figure 2.12: Multi-purpose winding eye: fiber guiding, fiber impregnation, winding tension monitoring, and control. ©ICD, University of Stuttgart.

a cyber-physical industrial robotics system. Winding tension directly impacting the amount of pre-tension induced over the entire structure. Fiber impregnation with epoxy resin is defined as the FVR. These elements are characterized from a mechanical engineering and material science perspective by Mindermann et al. [84].

RCFW relies on the physical manipulation of anisotropic material under controlled pre-tension [84]. Hence, the presented research and development focused on controlling the robot velocity measured at the TCP. In industrial robotics, kinematics control and robot velocity control are fundamental robot programming parameters. While precise kinematics control of the robot arm in winding operations is known from state-of-the-art presented in Bodea et al. [8], sensor-informed velocity control had not yet been implemented. This Dissertation identifies the importance of sensor-informed velocity control. It postulates that a tension sensor positioned in contact with the fiber bundle in proximity to the TCP can successfully control winding tension, help calibrate the optimal fiber impregnation degree, and control robot velocity through a series of interdependent feedback loops for FPT control and FVR dosing.

2.3.3.1 Winding tension control

Winding tension is a parameter that directly impacts the fabrication of the planned morphology. Both GF and CF have low elongation coefficients and high tensile strength. Hence the fabrication process aims to control the amount of tension while winding as a measure of informing formfinding of the fibre lattice through dynamic relaxation. The integrated pretension mechanism implemented in the setup is pictured in Figure 2.13. It is horizontally mounted, directly above the CF creel (Article C [7]). Since the fiber handling system is friction-based, the evaluation point for fiber pre-tension has been chosen immediately before the fiber leaves the winding tool, at the winding eye. A calibrated tension sensor controls the robot velocity in an internal negative feedback loop. The device chosen as well as the methodology to control and evaluate the FPT are described in Article C [7].

2.3.3.2 Robot velocity control

Sensor guided motion is well established in industrial robot programming [73]. For the presented application, the tension sensor controls the robot motion by overriding a pre-programmed velocity value, proportionately to a registered FPT value. Three robot velocity override domains were experimentally determined to be sufficient for velocity control. Target robot velocity values were assigned online depending on

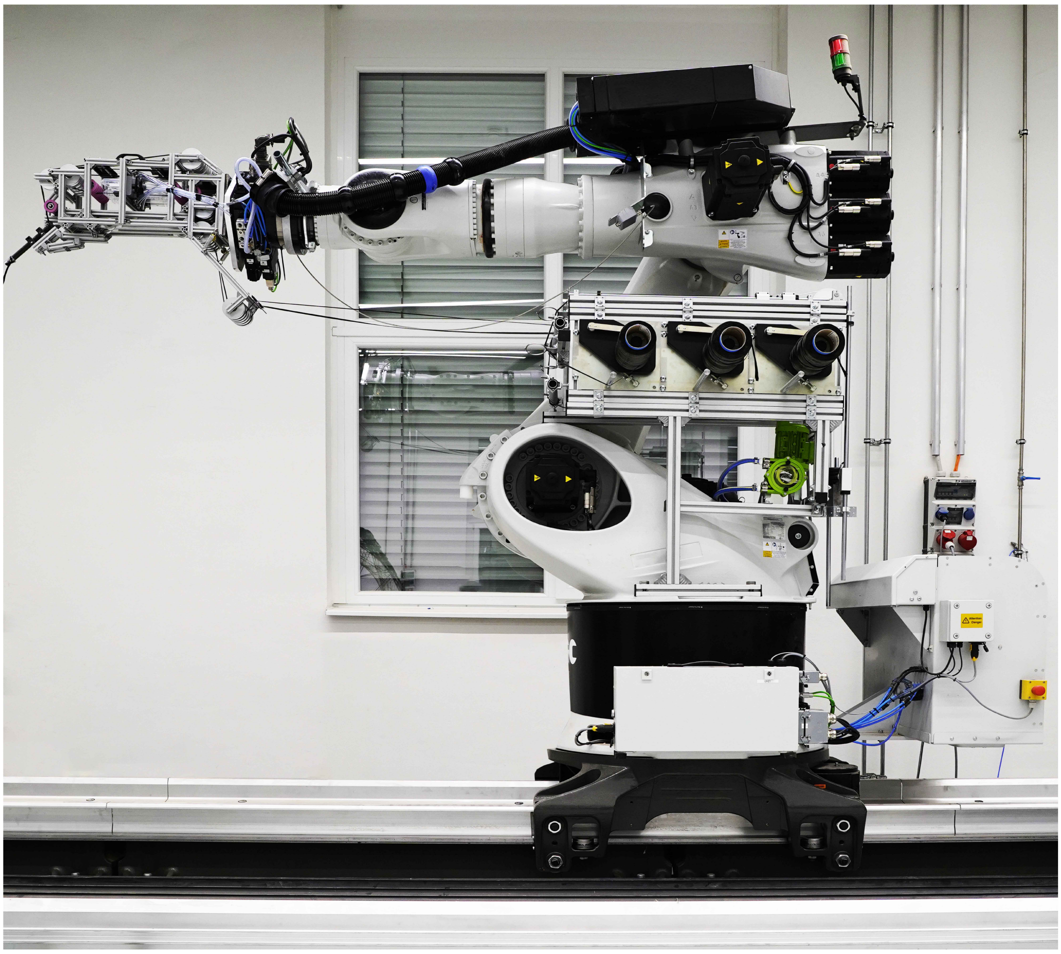


Figure 2.13: Physical implementation of the Cyber-Physical Robotic Coreless Filament Winding (CPRCFW) system consisting of industrial robot kinematic system, automated fiber guidance, winding tension control, and fiber impregnation. ©ICD, University of Stuttgart.

winding tension settings, dynamically mapped to “high,” “medium,” or “low” experimentally determined intervals. These domains were dependent on the geometric characteristics(i.e. amount of curvature of the simulated lattice) of the winding path (i.e., wrapping or traveling) or within allowable domains given the GF or CF material. In turn, the adjusted robot TCP velocity controls the automatic FVR.

2.3.3.3 Automatic fiber impregnation

A genuine composite industry emerged in the 1940s. Since then, industrial automation has included design evaluation and the fabrication process. Article B [8] illustrates different automated applications of CFW in the industry and in construction tracking the appropriation automation technology , in particular industrial robotics. The robot arm itself is a cyber-physical system that integrates and controls the physical components of a robotic manipulator through a numerically controlled and programmable system; the robot controller is a computer with dedicated software from the robot manufacturer. However, the industrial robot may be utilized as a CNC machine that executes a pre-programmed operations, with no feedback from the fabricated piece. Thus, for the purpose of proposing an industrial process for RCFW, the research scope has been limited to offline automation illustrated in Article B [8].

Article C [7] discusses the RCFW fabrication methods based on FPT and FVR evaluation and control as forming an integrated cyber-physical production method. Together with the physical elements of the system, integration and control were identified as essential constituents of cyber-physical production systems and represented a significant part of research and development. On the one hand, automation and digitalization increase autonomy and flexibility, but on the other hand imply harder engineering challenges and additional precision. The same source, also illustrates how the domains for digital control of the Rotations Per Minute (RPM) of a peristaltic pump were calculated, considering the volume of an impregnation chamber and a given TCP velocity [74]. A peristaltic pump was chosen because the thermoset epoxy resin should not contact the pump‘s mechanism (See Fig. 2.13). The resin can thus be precisely dosed to the impregnation system through a supply tube connected directly to the epoxy supply through the pump.

Thus, the proposed CPRCFW system integrates the essential cyber-physical components to establish a feedback loop between the material system / fabricated composite lattice and the robot manipulator. The platform utilized for the programming and monitoring bespoke kinematic systems was KUKA WorkVisual

[72]. Each physical device is associated with a programmable logic controller(PLC) and programmed through dedicated KRL modules(.src) written and calibrated by user-defined parameters stored in dedicated data files(.dat).

2.3.4 Adaptive robot control technology

The motion control module is programmed offline by a "Winder" class where every robot motion target is either a "winding" or "travel" winding instance. Article C [7] provides a detailed description of the modular programming method utilized in CPRCFW, highlighting the structure of the robot code. Particularly important for the application is the calibration and integration of the tension sensor, a radial strain gauge commonly utilized by the FW industry. Every RCFW control module performs two initialization functions related to the cyber-physical system: enabling; disabling; initializing a multidimensional fabrication data set and appending fabrication data.

Section 2.2.3, has illustrated an additional control procedure developed for the control of the external kinematic system. For the application presented in Article C [7], separate procedures were developed to calibrate, align, and control the two horizontal axes(robotic positioners) corresponding to the two different winding scaffolds. Each axis was thus calibrated individually and fed separate set of robotic targets. Finally, a KRL text editor programmed in Python [103; 95] parsed all the data streams into a motion module executable by the robot controller. For the multidimensional data set signals coming from the force sensor and pump were transmitted through wired connections to dedicated PLCs, an amplifier box for the sensor and a control cabinet for the pump and subsequently transmitted to the robot controller via an experimental control device developed by the technology integrator at the ICD Computation and Construction Laboratory.

2.3.5 Process monitoring and quality control

The CPRCFW system can be operated manually or automatically. Manual mode was used for testing and calibration, while automatic operation was verified the proof-of-concept G/CFRP demonstrator.

2.3.5.1 Fabrication data acquisition

During the process, industrial manipulator data and fabrication data, specific to the handling of the G/CFRP system, were automatically recorded aggregated. FPT data is of particular interest for RCFW since this parameter was sensor-controlled during the CPRCFW operation. FPT data is recorded in an analog format as a float number. It is then converted to Newtons equivalent and recorded as a one-dimensional array. First, the robot velocity is adjusted in negative feedback with the force-sensor. Then the robot velocity value is remapped to three experimentally-determined pump-frequency values. Article C [6] explains that programming the pump for a target frequency is more efficient than mapping robot speeds to frequency domains. This decision was motivated by latency inherent to the mechanical system. Given that the robot arm is in motion and acceleration/deceleration, inertia of the fluid plays a role for the correct functioning of the impregnation system. Thus the flow rate must be allowed to stabilize. It has been experimentally determined that such stabilization occurs faster and more reliably if flow rates are mapped to several pre-defined domains.

2.3.5.2 Fabrication data set

The CPRCFW data set is a text(.txt) file temporarily stored in the robot controller memory and subsequently added to a CPRCFW database. A new data point is recorded every 500 ms and appended. The parameters stored for every data point are:

- Robot velocity;
- Force sensor value;
- Pump flow rate.

A raw data sample recorded during fabrication is presented in Table 2.2. The recorded data can be used in online or offline system monitoring or inform CPRCFW simulation processes. Both purposes require a pre-processing methodology, including data filtering, calibration, and normalization steps. Article C [7] provides an overview of data pre-processing steps and the following section elaborates on the methodology.

A bespoke data pre-processing module was developed using analytical tools in Python. This module functions as a stand-alone extendable script that reads, processes, and visualizes the data analyses.

First, the dataset is filtered to exclude prolonged periods of downtime (robot velocity is 0.00). The filter acts on the robot velocity part of the data set and simultaneously excludes the associated force sensor and pump frequency values. These are not discarded but stored in a downtime dataset. These signify hardware or software faults. In a subsequent step, tension sensor values are amplified by direct multiplication with an analytically deduced and experimentally verified sensitivity coefficient - 819.175, to quantify the physical orientation of the sensor. The tension

Data Point	**Robot Velocity (mm/s)**	**Tension (N)**	**Pump Flow Rate (ml/min)**
0	172.0	8.05	120
20	34.4	3.90	1.92
40	103.2	7.88	189.6
60	156.3	9.10	169.3
80	156.0	11.44	156.8
100	155.0	10.45	149.7
120	156.3	8.14	167.4

Table 2.2: Sample of the CPRCFW raw data set; Data Point entry corresponds to the raw values indicated as normalized values Table 2.3 in Figure 2.14 . ©Serban Bodea.

sensor values were converted to newtons.

In a different preprocessing step, the flow rate (F)(Eq. 2.2) can be calculated from the recorded pump frequency(f) and the system volume(k) (Eq. 2.1):

$$f = \frac{F}{k} \tag{2.1}$$

$$\begin{cases} \left(v(g/m)\right) / \left((3\rho)\right), & \text{if } v < 0.06 \\ \left(2\,(g/s)\right) / \rho, & \text{if } 0.06 \leqslant v \leqslant 0.12 \\ \left(\left((g/m)\left((3v/8) - 2.5(m/s)\right)\right)\right) / \rho, & \text{if } 0.12 < v < 0.2 \\ \left(5(g/s)\right) / \rho, & \text{if } v \geqslant 0.2 \end{cases} \tag{2.2}$$

f = pump frequency (Hz);
k = 0.779 (cm^3);
F = flow rate (cm^3/s);
ρ = density of the resin (g / cm^3);
v = TCP velocity (m / s).

Tension sensor data, robot velocity at TCP data, and flow rate data are normalized by remapping the values from their respective units of measurement to the domain [0,1]. The digital filter Savitzky–Golay [110] (data range 51, polynomial order 2) is applied to the data to increase the precision of the data points. The use uf this digital tool does not affect the signal tendency. Thus, patterns in the functionality of the different components can be identified by direct data correlation (Table 2.3).

Data Point	**Robot Velocity**	**Tension**	**Pump Flow Rate**
	normalized	**normalized**	**normalized**
0	0.951	0.625	0.646
20	0.013	0.001	0.0
40	0.647	0.583	0.988
60	0.909	0.703	0.882
80	0.907	0.94	0.817
100	0.904	0.913	0.78
120	0.909	0.992	0.872

Table 2.3: Sample of the CPRCFW pre-processed data set; Data Point entry corresponds to the position indicated in Figure 2.14. ©Serban Bodea.

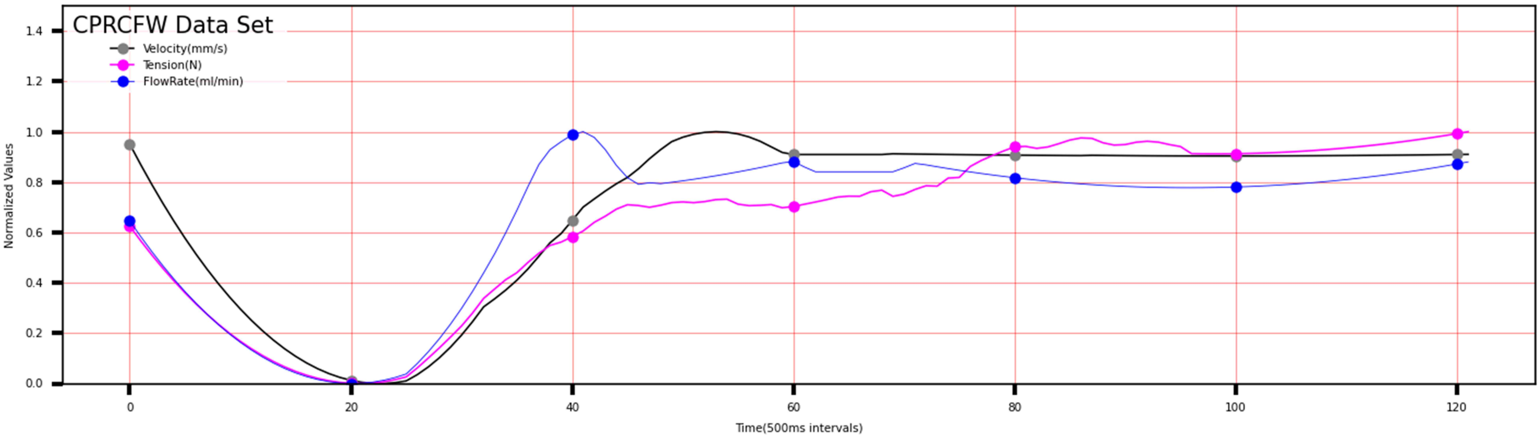


Figure 2.14: Process monitoring and visualization of the CPRCFW preprocessed fabrication data set correlated with Table 2.2. ©Serban Bodea.

The fabrication data set is visualized in a subsequent step, similar to the visualization of the data sample in (Table 2.3) automatically generated from raw fabrication data(Table 2.2). The visualization of this data sample is presented in Figure 2.14 as an exemplification of the developed methodology. The pre-processed velocity, tension, and flowrate arrays are simultaneously plotted to highlight correlations and identify the impact of the epoxy impregnation and kinematic system on the final composite structure. This automated system represents the foundation of automated process monitoring, steering, and composite quality control for RCFW.

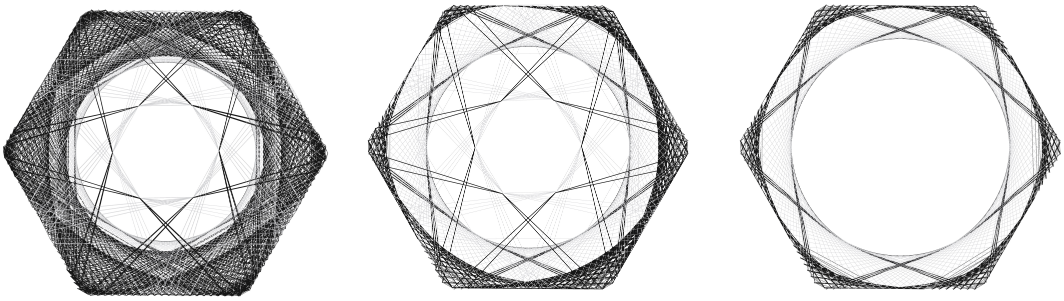
3

Results and Discussion

3.1 Industry-ready RCFW

Each of the Dissertation aims was organized as a set of interdisciplinary task. The contributing disciplines were architecture and building technology, computational design, digital fabrication, mechanical engineering and industrial robotics, and material science. For the presented work, computational design and digital fabrication are the main areas of expertise of the author which allowed this research domain to take the leading role in the framing the necessary breath and c=scope of the investigations and coordination of the necessary technology development. As a result, each of the main aims of the Dissertation was accomplished, mainly addressing two levels. First, RCFW prefabrication setups were designed and implemented physically for both upscale and advanced automation. Secondly, each fabrication method component was verified through the prefabrication of a 1:1 scale demonstrator.

Work Module 4 is a conduit for the the dissemination of experimental results and technological and methodological insights. Research dissemination was realized through a publication plan resulting in several scientific publications included in this Cumulative Dissertation. The same module synthesizes the research and development output of Work Module 1 through research tasks 1.1, 1.2 and 3.1. Upscaling the robotic fabrication methods is contextualized in applications at component and building scale, realised through task 3.1. In collaboration with the industry, the resulting state of technology for RCFW yielded high precision building components. Figure 3.1 illustrates surface-like(slab) building elements and Figure 3.2 beam-like(tubular) elements. The surface-like elements were the typology util-



C25_Small Aperture
0.H,1.H,2.H,3.H,4.H,5.H
Fibers Length 3.06 km, 65 kg

C32_Medium Aperture
0.M, 1.M, 2.S, 3. L, 4.M, 5.L
Fibers Length 1.97 km, 42 kg

C13_Large Aperture
0.L,1.L,2.L,3.S,4.S,5.M
Fibers Length 1.64 km, 35 kg

Figure 3.1: Surface-like building components, precursor to the research presented in the current Dissertation. ©ICD, University of Stuttgart [99].

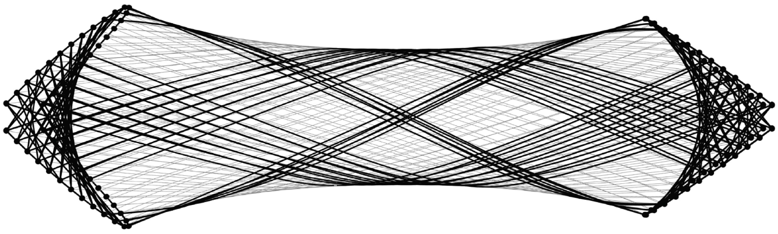


Figure 3.2: Rod-like building component typology, part of the research presented in the current Dissertation. ©ICD, University of Stuttgart.

ized in the ICD/ITKE Research Pavilion 2013-14 [100] and in the Elytra Filament Pavilion [99]. This component type and building system was conceptualized at the ICD and ITKE prior to the start of the presented research. From a fabrication point of view, their main advantages were: ease of production and versatility. Through the process, a wide variety of polygonal shapes could constitute the elements' boundary conditions, the fabrication process requiring minimal and off-the-shelf production equipment.

The two research pavilions referenced above constitute the demonstrators of the surface-like component segmentation approach. The first research pavilion illustrates a building system relying on individually-shaped building components with tailor-made fiber arrangements that make up a segmented grid-shell [100]. The Elytra Filament Pavilion illustrates the use of components with identical boundary conditions. Here, the fiber layout is designed to meet multiple engineering constraints and loading conditions along the column-supported canopy. However, we argue that the application of surface-like elements in long-span application is limited. They rely on a high number of winding pins, along their entire perimeter and their scalability is largely dependent on the work-envelopes of industrial robots. Importantly, the need to develop beam-like(tubular) building elements emerged because of these limitations. Thus, tubular composite elements were conceptually presented by ICD and ITKE researchers prior to the presented research [99; 100]. Initial designs for these components entailed a further discretization of the polygonal boundaries of the previous elements into individual coreless-wound elements. The advantages envisaged were manifold: linear scalability of the elements (larger spans), reduced winding and connection points between elements (simpler fabrication), more efficient storage and transportation of long and slender components. Important for this research is to clarify that the detailed design of such elements, initiated at the ICD and ITKE in the interdisciplinary research context of the BUGA Fibre Pavilion represents an integral part of the presented Dissertation.

This contextualization allows us to define the specific contributions of the presented research on two levels :

- development and conceptualization of the tubular building component from an architectural and building system standpoint
- development and experimental demonstration of a novel RCFW production method, tailored to the new architectural and building system specifications

These developments were highly consequential for the related processes of detailed design, industrial fabrication, and structural verification at component and system scale. At the fabrication method level, our specific contribution is defined by the development of the production process driven by process and component scalability and automation requirements. As a result of interdisciplinary research led by the architecture discipline, the suitable geometry of tubular element candidates were defined, complete prototypes were RCFW and tested. The design-engineering-fabrication development included the component-to-component connection that triggered significant changes in existing RCFW methods.

The main contribution is a novel winding procedure where the winding eye TCP wraps winding pins normal to the component's surface (Fig. 2.7). This eliminates unwanted fiber discontinuities that previously limited load-induction and load transmission. Another specific contribution is the implementation of an ample robotic movement and specific robotic motion control methods to mitigate kinematic singularities (Fig. 2.8). These developments were conducted in direct correlation with design engineering developments in response to the components' length and significant loadbearing requirements. The resulting RCFW methods are presented in detail in Article B [8]. Further developments to the fabrication system are the introduction of a robotic linear track and sensor system which are presented in detail in Article C [7]. Another major contribution was a novel method to allow winding a predefined number of circuits around the components' circumference. In previous RCFW implementations [99; 100] winding syntax was conceived as 1st degree polyline where each polyline vertex corresponded to a winding pin. In other words, the path that a single fiber takes between winding pins emerges from the position of the pins and the incremental deformation of the free-spanning fiber bundle. In the presented RCFW approach, detailed in Article B [8], the fiber path between winding pins is precisely controlled by means of "travel points" constructed from the provided fiber syntax at a specific offsets from the target surface of the composite element. This innovation in defining the robot travel path was key towards the successful implementation of the tubular component typology. Through the combination of form-finding through dynamic relaxation and simulation enabled by the presented fabrication method it was possible to design a fiber winding syntax closely tailored to component surface characteristics. Hence, component surfaces with lower curvature were reinforced by latices of CF reinforcement (Fig. 3.3 and 3.4). This led to the distinctive aesthetics so clearly expressed in the BUGA Fibre Pavilion structural elements. Here, even the casual observer can clearly identify the force flows both at component and at building system level.

Article B [8] presents a detailed analysis of the data recorded during the fabrication process. The publication concludes that significant productivity gains are possible through the industrialization of RCFW. Indeed, the winding process itself was successfully automated. Presently, there is a positive correlation between fabrication time and geometric complexity. However, it is expected that with increased automation, the prevailing aspect to influence fabrication time will become the physical length of the path covered by the robot while winding. In other words, the length of the wound fiber should be the dominant factor influencing fabrication time. When that happens, "Series 0" production becomes feasible at no economic disadvantage compared to serialized production.

The industrial fabrication of the load-bearing structure of the BUGA Fiber Pavilion (Fig. 3.5) translates the innovation on a technical level into a unique technological process tailored to material specifications of advanced composites at construction scale. The RCFW application was developed for industry readiness in a compressed time frame, highlighting merging goals, milestones, and constraints between scientific research and industry-driven development. Thus, Article B [8] discusses the development required for a wide-ranging industrial application. It identifies

Figure 3.3: Steps of the RCFW process: a. winding tool preparation and calibration; b. RCFW of GF elastic lost mold/liner; c. Incremental reinforcement of the GF elastic mold/liner with CF rovings; d. Scanning/surveying the final RCFW G/CFRP building component for quality control. (©ICD, University of Stuttgart)

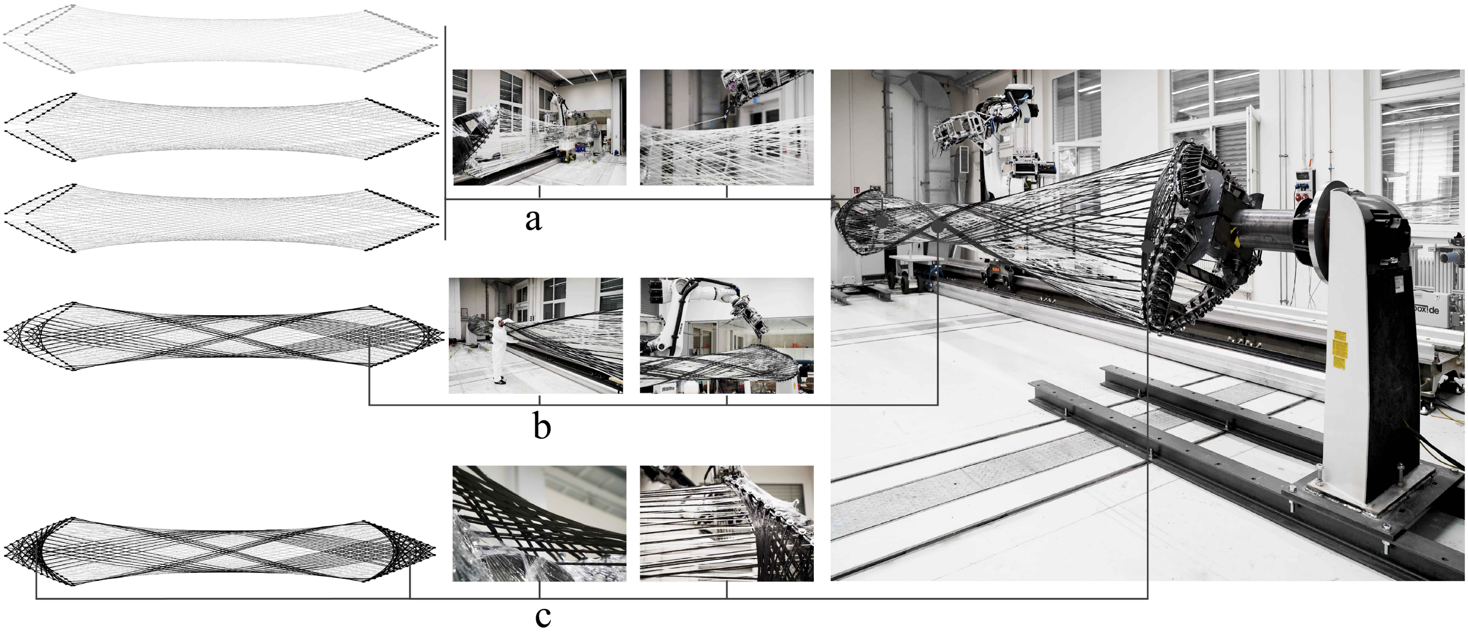


Figure 3.4: Steps of the CPRCFW process: a. CPRCFW of GF elastic lost mold/liner in full automated mode; b. Fully automated incremental reinforcement of the GF elastic mold/liner with CF rovings; c. Fully automated incremental reinforcement component boundary conditions by means of bespoke fiber syntaxes in CF. ©Serban Bodea.

the potential for all ancillary operations: winding eye, assembly, calibration, automated mixing of the resin system components, and online process monitoring to be automated. However, particular emphasis is placed on monitoring and controlling winding pre-tension(FPT) and on automated fiber impregnation(through automatic FVR control).

3.2 Cyber-physical RCFW

Work Module 3 and Work Module 4 are interrelated through tasks 3.1 and 3.4 and corresponding task 4.2 and 4.3, highlighted in the research plan. The important goal of upscaling the robotic fabrication methods is realized at component-scale applications, reported on by task 3.2.

The presented prefabrication method (Section 2.3), postulates that the two parameters essential for process monitoring and quality control are FPT and FVR. Thus, a fabrication methodology to link these parameters, termed Cyber-Physical Robotic Coreless Filament Winding(CPRCFW), was developed, implemented, and verified at 1:1 scale through a large-scale demonstrator. At the beginning of the research, it was postulated that the enhanced fabrication methods could expand previously-

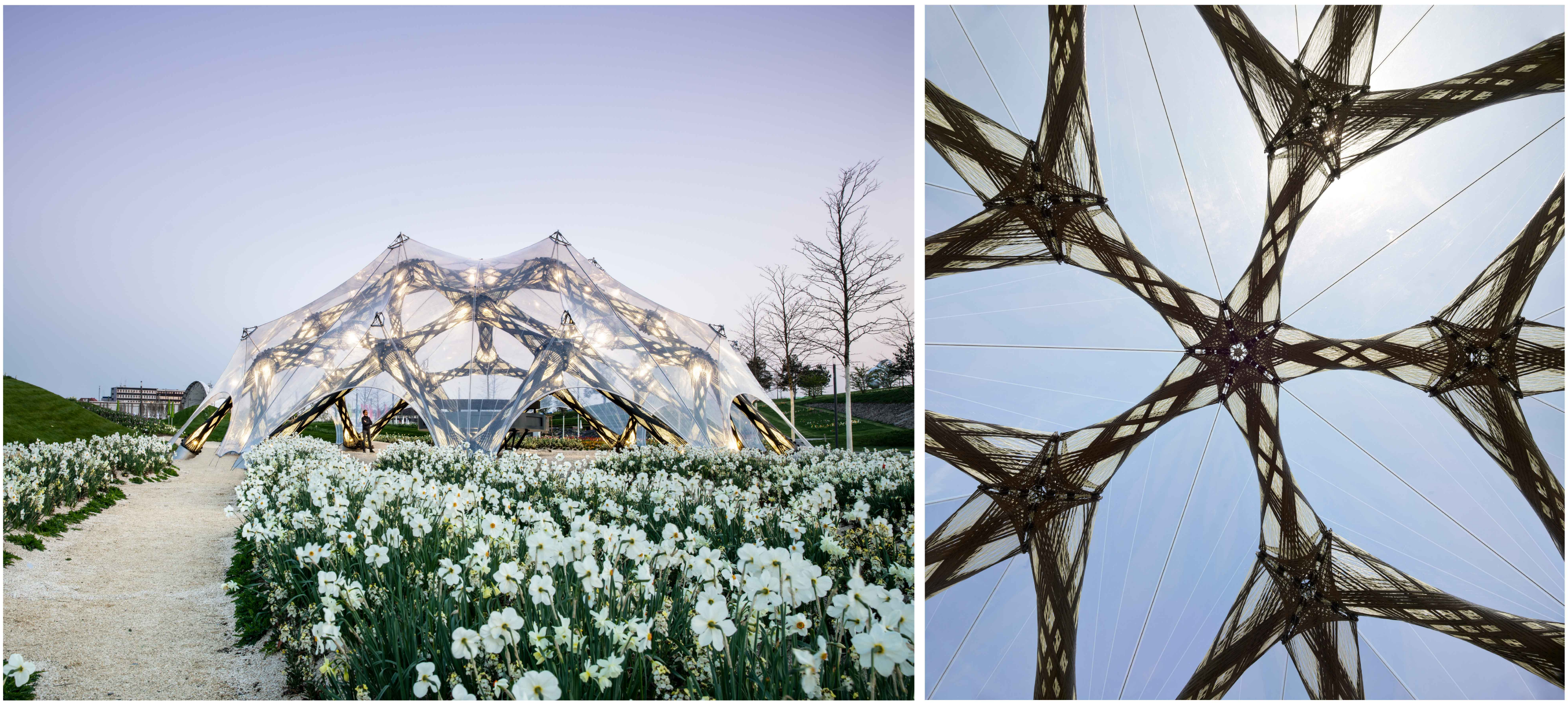


Figure 3.5: Results of the RCFW research and development: a. Exterior impression of the BUGA Fibre Pavilion G/CFRP segmented dome structure and the ETFE membrane supported by integrated cables façade system. (©ICD/ITKE University of Stuttgart); b. Interior impression of the BUGA Fibre Pavilion's characteristic fibrous node configurations: the dome structure exhibits five axes of symmetry. (©Roland Halbe)

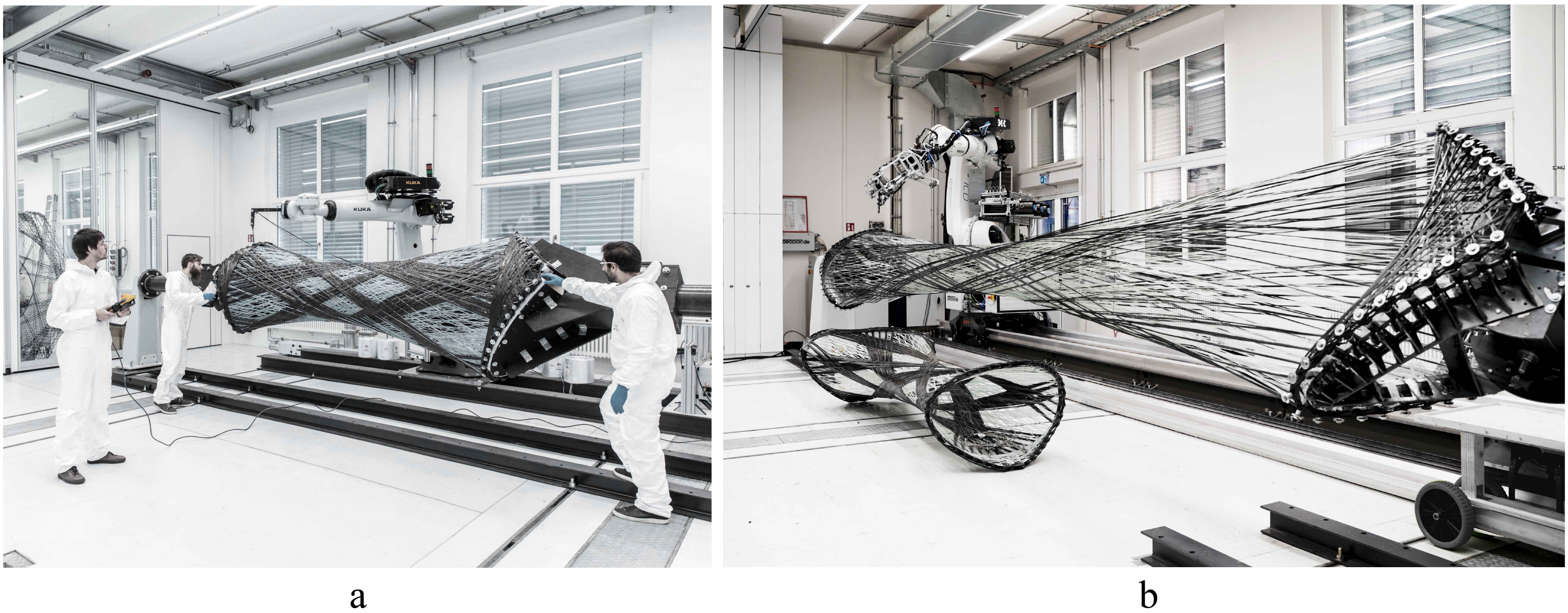


Figure 3.6: Research and development results: a. RCFW system with a 3.8-meter-long structural G/CFRP construction component; b. CPRCFW with a 9.2-meter-long proof-of-concept G/CFRP construction component. (©ICD, University of Stuttgart)

achieved component dimensions. Thus, a proof-of-concept composite element was designed to verify this initial hypothesis. The process acquired data on the essential fabrication parameters. The proof-of-concept demonstrator (Fig. 3.6) presented by Article C [7] utilizes the interactions of thousands of fiber strands in the process of reciprocal deformation of free-spanning fibers [8; 138]. The upscale is significant, compared to the length achieved for the largest BUGA Pavilion component, which stands at 4.8m (Pictured in Fig. 2.8). It illustrates that composite filament winding of elements over 9m in length is feasible. Industry-wide implementation of the this cyber-physical methodology presented may also enhance current simulation procedures. Until now, design methods in construction have utilized a combination of empirical methods - such as scale-models and intuitive computational methods - such as physics-based dynamic relaxation to model to anticipate the final form. The fabrication of the proof-of-concept structure presented in Article C [7] showed that the proposed methods perform well in fully automated fabrication scenarios. However, the online adjustment of the winding syntax based on fabrication-specific feedback, although experimentally tested through path-correction robotic routines, is yet to be implemented in a robust and extendable fabrication method and, thus, lies outside the scope of this Dissertation.

3.3 Process-monitoring and quality control methods for RCFW

Sections 2.2 and 3.1 presented research methods and results corresponding to the upscaling of the RCFW fabrication methods. Importantly here, as part of process monitoring and quality control, the operator recorded the fabrication duration of the numerous fabrication stages for each fabricated component. Also recorded were programming or mechanical faults observable during the process for a separate data set which were interesting from a process monitoring and quality control point of view. Section 3.1 and Article B [8] presented and analyzed the most significant trends derived from process analysis. However, up to this point, the process monitoring and quality control depend on a manually recorded data set. The subsequent development, in Sections 2.3 and 3.2, presents online process monitoring and automatic data acquisition. Thus, SO3 formulated the development of appropriate process monitoring and quality control methods for RCFW. These can be categorized into online or offline measures.

- Online measures include adaptive robot velocity control in negative feedback with the recorded fiber tension, leading to quasi-constant winding tension.
- Offline measures included the implementation of an automated fabrication data acquisition routine resulting in a multidimensional fabrication data set. The post-processing and analysis of this dataset, became an essential part of the process monitoring and quality control strategy. The required technical development is presented in detail in Section 2.3.5 and Article C [7]. The analysis yielded interesting conclusions and insights into the functioning and effectiveness of the prefabrication setup. Thus, complex geometry and robotic motion control could be correlated to accurate fiber tension-control and fiber-impregnation.

The experimental operation and monitoring of the process thus allows this research to conclude that human intuition is essential in design-engineering and programming, monitoring, and control of the RCFW process. The process may be highly enhanced by complementary manual and automated data acquisition methods . A human operator can record and intuitively react to complex fabrication process scenarios. Thus, Articles B [8] and C [7] demonstrate a direct link between the degree of automation of RCFW and its robustness and efficiency. As our technology reviews indicated, this invariably leads to more autonomy of the cyber-physical system and a less labor-intensive process for the operator overseeing the CPRCFW process. Moreover, increased automation becomes a vector towards increased productivity, precision, and quality, yet to be implemented at industrial scale for an emergent fabrication technology such as CPRCFW. As the two applications illustrated in the previous chapters in terms of methodology, technology, and results demonstrate, the two major objectives of this research:

- To improve the scalability of the existing RCFW fabrication at a building element and process level; and
- To advance the automation of RCFW by integrating bespoke sensor systems for process monitoring and quality control;

have been successfully demonstrated. The implications of these results will be further assessed in the following chapter.

4

Conclusion and Outlook

This Dissertation has discussed emerging technologies in composite construction from an upscaling and automation standpoint. The thesis identified research opportunities between academia and industry to contribute to the state of technology with developments rooted in interdisciplinary research. A significant challenge of the work was to extend existing fabrication methods beyond the “file-to-factory” paradigm. This development was only possible through the implementation of robotized prefabrication routines that achieve higher automation and quality control levels.

The first research objective, to develop a prefabrication method for large-scale tubular composite components was successfully demonstrated. To this point, the robotic coreless filament winding method integrates architectural design input, regarding fibrous morphology, and structural design input regarding load induction and transmission in tension an compression. However, in future research, the simulation methods of the reciprocal deformation of free-spanning fiber need to be improved. This could be achieved through more sophisticated dynamic relaxation methods that include information on the winding agent and on the fiber reinforced polymers. The data sets that bench-marked designs versus results can be used to calibrate these design-engineering models.

Article A [9] contextualizes the role of fabrication-aware RCFW in interdisciplinary research towards a more robust industrial application while identifying the critical challenges of the process: upscale and automation.

The second research objective, to upscale the methods and physical infrastructure towards a robust and industry-ready technology was successfully demonstrated. The parametric robotic coreless filament winding methods enables the exchange of data and procedures with industry partners, To this point, the BUGA Fibre Pavilion is the largest building where the entire composite loadbearing structure is robotically coreless wound. However, in future research the technology can be improved towards economical Series 0 production. This could be achieved through more generalizable syntax design and motion simulation methods, and through automation of ancillary operations and more modular winding equipment.

Upscale is an essential focus of Article B [8], which captures the transition from a lab-based experimental technology to an industrial process that delivers the structural elements of a complete building system economically and with minimal offcuts. While automation is advanced through more modular and intuitive robot programming methods, the technology presented in Article B [8] is essentially a file-to-factory process with fabrication data manually recorded by the human operator.

The third research objective, to develop cyber-physical methods of process control, monitoring, data acquisition and analysis was successfully demonstrated. The methods integrate interdisciplinary research from mechanical engineering, industrial robotics, textile and composite materials engineering, To this point, the technology has only been calibrated for, GF and CF reinforced composite systems. The technology currently evaluates winding pre-tension to control the TCP velocity of the robot with impact on component form and structural performance and quality of the composite layup.

Cyber-physical systems represent a significant development in applied computer science and technology. They impact manufacturing as a set of comprehensive technologies known as Industry 4.0 [65]. For composite construction, the technological model provided by cyber-physical system development entails connectivity, communication, and control. Connectivity enables multiple cyber-physical systems to link and exchange information while a controller manages the system's internal state. As Article C [7] explains, the ability to assess the system's internal state is of equal importance. As a result of the presented research, this assessment is automatic based on fabrication data utilized to adjust fabrication parameters in real-time. The parameters of the production system were recorded in a fabrication data-set and utilized in qualitative and quantitative evaluation of the fabrication method.

The method upscale and method automation represent solutions to significant challenges faced by sustainable and economical composite construction. Undoubtedly, fully automated RCFW depends on interdisciplinary research in areas outside the scope of this Dissertation, such as material system development. The presented data acquisition methods may contribute to process-informed form-finding.

However, the technology must be extended to enhance automation, to address sustainability, and answer safety concerns in construction applications. Automation can be improved through cyber-physical integration of additional sensor systems and process monitoring and quality control methods, for example active spooling, tension control. Safety and sustainability concerns can be addressed through calibration of the method to fibers and resins sourced from renewable resources. Fire safety can be addressed through ceramic or cementitious matrices. For unpredictable natural composites, adaptive cyber-physical methods will prove essential.

Beyond its current application to G/CFRP filament winding, the presented methodology constitutes a holistic approach towards the complete automation of additive manufacturing. Although limited to the monitoring and control of just a few fabrication parameters, the advantage of the presented method lies in its extendability and applicability to a wide range of manufacturing technologies in construction. Usually, the industry focuses on short-term gains and incremental innovation, while academia favours fundamental research and small-scale experiments. Operating at the interface between academia and industry has been used as a departure point for evaluating the scale and scope of composite construction through RCFW.

An obvious application for the proposed fabrication methods is lightweight construction. Structures such as the Elytra Filament Pavilion [99] or the BUGA Fiber Pavilion [8] have provided first evidence on the feasibility of composite construction in large-scale architectural applications. What remains to be demonstrated is the potential of composite structures to be deployed in dense urban settings where their lightweight and modularity may become a distinct advantage in competing with conventional building systems. Undoubtedly, the most considerable potential for lightweight composite construction lies in long-span applications such as roofs or large-scale domes. As Article B [8] and Article C [7] illustrate, significant efficiency gains are still achievable in industrial RCFW to make the technology more competitive. Moreover, scalability is far from reaching its limit even for a building system similar to the one utilized for the BUGA Fiber Pavilion. Doubling the component lengths means fewer components and enables buildings with larger spans. These arguments position long-span roof systems as the apparent next building application.

As an outlook to ongoing research the work presented in this dissertation has contributed to we may give reference to the research cluster Integrative Computational Design and Construction(IntCDC) [126] which has positioned Fibrous Morphology investigations at the center of an multidisciplinary research network. Its mission is to advance composite construction methods beyond incremental innovation, at large scale, and in close academia-industry cooperation.

As we witness the emergence of new lightweight composite structures it is exciting to remark that Robotic Coreless Filament Winding represents an investigation avenue where architectural academic research and development stand at the basis and constitute the driving force of an otherwise technologically-driven research field.

The work presented by this Dissertation has sought to demonstrated that such a design-driven approach to novel cyber-physical automation is integral to the long-term dissemination and success of lightweight composite architecture.

5

Article A: BUGA Fiber Pavilion: Towards Robotically-Fabricated Composite Building Structures

S. Bodea, N. Dambrosio, C. Zechmeister, M. Gil Perez, V. Koslowski, B. Rongen, M. Doerstelmann, O. Kyjanek, J. Knippers, A. Menges, 2020. Buga Fibre Pavilion: Towards Robotically-Fabricated Composite Building Structures. FABRICATE 2020 [9]

The work presented in this article was conducted by S. Bodea, N. Dambrosio, C. Zechmeister, M. Gil Perez, V. Koslowski, B. Rongen, M. Doerstelmann, O. Kyjanek, under the advising of J. Knippers, and A. Menges and project management by Monika Goebel. It builds upon prior research at the University of Stuttgart institutes ICD and ITKE and is complementary to published research by the authors [9; 8; 18]. The Conference article describes the interdisciplinary research and development that led to the BUGA Fibre Pavilion. The complete list of authors and project partners from the University of Stuttgart and elsewhere are listed in the BUGA Fibre Pavilion project credits below:

Project Partners

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Prof. Achim Menges, Serban Bodea, Niccolo Dambrosio, Monika Goebel, Christoph Zechmeister

ITKE Institute of Building Structures and Structural Design, University of Stuttgart

Prof. Jan Knippers, Valentin Koslowski Marta Gil Pérez, Bas Rongen

With support of: Rasha Alshami, Karen Andrea Antorvaeza Paez, Cornelius Carl, Sophie Collier, Brad Elsbury, James Hayward, Marc Hägele, You-Wen Ji, Ridvan Kahraman, Laura Kiesewetter, Xun Li, Grzegorz Lochnicki, Francesco Milano, Seyed Mobin Moussavi, Marie Razzhivina, Sanoop Sibi, Zi Jie Tan, Naomi Kris Tashiro, Babasola Thomas, Vaia Tsiokou, Sabine Vecvagare, Shu Chuan Yao. **FibR GmbH, Stuttgart**: Moritz Doerstelmann, Ondrej Kyjanek, Philipp Essers, Philipp Guelke, Leonard Balas, Robert Besinger, Elaine Bonavia, Yen-Cheng Lu. **Bundesgartenschau Heilbronn 2019 GmbH**: Hanspeter Faas, Oliver Toellner. **Project Building Permit Process** : **Landesstelle für Bautechnik**: Dr. Stefan Brendler, Dipl.-Ing. Steffen Schneider. **Proof Engineer**: Dipl.-Ing. Achim Bechert, Dipl.-Ing. Florian Roos. **DITF German Institutes of Textile and Fiber Research**: Prof. Dr.-Ing. Goetz T. Gresser, Pascal Mindermann. **Planning Partners**: Belzner Holmes Light-Design, Stuttgart, Dipl.-Ing. Thomas Hollubarsch, BIB Kutz GmbH & Co.KG, Karlsruhe, Dipl.- Ing. Beatrice Gottlöber. **Transsolar Climate Engineering, Stuttgart**: Prof. Thomas Auer. **Frauenhofer-Institut ICT**: Dipl.-Ing. Elisa Seiler. **Project Support** : State of Baden-Wuerttemberg, University of Stuttgart, Baden-Württemberg Stiftung, GETTYLAB, Forschungsinitiative, Zukunft Bau, Leichtbau BW, Pfeifer GmbH, Ewo GmbH, Fischer Group.

All these parties contributed to the group project under an interdisciplinary research framework into design-engineering methods, fabrication and construction processes and material and building systems. The framework for collaboration was set by the partner institutes ICD and ITKE. S. Bodea's contribution to the underlying research into RCFW is defined at the level of the conceptualization, design, implementation and verification of the RCFW methods. S. Bodea also designed and operated the fabrication setups utilized in research and development of the tubular composite elements. S. Bodea contributed to winding eye and winding scaffold development. Additionally, S. Bodea contributed to the design and production of the component-scale and building scale demonstrators presented in this work. During industrial production, S. Bodea was in charge of process monitoring, quality control, and fabrication data acquisition, on behalf of the University of Stuttgart, sharing this contribution, in equal amount with N. Dambrosio, C. Zechmeister, and in cooperation with FibR GmbH. During the construction process of the BUGA Fibre Pavilion, at the Bundesgartenschau 2019, in Helbronn, Germany, S. Bodea was in charge of construction site supervision on behalf of the University of Stuttgart, sharing this contribution, in equal amount with N. Dambrosio, C. Zechmeister, and in cooperation with FibR GmbH. Research work conducted by S. Bodea closely aligns with the Additive Manufacturing of Large Fibre Composite Elements for Building Construction (AddFiberFab)" [61] research project let by ICD, University of Stuttgart.

The original research, scope definition, and organization of this conference publication originate from S. Bodea under the advising of A. Menges and J. Knippers. Documentation work for this publication covered the State of the art in composite material manufacturing through filament winding, emphasizing CFW applications in construction. The majority of the references were researched by S. Bodea, with additional references suggested by C. Zechmeister, N. Dambrosio, V. Koslowski, and M. Doerstelmann. A. Menges recommended several additional references contributing to the contextualization of the research. S. Bodea formulated the prefabrication strategies for geometrically-complex building elements wound out of G/CFRP through RCFW, described the development of the fabrication method, conducted and systematized the experimental work included in this publication. S. Bodea organized and coordinated the original contributions from N. Dambrosio – building system, C. Zechmeister – computational design methods, M. Gil Perez – structural design and simulation of the composite material component, V. Koslowski – structural design and simulation of the elastic membrane, B. Rongen – overall building structural design simulation and optimization, M. Doerstelmann – coordination of the industrial fabrication process, O. Kyjanek – technical implementation and development of the industrial fabrication process. S. Bodea wrote the first draft and conducted the preparation of the manuscript with advising from A. Menges. All authors participated in revisions and responses to peer review.

BUGA FIBRE PAVILION
TOWARDS ROBOTICALLY-FABRICATED COMPOSITE BUILDING STRUCTURES

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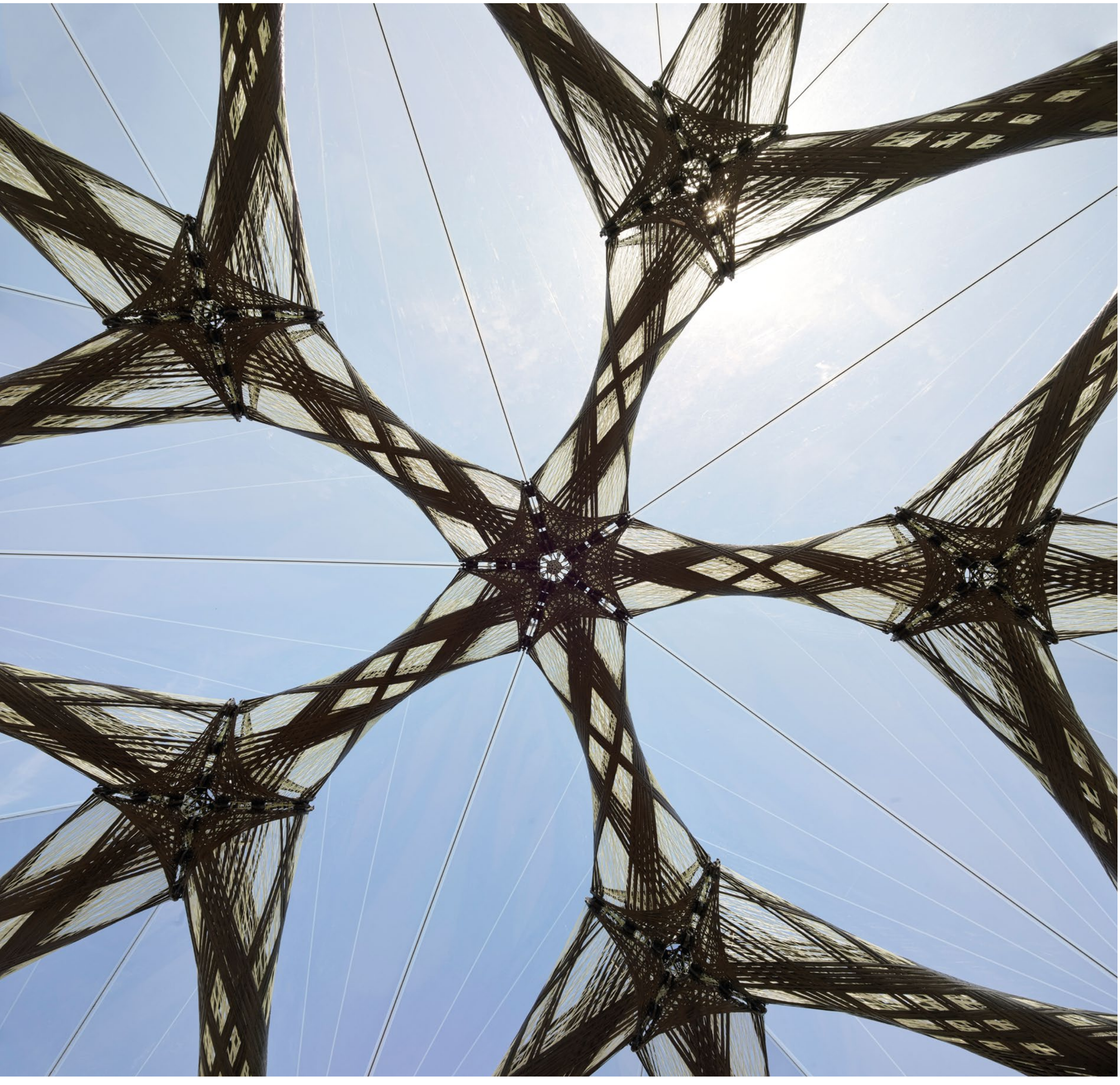
Synergy between academia and industry stands at the core of the BUGA Fibre Pavilion (Fig. 1), a research-driven project focused on a novel, robotically-fabricated composite building system suitable for long-span architectural applications. Lightweight, load-bearing elements were fabricated entirely out of Glass and Carbon Fibre Reinforced Polymers (G/CFRP), to complete this large-scale composite structure at the Bundesgartenschau 2019 in Germany, the first building of this kind. Accelerating development in the field of research into composite building structures at the University of Stuttgart, the project integrated design-engineering that conceptually and technically transferred biological principles from natural fibre morphology into architecture.

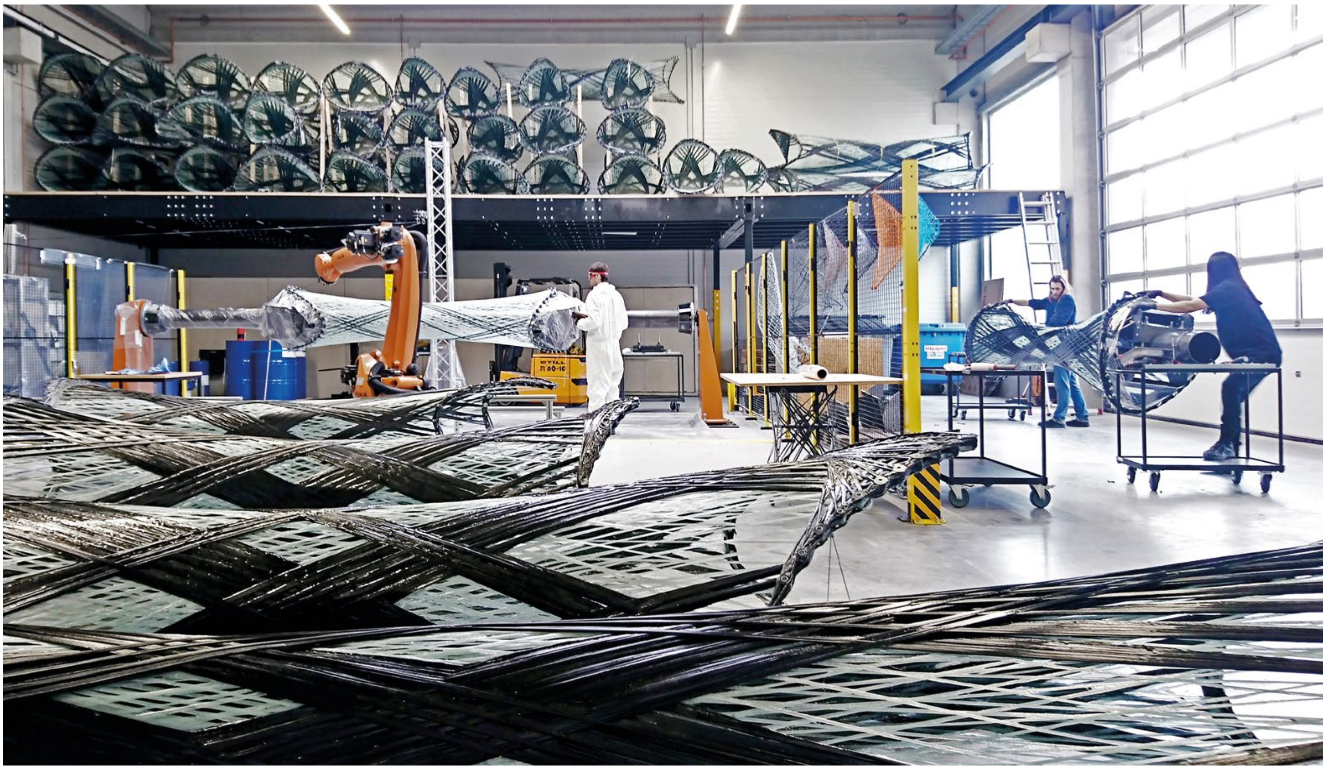
In this paper, the authors present a pre-fabrication method built on recent industrial-scale advances into robotic coreless filament winding. Improved fabrication procedures are complemented with advancements in structural design methods, contributing to this building system's applicability and showcasing the architectural qualities inherent to fibrous morphology.

Novel Fibre Composite Building System for Long-Span Structures

In January 2018, The Institute for Computational Design and Construction (ICD) and The Institute of Building Structures and Structural Design (ITKE), together with industry partner FibR GmbH and client Bundesgartenschau Heilbronn 2019 GmbH formed a research consortium for the development of the BUGA Fibre Pavilion. This is the first building where the entire load-bearing structure was robotically fabricated out of G/CFRP (Fig. 1). Inter-disciplinary work enabled the development of novel computational design and numerical structural evaluation methods along with integrated automated fabrication and construction processes.

The novel fibre composite building system integrated and interfaced with a hierarchy of subsystems adapted to structural and functional needs. The building component, a load-bearing hyperboloid fibrous body, succeeded in being both light-weight and large-scale, balancing morphological complexity of the fibrous lattice with economic feasibility through pre-fabrication.





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Sixty building components of twelve types, assembled by means of variable-angle steel connectors, articulated into distinctive nodal configurations. The composite load-bearing structure transferred loads directly to concrete foundations, embodying efficient load induction and eliminating unwanted discontinuities in the composite fibrous body. The building envelope consisted of a transparent ETFE membrane. This pre-tensioned membrane integrated a cable net structurally supported by the composite structure.

State-Of-Technology and Preliminary Work on Composite Building Structures

The presented contribution to the state of technology builds upon over fifty years of international research on filament-wound structures. Research includes anisotropic grids (anisogrids), a system of continuous unidirectional, densely-wound, helical, circumferential and axial ribs fabricated from composite materials. Anisogrid lattices are efficient fibre-wound structures, a reason for the extensive research into their development. Huybrechts et al. (1999) provides a comprehensive report on anisogrid history from The United States of America and The Soviet Union.

One of the best examples of anisogrid structures originated at the Central Institute of Special Machine Building in Moscow (1981-1985). Interstage components of spacecraft were fabricated through automated filament winding of carbon fibre tows into grooves machined in foam coating applied to a mandrel. Integrated design, manufacturing and testing, highlighting the lattice's self-stabilisation behaviour under axial compression, were central to the research (Vasiliev et al., 2001).

The next step in automation was robotic filament winding. Sorrentino introduced research where an industrial robot replaced the kinematic system utilised by Vasiliev. Here too, foam coating applied to a mandrel was used to ensure fibres were wound at specified angles (Sorrentino et al., 2017).

In aerospace, efficient and cost-effective composite trusses were developed for the design and construction of Gamera II (Woods et al., 2016). Geometric complexity of the aircraft's structure demanded the development of a novel coreless filament winding process. The high structural performance of the design, at multiple scales, was demonstrated in laboratory and flight-tests at the 2012 AHS Sikorsky Prize competition.

The 'ultra light fibre placed truss', was developed utilising the weight to strength ratio advantage of composite materials. This design is highly compatible with efficient, long span, construction systems. Filament winding on a mandrel enabled customisation of the truss' cross-sections. The high stiffness of these elements matches their ability to incorporate variable densities and contributes to an enlarged design space (Langone et al., 2016).

Consequential research on composites and coreless filament-wound structures has been conducted at the University of Stuttgart since 2012. The ICD/ITKE Research Pavilion 2012 (Reichert et al., 2014) proposed a monocoque FRP structure translating biological fibrous morphology into a pavilion-scale installation. Longer spans and increased efficiency in load distribution were achieved with the ICD/ITKE Research Pavilion 2013-14. Here, a freeform segmented shell was built out of light-weight hyperboloid components (Dörstelmann et al., 2015). The project implemented robotic pre-fabrication: two synchronised robotic arms carrying winding scaffolds wound G/CFRP by orienting about a stationary fibre source.

Throughout these examples, the scalability and adaptability of the material and building systems were major challenges. The Elytra Pavilion (Prado et al., 2017) showed that fibre structures can be designed for efficiency and scalability. The pavilion integrated structure and function for an over ten-metre span enclosure and remains a milestone for the implementation of coreless wound composite building systems in site-specific installations.

Based on the experience from the above-mentioned academic work, FibR GmbH was established in 2017 to transfer the underlying computational design and robotic fabrication strategies into architectural applications, enabling their implementation on an industrial scale. FibR offers integrated design, construction detailing, robotic fabrication and on-site installation services for high-performance, lightweight structures with projects ranging from façades and load-bearing structures, to modular lightweight systems for exhibitions, fairs, architectural interiors and furniture.

Drawing from the academic background in cross-disciplinary research of its team, FibR perfectly fit the research consortium's agenda of inter-disciplinary collaboration, thus enabling a novel, explorative design and construction repertoire.

Towards Robotically-Fabricated Composite Building Structures

The BUGA Fibre Pavilion is illustrative of the co-design framework through its operational loops: the first, design-engineering-to-construction involves computational design methods and building logistics while the second, material-to-fabrication, works at element-material-system level. Fabrication processes, material systems and engineering methods are thus inherently interdisciplinary (Fig. 5).

Design Methods

Historically, long-spanning domes proved a suitable typology for architectural production, given their ultra-efficient volume to surface area ratio. For the BUGA Fibre Pavilion, multiple design iterations utilised the qualities of the building system to enable an open, bright space ideal for semi-outdoor events. Of upmost importance for the design process was the ratio of different component types over the total number of components. A hemisphere, as underlying surface for the dome, was geodetically discretised into five identical sectors and the resulting three-dimensional grid, subsequently structurally optimised (Rongen et al., 2019). This resulted in an optimisation of the ratio, greatly simplifying fabrication.

Simulation and Fibre-Syntax Development

The components' fibre morphology consisted of continuous multi-performative layers geometrically encoded as 'syntaxes', encompassing structural demands, material properties and architectural requirements. In coreless filament winding, fibres span freely in space under tension, anchored around winding pins. When fibres are laid over existing ones, they deform at intersections. Over many iterations, the result is a structural lattice. Understanding the behaviour of thousands of fibre strands proved challenging as conventional geometrical means hardly offer robust ways of constructing surfaces arising from such reciprocal deformation of free-spanning fibres. ICD/ITKE-developed dynamic-relaxation simulation tools were integrated into the computational design workflow to form-find the geometry of the components. This resulted in the

1. Interior impression of the BUGA Fibre Pavilion's characteristic fibrous node configurations: the dome structure exhibits five axes of symmetry. Image © Roland Halbe.

2. Industrial fabrication process featuring robotic core-less filament winding and the already fabricated composite component pieces. FibR GmbH, Stuttgart, Germany. Image © FibR GmbH.

benchmarking of multiple winding approaches (Fig. 3c), ensuring efficient material use and optimal fibre interaction (Zechmeister et al., 2019).

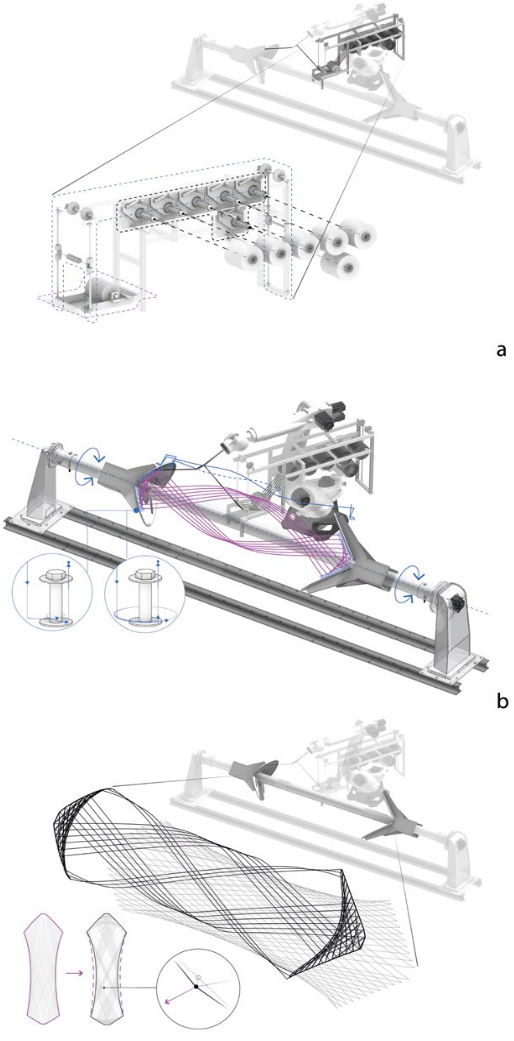
Material System Research and Development

Robot programming tools developed at the ICD contribute to the well-established industrial planning practice for technical composites presented in Bock (2007) and Peters (2011). Developments include adaptive motion planning methods for robotic coreless filament winding. Fabrication simulations allowed the efficient mapping of all robot-targets inside the working envelope of the standard KUKA Robot210-R3100, which was equipped with a custom winding effector and controlled an external kinematic system, a mechanically-synchronised standard 1-axis positioner. Performing a combination of automated wrapping and travelling motions, the robot sequentially added fibres, pulling them through a drum-type epoxy-resin bath (Fig. 3a) and anchoring them around winding pins fixed to an open winding scaffold, attached to the external kinematic system. The motion instructions for the robot setup were based on the specific fibre syntaxes of each layer. These fibre syntaxes served as blueprints for generating the machine code (Fig. 3b).

The physical manifestation of the digital syntax, the fibrous bodies, were fabricated from three materials: the translucent glass-fibre lattice, the black carbon-fibre reinforcement, bound together by an epoxy-resin matrix. Glass-fibre was wound first, physically form-finding an initial surface and performing as an elastic 'lost mould'. Carbon-fibre was wound next and constituted the structural material, primarily considered in all structural engineering and verification. Figures 4 and 5 illustrate the precise tailoring of carbon-fibre directions to structural force-flow resulting in the distinctive aesthetics of the completed structure.

Engineering Methods

Numerical structural analysis (Fig. 5) allowed the modelling of loads from the pre-stressed membrane and cables-net into a set of forces, informing fibre layup and steel connection design. The components' fibre bundles were modelled and evaluated for buckling while bundle thicknesses and buckling lengths required for stability were also computed. A particularly consequential evaluation was performed for the components' edge conditions; here, an 'edge reinforcement ring syntax' was implemented, to successfully induce loads generated by the ETFE membrane.



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3. Research and Development of the BUGA Fibre Pavilion: (a) Integrated fibre impregnation system and roving tension control; (b) 7-Axis Kinematic System; (c) G/CFRP filament form-finding for multistage winding procedure. Image © ICD/ITKE, University of Stuttgart.

4. Research and Development of the BUGA Fibre Pavilion – Robotic core-less filament winding: Modular winding scaffold – winding preparation; Glass fibre – winding process; Carbon fibre – winding process. Image © ICD/ITKE, University of Stuttgart.

5. Engineering methods – Global model, digital environment merging different types of information: (left) detailing; (middle) finite element analysis (red indicates zones of higher stress); (right) abstract geometrical description. Image © ICD/ITKE, University of Stuttgart.

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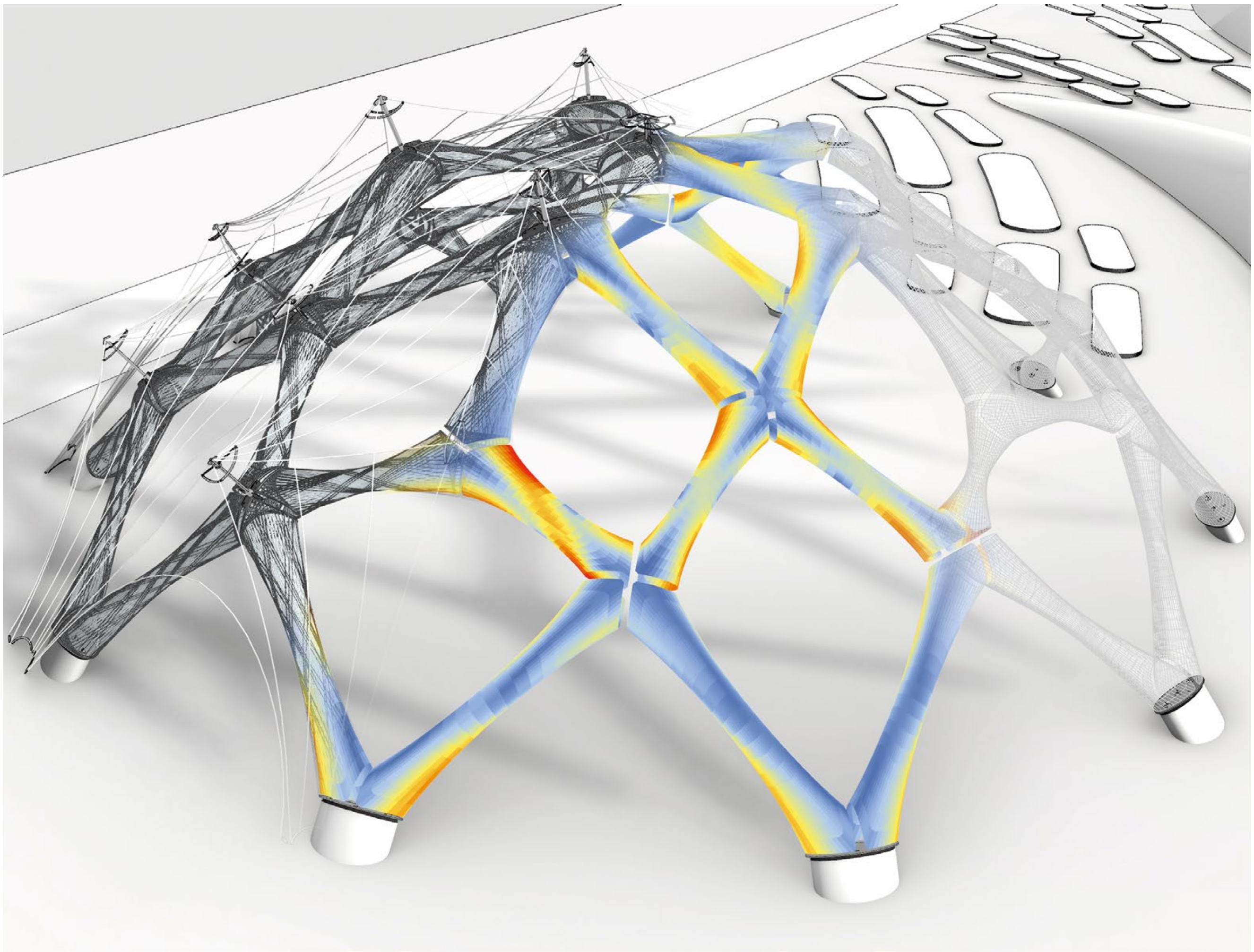

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Additional engineering development involved component connections which were optimised through a set of structural tests on robotically-fabricated fibre specimens. Load transfer between steel connectors and the fibrous body was thus successfully modelled. A computational tool was developed to compute the alignment angle of fibre bundles to component edge condition – parallel to loading direction (Gil Pérez et al., 2019). Factors influencing the failure modes of fibre composite structures were identified, evaluated and optimised, thus enhancing feedback between structural modelling, testing and fabrication, enabling lighter, more efficient designs.

Experimental Validation

As compared to steel, wood or concrete structures, there exist limited engineering codes for structural composites. Therefore, this project developed its own experimental validation methodology. Structural evaluation methods developed in collaboration with the Baden-Württemberg building authorities informed the work of all involved partners (Fig. 6). According to the structural validation methodology, all twelve component types were non-destructively tested to resist 60 to 80 KN. Thus, structural implications and fabrication constraints could be simultaneously evaluated. Subsequently, three destructive structural tests were performed and successfully passed, at 250KN per component. Complete data sets of geometrical and structural failure data were generated. The results were subsequently used to verify the structural capacity for all component types.

Industrial Fabrication

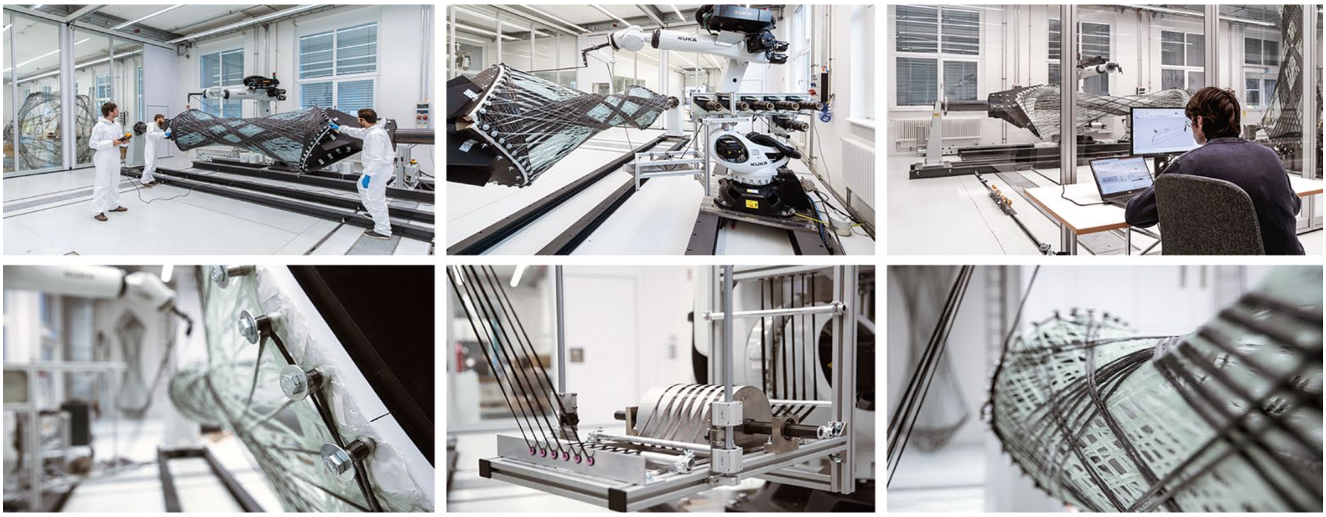
At FibR, sixty components were fabricated using reconfigurable, modular winding scaffolds that allowed all twelve different component geometries ranging from three to five metres to be efficiently pre-fabricated. The winding scaffold was composed of a central shaft with two steel clamps equipped with removable metric bolts that served as anchor pins. Each anchor pin was additionally equipped with thin-walled aluminium spacers that remained embedded in the cured composite. The function of the spacer was twofold: to create a precise interface between the anchor pin and the composite and to serve as interface for the component-component connections of the completed structure.

After the necessary quantity of fibres was applied, the central shaft was decoupled from the positioner. The composite cured together with the shaft and the winding scaffold in a non-pressurised oven, according to a curing profile for constant high strength and thermal stability of the composite. Once cured, each composite component was removed from the reusable winding scaffolds (Fig. 2).

The curing temperature, ambient temperature and humidity during the winding process were recorded for each component and subsequently compiled in a quality-assurance protocol.

6. Experimental validation of fabrication prototypes at the ICD Computation and Construction Laboratory, Stuttgart, Germany. Image © ICD/ITKE, University of Stuttgart.

7. Research and Development of the BUGA Fibre Pavilion at the ICD Computation and Construction Laboratory. Top row: Robotic core-less filament winding; Bottom row: Fibre impregnation system and quality control. Image © ICD/ITKE, University of Stuttgart.



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Development of the BUGA Fibre Pavilion 2019

Design-engineering methods supported automated fabrication processes which, in turn, enabled a research-driven material system. All solutions incorporated evaluations of structural capacity, while informing architectural and spatial implications early in the development (Fig. 5).

Utilising Finite Element Analysis, the composite structure could be improved to better align with requirements coming from the wind-loaded membrane. The structural optimisation resulted in a 27% reduction of critical forces while complying with all fabrication and architectural constraints (Rongen et al., 2019).

Concomitant to research and development of building component types and building system details, fabrication of the composite load-bearing structure was carried out between November 2018 and March 2019, at FibR GmbH (Fig. 2). ICD and ITKE adopted a scientific-support and quality-control role, thus all sixty components were produced on schedule, by 5th March. The efficiency of the process gradually increased, achieving an eight-hour fabrication time per component, with five to six hours of effective winding time.

The successful technology transfer from academia to industry underlines the importance of application-oriented research in architectural fabrication methods and its testing in 1:1 demonstrator projects (Fig. 7).

Advancing Industry Standards for Automated Composite Construction

Compared to previous composite building systems, the ratio winding scaffold perimeter to distance between winding scaffolds was reduced. The Elytra Pavilion exemplified a ratio close to 20. For the BUGA Fibre Pavilion, this ratio is equal to 1. This translated to fewer winding points, simpler connections, longer spans and a more efficient structural utilisation of fibres. Furthermore, while previous systems could only scale up through significant component-number increase, the BUGA Fibre building system scales through its components.

The composite load-bearing structural elements, weighed on average $7.6Kg/m^2$, resulting in a load-bearing composite structure of only 4.8 tonnes. Spanning 23 metres and covering an area of $400m^2$, the building offered an immersive experience of the sinuous landscape of the Horticultural Show (Figs 1, 8). From April to October 2019 the BUGA has been visited by over 2.3 million visitors and was considered a showcase for the State of Baden-Württemberg’s digital transformation through innovation in building integrative design and construction processes.

The Pavilion demonstrated the potential of fibre composite lightweight structures fabricated through coreless filament winding for building industry applications, for the first time at large-scale outside an academic experimental context (Figs 2, 7).

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During the course of the project, the coreless robotic filament winding process was proven to be robust, efficient and scalable. Quality control measures contributed to process stability. The project offered a unique opportunity to improve fabrication and automation efficiency (Figs 2, 3, 4) and paved the way for further applications in construction projects that are currently under research at the University of Stuttgart and being commercially developed at building-scale at FibR GmbH.

Finally, the building exemplified differentiation in performance through the local tailoring of geometry and physical properties, from component to load-bearing structure. Each robotically wound element utilises finely calibrated fibre pre-tension in form-found lattices to achieve structural equilibrium and usher in new aesthetic possibilities (Fig. 9).

Through the use of the latest computational technologies and fabrication methods, the project offers an insight into lightweight architecture that, only a few years ago, would have been impossible to design or build.

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8. Exterior night time impression of the BUGA Fibre Pavilion at the Bundesgartenschau2019, Heilbronn, Germany. Image © Roland Halbe.

9. Interior night time impression of the BUGA Fibre Pavilion dome structure, featuring the light-conductivity of the transparent fibreglass body exposed by the integrated lighting installation, Bundesgartenschau2019, Heilbronn, Germany. Image © Roland Halbe.

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Article B: Robotic Coreless Filament Winding for Hyperboloid Tubular Composite Components in Construction

S. Bodea, C. Zechmeister, N. Dambrosio, M. Doerstelmann, A. Menges, 2021. Robotic coreless filament winding for hyperboloid tubular composite components in construction. Automation in Construction [8].

The work presented in this article was conducted by S. Bodea, C. Zechmeister, N. Dambrosio, M. Doerstelmann, under the advising of A. Menges and project management by Monika Goebel. It builds upon prior research at the University of Stuttgart institutes ICD and ITKE and is complementary to published research by the authors [9; 7; 138; 18]. The Journal article focuses on the RCFW fabrication method developed for the construction of tubular composite elements constituting the lad-bearing components of a dome structure named the BUGA Fibre Pavilion. The complete list of authors and project partners from the University of Stuttgart and elsewhere are listed in the BUGA Fibre Pavilion project credits below:

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All these parties contributed to the group project: the ICD researchers S. Bodea, C. Zechmeister, N. Dambrosio were in charge of research and development while M. Doerstelmann (FibR GmbH) led the industrial production process. The framework for collaboration was set by the ICD and FibR GmbH. S. Bodea's contribution to the underlying research into RCFW is defined at the level of the conceptualization, design, implementation and verification of the RCFW methods. S. Bodea also designed and operated the fabrication setups utilized in research and development of the tubular composite elements. S. Bodea contributed to winding scaffold and winding eye development. Additionally, S. Bodea contributed to the design and production of the component-scale and building scale demonstrators presented in this work. During industrial production, S. Bodea was in charge of process monitoring, quality control, and fabrication data acquisition, on behalf of the University of Stuttgart, sharing this contribution, in equal amount with N. Dambrosio, C. Zechmeister, and in cooperation with FibR GmbH. As part of the underlying research presented in this publication, S. Bodea developed and implemented a fabrication data analysis methodology leading to the quantitative assessments presented in this publication, under advising from A. Menges. Research work conducted by S. Bodea closely aligns with the Additive Manufacturing of Large Fibre Composite Elements for Building Construction (AddFiberFab)" [61] research project let by ICD, University of Stuttgart.

The original research, scope definition, and organization of this journal publication originate from S. Bodea under the advising of A. Menges. The literature review for this publication covered the State of the art in composite material manufacturing through filament winding in both industry and construction, concentrating on CFW in construction. The majority of the references were researched by S. Bodea, with additional references suggested by C. Zechmeister. A. Menges recommended many additional references to more precisely contextualize the research. S. Bodea formulated the prefabrication strategies for geometrically-complex building elements wound out of G/CFRP through RCFW, described the development of the fabrication method, conducted, and systematized the experimental work included in this publication. A. Menges provided theoretical guidance and content revisions to highlight the original research contribution. C. Zechmeister and N. Dambrosio contributed original sections regarding the development of the computational design method and building system, respectively, reviewed and systematized by S. Bodea. S. Bodea also developed the data analysis methodology. M. Doerstelmann provided the raw fabrication data set utilized in the data analyses. S. Bodea wrote the first draft and conducted the preparation of the manuscript with advising from A. Menges. All authors participated in revisions and responses to peer review.

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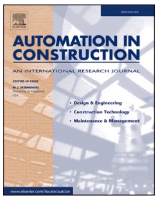

Robotic coreless filament winding for hyperboloid tubular composite components in construction

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ABSTRACT

Novel fabrication methods are necessary to capitalize on the high strength-to-weight ratio of composites engineered for construction applications. This paper presents prefabrication strategies for geometrically-complex building elements wound out of Glass and Carbon Fiber Reinforced Polymers (G/CFRP). The research focuses on Robotic Coreless Filament Winding (RCFW), a technology that eliminates formwork, proposing upscaling and industrialization strategies combined with updated robot programming and control methods. Our application addresses the prefabrication of hyperboloid, tubular components with differentiated geometry and fiber layout. We examine how the proposed methods enabled the industrial prefabrication of a building-scale G/CFRP dome structure and discuss the industrial process relative to key fabrication parameters. Highlighting the interdisciplinary nature of the research, we envisage future directions and applications for RCFW in construction. Overall, we find that synergy between academia and industry is essential to meeting research, productivity, and certification goals in the rather conservative building industry.

1. Introduction

Manufacturing methods for composites undergo constant industrial development motivated by the materials' high strength-to-weight ratio and formability. Historically, construction has been an adopter rather than a developer of composite manufacturing technology. Thus, it helps to first illustrate the use of composite materials and products on a project-by-project basis, highlighting the interplay between technology and economy when motivating their use. The San Francisco Museum of Modern Art [1], the Heydar Aliyev Center [2], and the Bing Concert Hall [3] for example, are buildings that utilize aerospace-grade composite technology, prohibitively expensive for extensive use in construction. Because of high manufacturing costs, larger projects typically rely on less technologically advanced fabrication and compensate by utilizing intensive human-labor. Such is the case of the Makkah Royal Clock Tower [4] façade or the Apple Cupertino Auditorium [5] roof. Consequently, in construction, the adoption of composite technology is slow, owing to their high price and low productivity of the manual labor involved. Advancing composites in construction requires new automated solutions that address upscaling, customization, and production-cost reduction, all specific demands of the building industry.

Utilizing composite materials in construction presents significant advantages. Composites can be engineered and designed for lightweight and high strength in precise directions and loading conditions, a potential not found in many traditional building materials. These advantages derive from mechanical anisotropy, making this property an essential design handle. Physics defines anisotropy as the property that allows materials to assume different properties when measured along different axes or directions [6–8]. Design-engineering research on lightweight composite construction based on mechanical anisotropy is essential for understanding the interrelations between geometry, structural behavior, and directional fabrication.

For the composite construction industry, advances in automation signal the transition from labor-intensive [9], costly or experimental applications towards easier-to-implement, economically-competitive building technologies applicable on a large scale. Industrial robotics has great potential because of its ubiquity and the capacity to increase productivity inherent in its precision, flexibility, and operation speed.

Industrial robots have been recently integrated into the composite manufacturing processes of *filament winding* and its construction-

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adapted variant *coreless filament winding*. Utilizing primarily Glass and Carbon Fiber Reinforced Polymers(G/CFRP), the new methods enabled experimental composite structures that combined prefabrication with high customization of their fiber arrangement.

This paper presents a novel coreless filament winding application that upscales existing fabrication methods. Overall, our work seeks to verify the proposed methods at building scale, utilizing an interdisciplinary research platform and newly formed industrial partnerships.

2. State of the art in composite manufacturing through filament winding

Next, we provide an overview of Filament Winding(FW) across the industry and contextualize its application in construction. An overview of state of the art in Coreless Filament Winding (CFW) is presented in reference to several industrial patents. Subsequently, our focus shifts to industrial and experimental construction applications of Robotic Coreless Filament Winding (RCFW).

2.1. CFRP and GFRP manufacturing methods

The composite manufacturing industry operates by tailoring material performance to structural requirements – stiffness through form [9,10]. To create a carbon or glass fiber reinforced polymer, for example, thermoplastic or thermoset polymers bind the fiber filaments [11]. Manufacturing processes such as automated tape laying, automated fiber placement, and filament winding have been extensively automated and constitute the industrial standards for precision, efficiency, and economy [12]. In the textile industry, knitting is also utilized. Its potential to create complex surfaces for construction applications was explored at the Centre for Information Technology and Architecture, which provided first evidence on a new class of membrane materials with varying tailored local material properties [13]. Hybrid systems of knitted formwork and sprayed concrete for thin form-active structures are described in [14]. These researches expand the applications of composites, developing a toolkit of fabrication and analysis methods. They represent viable research directions and potentially competitive alternatives to FW in construction applications.

Next we will focus on FW, the process in which fibers are consolidated against supporting negative forms, mandrels, or dies in a continuous *pultrusion* operation called *winding* [15]. FW is compatible with most technical fibers, e.g., carbon fibers(CF), glass fibers(GF), basalt or aramid filaments, rovings, or tapes [11]. An additive manufacturing process, FW is distinguished from 3Dprinting [16], which usually recreates a sliced 3D model through *extrusion*. Advances in composite 3D printing promise to deliver outstanding performance and design freedom through the ability to deposit the composite only where structurally or functionally needed [17]. While composite 3D printing becomes increasingly reliable, the process-scalability is yet to be convincingly resolved at building scale.

2.2. Filament winding in the industry

An older fabrication method, FW, has incrementally diversified and upscaled its applications. First mentioned in 1944 in Lubin and Greenberg's applications at Bassons Industries, FW was utilized by R. E. Young and M. W. Kellogg as early as 1946 for the fabrication of high-strength rocket motor casings [9,15]. Additionally, composite isotensoids and toroids are utilized in fuel tanks and pressure vessels for medical devices [18]. Composite tubes are used in the automotive industry as drive shafts [19] and in the extractive industry for pipe networks [9,15]. CFRP drill-risers [9] are utilized on deep-sea oil platforms. Furthermore, in the aerospace industry, the Proton-M [20,21] launch vehicle uses a filament-wound inter-stage adapter CFRP anisotropic grid structure [9], while ESA's Vega rocket first stage utilizes a filament-wound solid motor case structure [22]. In other applications, the CFRP Isotruss developed at Brigham Young University [23] replaces a bicycle's metal frame and the renewable energy industry utilizes CFRP turbine blades measuring tens of meters in length.

The technology most utilized for FW is based on a lathe-like system. A horizontal or vertical lathe holds a mandrel while a payout eye performs translation motions along its length [9,24]. The lathe rotation and the payout eye movement are synchronized such that the fiber filament is wound following a pre-programmed path without the payout tool touching the mandrel.

Despite the addition of multiple motion axes, the design space of FW on a core (perimeter winding [24]) is primarily optimized for axisymmetric parts. Most non-axisymmetric research focused on the winding of 'T' pipe joints [9]. An early robotic FW application for non-axisymmetric parts that tackled these limitations was described by Carrino et al. [25] and Polini et al. [26] [27]. Markov et al. [28] conceptualizes possible robotic FW setups while Van Brussel et al. present an offline programming methodology for a robotic tape winding cell [29].

2.2.1. Filament winding in construction

Construction primarily utilizes composite materials for their strength-to-weight ratio and workability, well exemplified by an application for an Ultralight fiber-placed truss [30]. The application incorporates customization of the structure's polygonal cross-section and includes variable fiber layup directionality and density. Despite the advantages of many similar examples, convincing applications of FW in construction are still missing. The limiting factor is FW's dependence on formwork. Removing and reutilizing formwork is particularly challenging. Construction has explored utilizing 3D printed or hotwire-cut doubly-curved formwork made from recyclable or dissolvable materials as exemplified for concrete casting [31]. However, for composite elements, controlling fiber direction and continuity is essential. For tubular composite components, removing the mold through cutting the composite is not acceptable since it means adding the extra step of gluing the resulting sections. Utilizing dissolvable molds also incurs additional fabrication steps and material specifications: the mold needs to withstand high curing temperature and pressure in an autoclave; the mold should not chemically react with the composite. The equipment also needs to shrink to allow contraction of the composite [24].

Nevertheless, flexible, elastic-coating silicone molds have been utilized to fabricate aerospace components [21]. However, in construction, technology benchmarks are, as of yet, missing. Therefore, it is clear that construction-adapted FW needs to deliver easily-implementable customization and scalability while reducing its use of support structures.

2.3. Coreless filament winding in the industry

CFW (cross winding [24]) is an adaptation of FW that drastically reduces the need for support structures. Fiber rovings are either spanned between longitudinal edges of the winding tool for trusses [32] or wound around pins or gaps in the tools for frames [24]. In both cases, the fiber impregnation system usually follows the industrial standard. However, in terms of kinematics, research has concentrated on applications utilizing multiaxial winding through the integration of industrial robot arms, more flexible for delivering non-axisymmetric components [24].

For comparison, patents [33,34] precede the integration of industrial robots; both involve the fabrication of two-dimensional truss structures and require specialist programming and control. The first is an adaptation of the lathe-type setup: a horizontal plate holds spools as winding pins are rotated around a vertical axis. The second proposes a gantry unit with a rotational fiber deposition eye, moving about a fixed winding plate with perpendicular winding pins.

Robotic applications of CFW for three-dimensional truss structures are presented in patents [35,36]. The first application utilizes two robots to position a winding tool while a third robot winds around pins mounted on the device. The second application uses an eight-axes kinematic system: a track-mounted robot synchronized with a horizontal

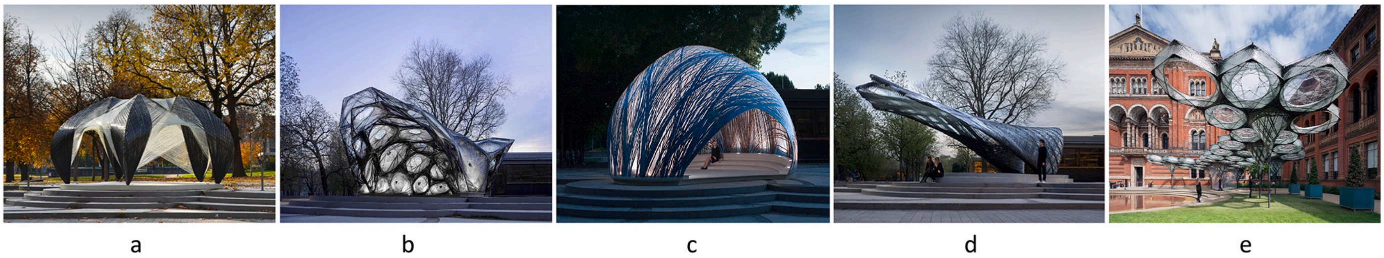


Fig. 1. ICD/ITKE Fibrous Morphology Research Pavilions: a. ICD/ITKE Research Pavilion 2012, (c) ICD/ITKE; b. ICD/ITKE Research Pavilion 2013–14, (c) ICD/ITKE; c. ICD/ITKE Research Pavilion 2014–15, (c) ICD/ITKE; d. ICD/ITKE Research Pavilion 2016–17, (c) ICD/ITKE; e. Elytra Filament Pavilion(2017), (c) ICD/ITKE

rotational axis.

In 2012, Woods et al. [32] developed a CFW application to produce a truss system for the lightweight fuselage of the experimental aircraft Gamera II. Here, CFRP rods are longitudinally fixed to an axis. A translational fiber payout eye deposits wet CFRP rovings on the rods to create a composite truss. However, construction applications are conditioned by the further development of the fabrication and structural systems.

Minsch et al. developed another CFW truss [37,38]. Their pending patent covers the component design and fabrication method, including looping the fiber completely around winding pins which become embedded in the final structure. This application utilizes two synchronized robots, one holding the winding tool, the other the fiber deposition end-effector. The process is described in [39] and the resulting truss structure in [37]. Rad et al. [19] conducted similar research into CFW automotive drive shafts. Similar to [38], these investigations utilized composite-embedded metallic inserts, but unlike [38], the winding was not automated.

2.3.1. *Coreless filament winding in construction*

One example of public art at building scale, made possible by the composite manufacturing industry's involvement, is Mae West, a sculpture installed in 2011, in Munich. The 40-meter-tall structure was designed by Rita McBride and fabricated by Carbon Grosssbauteile GmbH. The hyperboloid load-bearing structure, constructed out of individual 40 meter-long slender (275–225 mm diameter) conical CFRP elements, is adapted to its building application. Fabrication of the sculpture's lightweight (500 Kg/40-meter-long component) structure introduced several innovations: structurally tailored fiber arrangements wound in multiple stages; winding pins normal to the winding tool's metal surface; a fully automated 'mandrel-less' setup for FW; an integrated composite curing stage. At the time of its unveiling, the Mae West was the world's largest CFRP art installation [40].

Technology transfer between academia and industry and between industrial branches has always been a driver for innovation. The development of composite material systems is inseparably linked to specialized manufacturing technology [9,15]. In composite construction, technology transfer is primarily realized at the level of systems and processes. This section of state of the art focuses exclusively on G/CFRP material systems that utilize thermoset resins. CFW construction has adopted these material systems from the FW industry along with tooling (metal winding effector frames and modular winding pins [35,39]). The composite industry has also engaged in technology transfer, appropriating industrial robots from the automotive industry as early as the 1990s [29,41]. Advances on the FW of non-axisymmetric parts exist since the early 2000s [25]. Composite construction, however, has adopted industrial robots in prototyping and fabrication as generic tools. Innovation in the field was driven by the imperative to automate design and fabrication

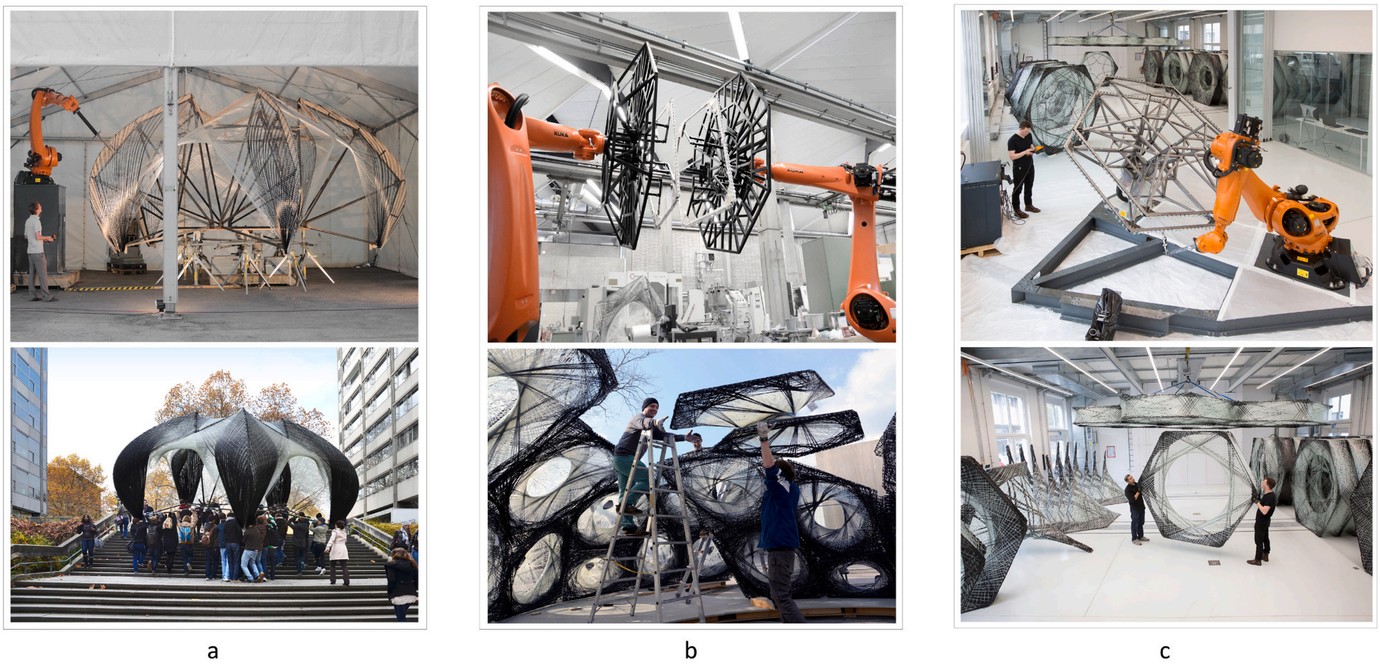


Fig. 2. Coreless Filament Winding in construction: a. ICD/ITKE Research Pavilion 2012: Top - RCFW setup, Bottom – Installation, (c) ICD/ITKE; b. ICD/ITKE Research Pavilion 2013–14: Top - RCFW setup, Bottom – Installation, (c) ICD/ITKE; c. Elytra Filament Pavilion(2017): Top - RCFW setup, Bottom - Component Types, (c) ICD/ITKE.

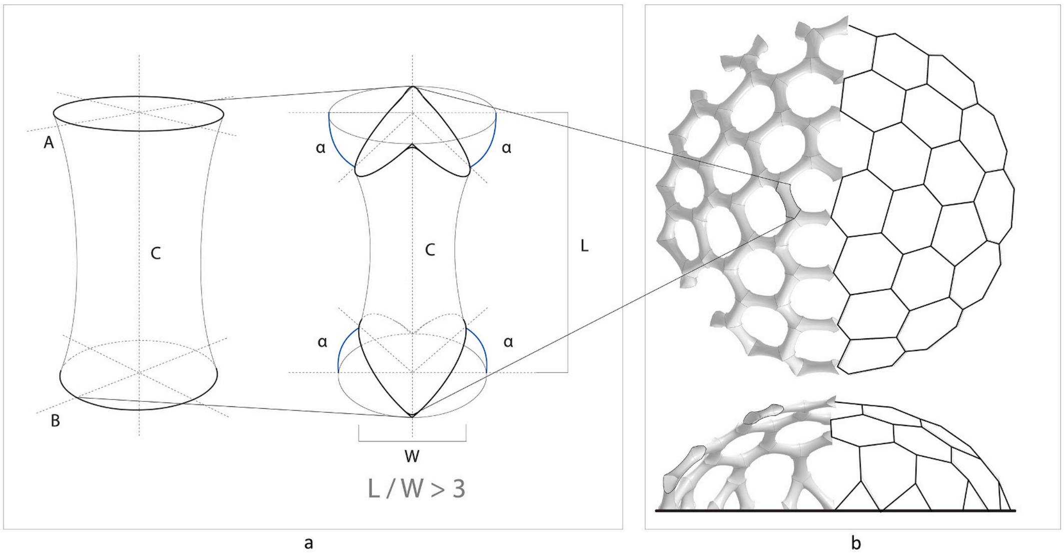


Fig. 3. Design of a tubular building component: a. tubular component: A, B - initial boundary conditions; C – axis of symmetry; α – angle component/component connection; L – component length; W – component width; b. network representation of a generic dome structure populated with tubular building components, (c) ICD.

to increase productivity. Industrial robots are adaptive platforms that can enable the economic construction of building systems to achieve geometrically unique elements if connected to a digital design system.

Thus, the expertise to produce lightweight composite structures has emerged from within the design-engineering communities with research conducted by the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) [42]. This body of work at the University of Stuttgart, referred to as *fibrous building morphology* [43], investigates computational design-engineering and fabrication methods and seeks to transfer contemporary biomimetic research [43] to construction applications. Fig. 1 shows some examples realized by ICD and ITKE over the last decade. Research here focuses on advancing automated additive fabrication processes towards broader adoption of technical composite materials in the building industry.

The ICD/ITKE Research Pavilion 2012 [43,44] was a small-scale monocoque structure (Fig. 1a; Fig. 2a). The CFW application utilized an industrial robot arm geometrically coupled with a horizontal turntable. Fiber rovings were wound between grooves in the edges of a modular metallic winding tool. The technology was geared towards placing G/CFRP along digitally designed and structurally evaluated loadbearing paths [44,45].

The ICD/ITKE Research Pavilion 2013–14 (Fig. 1b, Fig. 2b) was a freeform modular segmented shell. The fiber modules were form-found between polygonal boundary conditions. The component geometry was a hybrid between a hyperboloid-of-one-sheet and an anticlastic lattice [46]. The CFW application utilized two synchronized robotic arms carrying modular winding tools, equipped with modular winding pins. In this case, the RCFW application used the two robotic manipulators' synchronous motion in relation to a stationary fiber source [47]. After a brief display at the University of Stuttgart, the modular structure could be disassembled and reassembled in Shenzhen [48].

For the Elytra Filament Pavilion (Fig. 1e, Fig. 2c), large-scale G/CFRP components morphologically similar to those developed in [46] were supported by metal columns with integrated coreless filament-wound capitals. The structure weighing only 9Kg/m^2 achieved open spans of over 10 m [49]. It was composed of three component types with identical boundary conditions but differentiated by their load-adapted fiber arrangement. CFW was implemented utilizing a single robotic arm. The impregnated rovings traveled to the TCP of the end-effector. They were looped around winding pins fixed to a modular steel winding tool mounted on a two-axis industrial robot positioner [49]. After its display at the Victoria and Albert Museum, the modular structure could be disassembled and reassembled in Shanghai [50]. The Elytra Filament Pavilion represents the state-of-the-art composite building system before the presented research. The ICD/ITKE Research Pavilion 2014–15(Fig. 1c) and the ICD/ITKE Research Pavilion 2016–17(Fig. 1d) represent the state of the art in cyber-physical robotic filament winding methods in construction.

An overall conclusion on the presented state of the art is that, while the construction industry has adopted the material systems and much of the tooling from industrial CFW, construction research has always focused on the need for customization and large-scale applications, both important drivers for innovations in the field.

2.4. Research gap

As we have seen, the majority of CFW projects are either pavilions or larger art installations. Hence, the major challenge facing RCFW construction is process scalability for larger and lighter building components. One way of upscaling is prefabrication. It is essential for research to focus on industrialized prefabrication for large-scale building components rather than monocoque structures (e.g., the ICD/ITKE Research Pavilion 2012 [43,44]) which are currently still limited in scale by the work envelope of the machines utilized. Another essential requirement is to allow geometry variation yet ensure reasonable rationalization for an efficient fabrication process. Two previous examples represent different approaches in managing fabrication complexity. While the ICD/ITKE Research Pavilion 2013–14 implements an adaptable modular winding tool, the Elytra Filament Pavilion [49] utilizes a single metal winding tool. In the latter, complexity is transferred from tooling to the tailored fiber layups at the loss of morphological variation, limiting the architectural applications.

Consequently, new adaptive digital fabrication methods must allow geometric variation. Extended design space and larger component scale

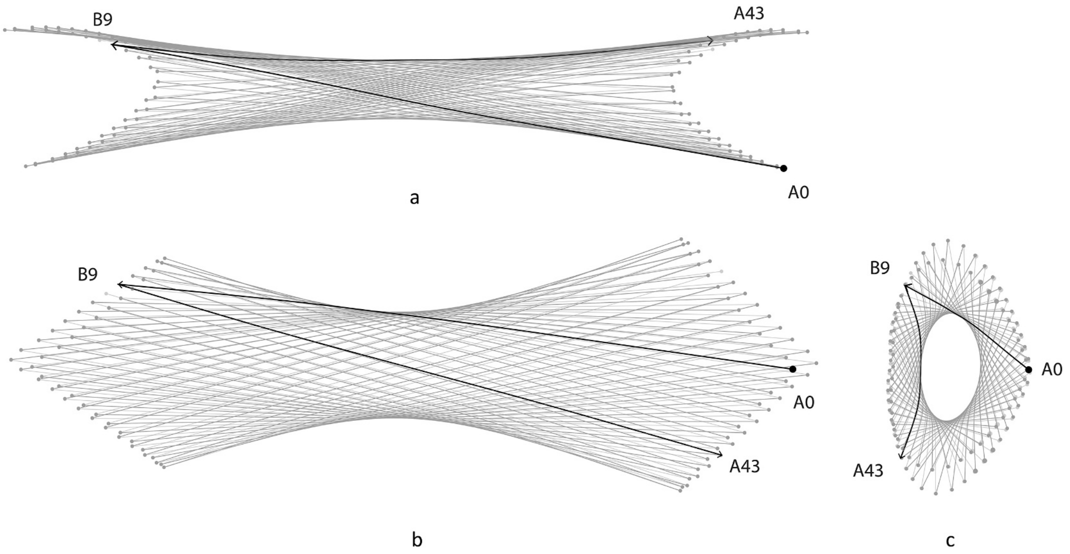


Fig. 4. RCFW fabrication method – simple fiber syntax, input for the computational robotic motion generator: a. fiber path A0-B9-A43, side view; b. fiber path A0-B9-A43, top view; *c. fiber* path A0-B9-A43, transversal view, (c) ICD.

imply accurate simulation and adjustable fabrication processes. Research must also incorporate quantitative analysis methods on the impact of geometric differentiation on process efficiency. Quality control must include multi-criteria process monitoring through recording and analyzing production data. Finally, the applicability of RCFW for the prefabrication of large-scale building components should be practically and experimentally verified through demonstrators at the building-scale.

3. RCFW method

RCFW capitalizes on mechanical anisotropy of fibrous materials, moving on from their dependence on formwork to exploring their form-finding potential [43]. Industrial robotics integration into CFW transforms this potential into fabricated reality.

3.1. Integration of additional geometries into the RCFW solution space

As suggested in the Research Gap section, our RCFW application addresses the challenge of winding large-scale building components with length/width ratios that proportionally define long structural elements.

Several design iterations considered two morphological candidates to define the inherent fabrication constraints: a surface-like component and a tubular, more elongated component. These candidates originated from two segmentation strategies for a prototypical dome structure: segmentation at the edges or at the structural network nodes. The fabrication-aware design process and the evaluation criteria for choosing the tubular morphology candidate are discussed in [51]. As a result, a component morphology with a 3:1 ratio (length: width) was selected. Minimal-surfaces that approximate the components' surface were generated based on network representations of domes and canopies. These represented structural building components mechanically assembled into multi-component nodes (Fig. 3). A description of the engineering method developed for testing fiber lattices for the chosen candidate morphology is detailed in [52,53]. The anticlastic component lattice geometry design is presented in [54].

The preliminary structural evaluation indicated the components' areas that need reinforcement to prevent buckling [53]. From here on, the minimal surfaces (Fig. 3a) served as input for the fabrication simulation and the fabrication system configuration. The geometric

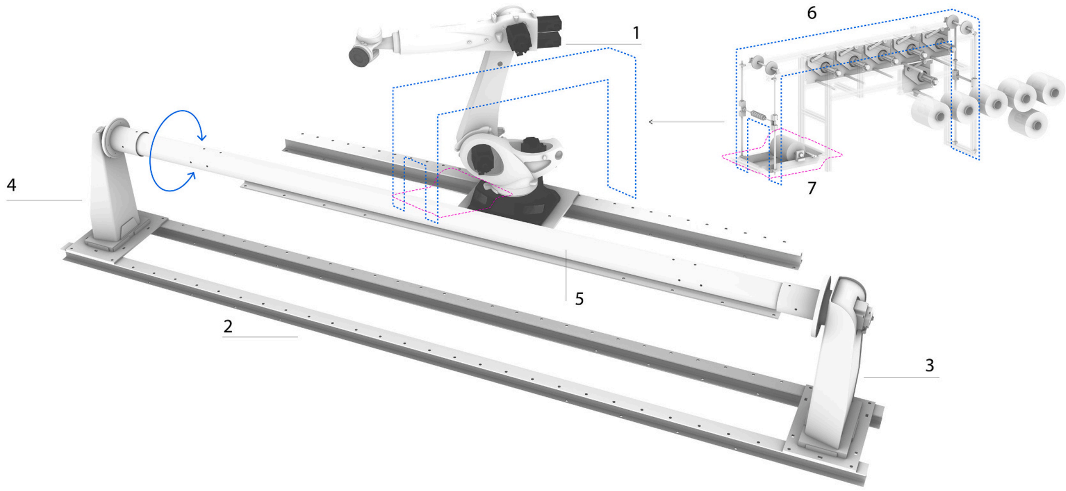
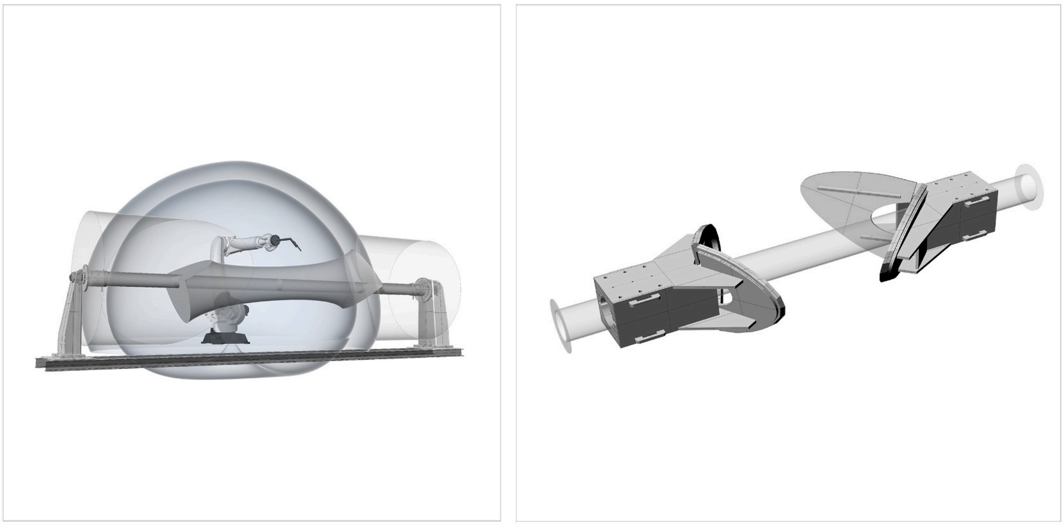


Fig. 5. The RCFW fabricator - kinematic system, fiber guidance, and fiber impregnation system: 1. industrial robot KR 210 R3100; 2. HEB 200 steel beams connected to concrete slab; 3. KP1 positioner passive part;, 4. KP1 positioner – active part; – 5. steel cylinder – rotational axis; 6. CF Creel, ,with integrated tensioning mechanism – mechanical dancer bar; 7. drum-type open resin bath, (c) ICD.



a

b

Fig. 6. The RCFW fabricator: a. robot work envelopes: robotic manipulator and external rotational axis - perspective; b. timber winding tool, (c) ICD.

characteristics of the surfaces and underlying segmentation logic were closely coordinated. The progression from component design idea to the tubular component compatible with a modular building system is presented in Fig. 3a. A generic segmented hemisphere populated with locally adjusted tubular elements is illustrated in Fig. 3b.

For connection and assembly, the initial hyperbolic geometry requires modification from planar circular boundaries to boundaries resulting from the intersection of multiple components in the nodes (Fig. 3a).

An example of a winding sequence that approximate the initial geometry is presented in Fig. 4. At its simplest, a coreless-wound fiber lattice consists of alternating fiber circuits, i.e., AB, BA, AB, BA. These are constructed between discrete winding positions evenly distributed on boundary curves A and B. The fiber rovings start out laying straight between their supports (slightly deformed under self-weight). They are iteratively deformed as new rovings are added on top under controlled pre-tension, a process described as *reciprocal deformation of free spanning fibers* [54].

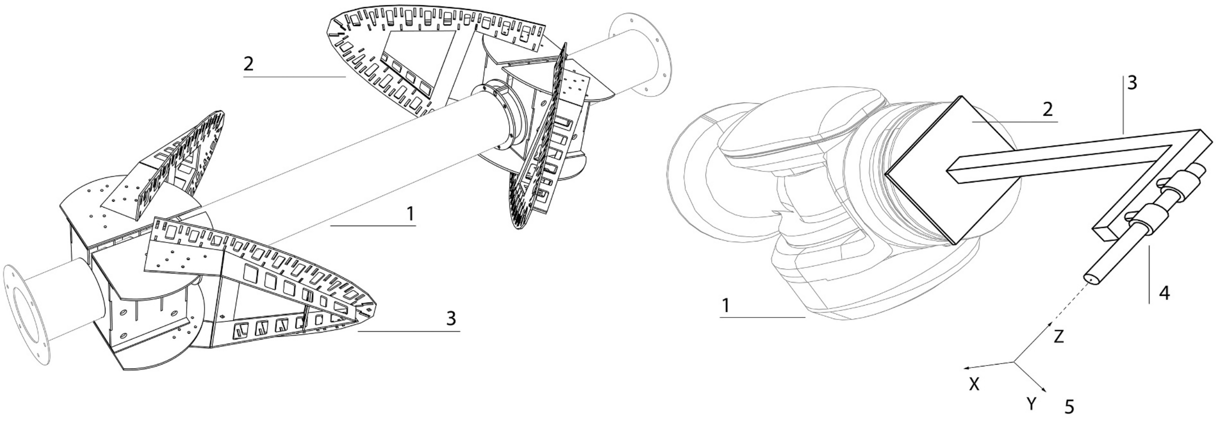
Ultimately, a 3D anticlastic lattice (Fig. 4) emerges from circuits' sequential disposition (i.e., A0-B9-A43…). The ordered data structure of 3D positions that denote the intended connectivity is called *a fiber syntax* [49,54] and constitutes a topological input for RCFW.

3.2. *Industrial robotics and industrial textile technology for RCFW*

3.2.1. *Design of the RCFW fabricator*

Analyses of the fabrication process for the ICD/ITKE RP 2013–14 [46] and of the Elytra Filament Pavilion [49] indicated that component scalability was essential for larger composite structures. In [46], scalability is addressed by utilizing two synchronized robotic arms to maintain a programmable distance between modular winding tools. However, this solution is only effective for components limited in length (depth) since the robot reach can easily be exceeded when approaching the stationary payout eye [9]. In [49], the kinematic system is simpler because significant process complexity is transferred to a modular winding tool. However, given that the maximum component dimensions depend on the robot's reach, this solution seems project-specific.

Upscaling of the additive manufacturing process and the composite component were the two most significant significant challenges and are described next. This led to a new kinematic system configuration, updated robot programming and control methods, and suitable RCFW tooling design.



a

b

Fig. 7. RCFW tooling: a. winding tools: 1. metal tube – interface with the KP1 rotational positioner; 2., 3. Modular steel winding tools; b. robotic end-effector - modular fiber guide: 1. KR 210 robotic manipulator wrist; 2. end-effector flange connection; 3. end-effector body – metal tube, square cross-section; 4. end-effector fiber guide - ceramic-fitted steel tube, round cross-section; 5. TCP local Cartesian coordinate system, (c) ICD.

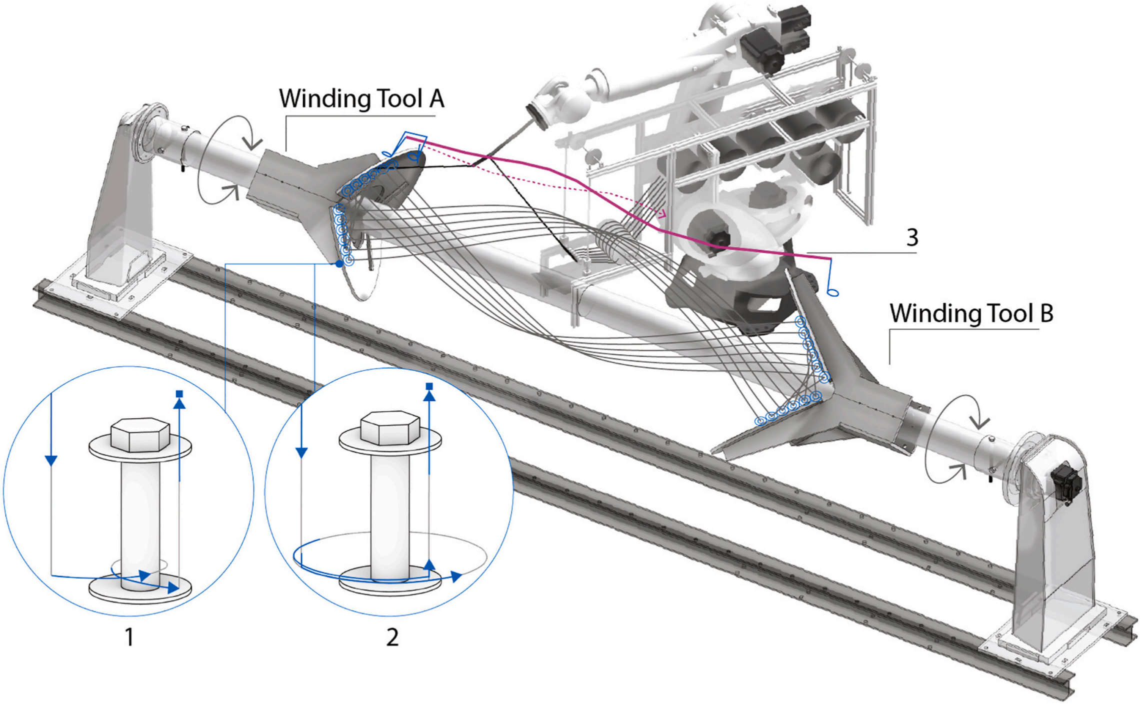


Fig. 8. The RCFW fabricator winding sequences - wrapping and motion sequences: 1. wrap across; 2. wrap around; 3. span across, (c) ICD.

3.2.2. Kinematic system

The kinematic system (Fig. 5) was configured around a stationary, floor-mounted robot that interacted with modular winding tools. These tools were mounted on mechanically-coupled one-axis industrial positioners. The selected robot (Appx.1 - Table 5) provided an adequate combination of payload, work envelope (Fig. 6a), and software capabilities. The model selection was motivated by process forces evaluated at up to 50 N combined with the weight of the robot end-effector of ~5 Kg, but foresaw:

i. utilization of heavier tools
ii. induction of higher pre-tension forces
iii. manipulation of the winding tool by the robot

The production system's envelope is the intersection of the hemispherical robot work envelope with a horizontal-axis cylinder that encapsulates the geometry of the two external winding tools. A rotational axis geometrically identical to the component axis was introduced to ensure all robot targets can be reached (Fig. 5:5; Fig. 6). An industrial positioner provided the necessary payload and torque to manipulate the winding tools, their infrastructure (up to 300 Kg), and the composite piece's added weight (up to 80 Kg, Appx.1 - Table 7).

3.3. RCFW tooling

3.3.1. Fiber source and impregnation system

The fiber source and impregnation system design targeted functionality, compactness, ease of maintenance, and robustness. It included fiber storage, integrated mechanical tension control, and a drum-type, open epoxy resin bath (Fig. 5:7). For CF, fibers were delivered from a modular creel with six bobbins capacity (Fig. 5:6). Because of the different unspooling principle (from the center of the spool), GF bobbins were arrayed not in a creel but around the robot manipulator.

3.3.2. RCFW end-effector

The robotic end-effector served two main functions: (i) guide the resin-impregnated fiber bundles around winding pins and (ii) facilitate quality control of the composite element. Function (i) was dimensioned for a 300 K fiber bundle. The end-effector build is relatively simple (Appx. 1: Table 6; Fig. 7b). The tool is composed of a steel tubular profile of adjustable length, attached to robot axis 6, and an aluminum fiber guidance tube mounted perpendicular to the first tubular profile (Fig. 7b). The tube axis represents the tool direction Z-axis originating at the tool center point (TCP). The fiber enters the guidance tube through one extremity and leaves it at the TCP. Function (ii) was achieved using ceramic eyelets fitted to tool/fiber contact points to minimize friction and eliminate fiber damage.

3.3.3. Modular winding tools

Similar to [46,49], the impregnated fiber rovings are spanned between metallic modular winding pins. Newly-developed robot-external winding tools provide the physical infrastructure for the three-dimensionally disposed winding pins. The winding tools are mechanically fixed to the external kinematic system through a seven-meter-long and 0.26 m in diameter hollow steel cylinder. The maximum distance reachable by the robot – 6.2 m, was an essential parameter in motion planning and informed the components' overall design. The component geometry's exact orientation and position to the rotational axis C (Fig. 3a) were physically encoded in the tooling (Fig. 5:5). Prototypical winding tools were first produced in timber (Fig. 6b) and subsequently constructed from steel (Fig. 7a). For efficient load induction, and unlike previous applications, the winding pins were mounted in normal orientation to the fibrous body [52]. Winding pin orientation was mechanically encoded in the tool geometry: instead of fixing the winding pin rigidly, winding pins were housed in a metal cartridge adjustable to design specifications [51]. In the design model, all pin orientations were remapped to discrete angle intervals with a 10° increment [52]. This angle included an additional 10° rotation necessary for the fiber rovings to slide to the bottom of winding pins and distribute evenly.

3.3.4. Calibration

The robot controller digitally referenced all elements of the kinematic system and tooling through a calibration procedure that included using a genetic algorithm to optimize the position of the multiple

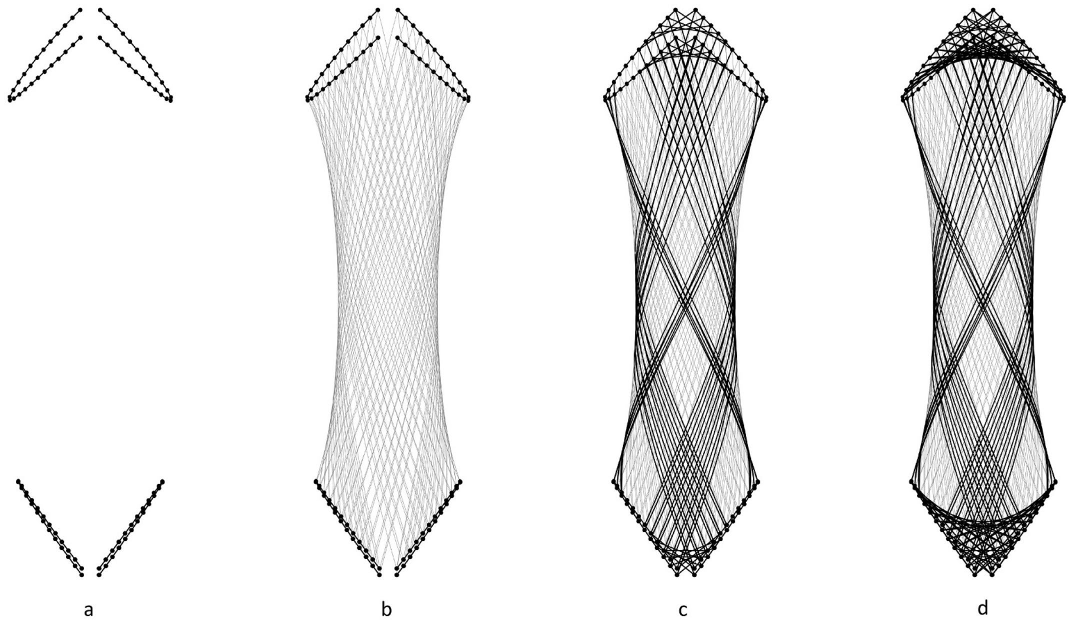


Fig. 9. Tubular G/CFRP component, fiber layup : a. edge ring syntax - CF; b. elastic lattice - GF; c. main reinforcement lattice - CF; d. corner reinforcement lattice – CF, (c) ICD.

mechanical sub-ensembles. Axes A4-A6 were set to 'rotational', thereby overriding the manufacturer's axis limitations [55]. Calibration of the winding effectors involved teaching every winding point and storing the data in a data module. Once calibration was completed, the module was parsed by the motion-planning algorithm. The three-dimensional pins' real-world position and orientation were used to generate a dynamic digital model of the tooling and of the geometry to fabricate.

3.3.5. *RCFW process*

In this RCFW application, dry fiber tows travel from the GF and CF fiber sources through the impregnation and tension control mechanisms to the end-effector and are subsequently pulled by the robot and wound around pins. In RCFW, the robotic end-effector does not touch the winding tool or the emerging fiber lattice. In contrast to FW or tape laying, CFW only utilizes minimal fiber supports in the form of the spatially positioned winding pins.

3.4. *RCFW motion planning and process control*

The requirements for robotic motion planning and process control included:

1. Adaptable bundling motion routines around winding pins
2. Modular organization of spanning sequences between winding pins:
   a. Optimal orientation of the winding end-effector in relation to fiber bundle while traveling
   b. Offline adjustment for the best orientation for every travel point and procedural remapping of its position in the robot working range
   c. Offline evaluation of optimal robot poses during CFW, to match the intended directionality of the fiber

Consequently, the end-effector TCP positions were constrained to strategically-chosen positions of the robot-external winding tools for efficient tool cycles. Robot-targets were procedurally rotated around the external axis at different angles calculated by a digital tool developed during the research. A similar procedure is known from Reichert et al. [44]. Our updates of the procedure are threefold. First, the robot targets are remapped along a 3-dimensional field containing the positions of all motion targets – rather than in a single plane. This update allows added control over the robot's specific poses in different tool cycles (Fig. 8; Appx. 1 - Tables 8, 9). Second, the remapping is horizontal, along the positioners' external axis, passing the robot's vertical plane of symmetry – more suited for floor-mounted robots. This enables maximum lateral reach, hence the ability to uninterruptedly perform ample motion sequences. Third, it integrates reorientation sequences at the end of each travel sequence: geometric checks determine the optimal orientation (Appx. 1 - Table 9: 1–4).

The RCFW motion was programmed offline. Adaptive methods for robot control and programming were developed based on Object Oriented Programming [56] in the Python and C#, inside the CAD modeling software Rhinoceros [57] and algorithmic modeling tool Grasshopper [58]. The updated motion-planning methodology incorporates several key developments compared to the motion planning precursors reviewed.

For the ICD/ITKE Research Pavilion 2012(Fig. 2a) [44], the ICD/ITKE Research Pavilion 2013–14 (Fig. 2b), and the Elytra Filament Pavilion (Fig. 2c) [46], the fiber-wrapping around winding pins constituted the main feature of the motion planning algorithm. Apart from robot reorientation steps executed between winding pins, the fiber wrapping and spanning sequences were not differentiated. The fiber path between winding pins was approximated either as a geodesic curve on the component's surface or as a straight line between winding pins, both shortest path representations. This motion-planning solution was optimal, given the relatively straight and long fiber paths encountered in [44] or the relatively small component length characteristic of the designs in [46,49].

In the presented research, the fiber component is characterized by a length/width ratio larger than 3:1. The fiber syntax design includes fibers that wrap around the lattice body at obtuse angles (Fig. 9c). These fibers can easily slide away from the intended position. Hence, the geodesic or straight-line methods cannot accurately describe fibers that wrap around at more than 180° since those would be approximated as the shortest path between winding pins supports. This additional design constraint was reflected in the new motion planning strategy. Consequently, the wrapping and spanning motions were differentiated in separate, consecutively executed RCFW routines, which allowed enhanced control over both.

Compared to previous fabrication methods [44,46,49], the spanning sequence is generated based on geometric input from the syntax design (Appx. 1 - Table 8). Every fiber path between winding points is discretized at adjustable intervals, allowing the TCP to follow the designed path for fibers that wrap around the composite lattice at angles that exceed 180°. The distance from the TCP to the composite lattice is also adjustable: based on an analysis of surface curvature, spanning points are mapped closer or farther to the composite lattice. Smaller distances to the lattice are preferred if surface curvature is high: this ensures precise fiber deposition and structural depth buildup. Larger distances to the lattice are preferred if surface curvature is low: here, fibers tend to lay straight, a property of RCFW exploited in designing the characteristic reinforcement grid [54] on the components' flatter areas.

Furthermore, the wrapping sequences (Fig. 8; Appx. 1 - Table 8) are generated separately from the spanning sequences: each spanning sequence begins and ends with a robot target object designating the required orientation for a smooth winding motion. The orientation of the winding pins is represented by a plane tangent to the component surface. The Cartesian position and orientation of these points are inputs to a parametric template written in KUKA Robot Language (KRL) that generates a suitable winding motion. Additional features were added to determine if winding happens between the two winding tools (boundaries of the component) or between points on the same tool (same component boundary). This made the winding code modular and allowed differentiated robot velocities at wrapping or spanning motions. The differentiated wrapping and spanning motions were collected into a template catalogue easy to adjust, extend, and debug.

In another development from [44,46] and [49], winding pins' orientation was changed from tangent to the lattice surface to normal to that surface. This orientation better matched structural load-induction requirements [52]. Consequently, the motion-planning methodology incorporated the possibility to wrap winding pins of multiple orientations- (defined by winding effector *Z*-axis, Fig. 7b) relative to the component surface.

Finally, an added control feature improved the winding end-effector's orientation during the newly-implemented spanning motion. It was determined that, especially in spanning operations, the angle between the tool and the currently-laid fiber is critical to correctly apply the composite without damaging the fibers. Consequently, the spanning motion sequence incorporated an evaluation step, bringing the effector in alignment (favoring an obtuse angle) with the currently laid fiber direction.

In the final stage of motion path generation, the procedurally-generated toolpath was parsed into KRL code by a digital tool and directly uploaded to the robot controller via Ethernet. The robot programming methodology enabled fast and accurate simulation of the winding motions. The digital environment replicated the mechanical and spatial characteristics of the physical RCFW setup with millimeter precision, proving essential for the reliability and repeatability of the process, well within building tolerances.

4. Fabrication case study: The BUGA Fibre Pavilion

The BUGA Fibre Pavilion (Fig. 12) [59–61] is the building demonstrator for the presented RCFW application. The research and development of the project were done by the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, for the client Bundesgartenschau Heilbronn 2019 GmbH. FibR GmbH executed the industrial fabrication of the pavilion's load-bearing structure (Fig. 14).

4.1. Research and development: RCFW of a hyperboloid tubular building component

4.1.1. RCFW system input: fiber syntax

As defined in section 3.1, the term *syntax* denotes an ordered list of Cartesian positions, representing a continuous fiber path between winding pins. In fabrication simulations, syntaxes are represented by polylines between winding pins (Fig. 4 and Fig. 9). Both physical and computational models were utilized to evaluate the reciprocal deformation of free-spanning fibers and the subsequent generation of the required fiber syntaxes [42]. Fiber-to-fiber intersections reduce the buckling length of cured fiber bundles. Procedural fiber syntax design ensures that fiber-to-fiber interaction is digitally controllable, according to structural and aesthetic requirements.

Table 1
G/CFRP Anisotropic material system.

Fiber		
Material	**Brand**	**Product**
GF	OCV	PS2300/2400
CF	Teijin	STS40 F13 48 K 3200tex CP

Matrix composition			
Function	**Brand**	**Product**	**Ratio**
Epoxy resin	Hexion	MGS LR 135	0.700
Hardener	Hexion	MGS LH 138	0.300

Fiber syntax design considers material properties for the additive manufacturing of an initial elastic lost-mold (Table 1). GF has higher elasticity than CF (Fig. 9b); hence, it keeps deforming longer in the RCFW process. CF strands iteratively reinforce (Fig. 9c, d) the initial GF surface. The sequential additive process ensures that fibers interweave to decrease buckling length. Each newly laid fiber bundle lies on the previously created lattice through incremental tensioning, deforming it further. Fiber pretension control is thus essential to obtain the highest mechanical performance [62]. Every different component form requires a bespoke fiber layup [63]. Fiber syntax design methods were described in detail in [54].

4.1.2. RCFW of the building component

The building component prefabrication case-study evaluated the integration of design-engineering and fabrication methods. The key objectives of the building component demonstrator were: (i) to experimentally test the interdisciplinary R&D framework; (ii) to experimentally test the digital design-to-robotic fabrication integrated loop; (iii) to control and calibration of fabrication parameters; (iv) to develop academia-industry data exchange protocols; (v) to implement a hybrid fabrication process where minimal human intervention precedes complete automation.

R&D supported by prototyping was conducted at ICD's Computation and Construction Laboratory [64]. The fabrication setup utilized a 3 × 6 × 2-m workspace that enabled the fabrication of building components measuring up to 1.5 × 1.5 × 5 m.

The robot initially wound two GF layers connecting all winding pins. The CF reinforcement layers were wound next, succeeded by additional CF layers that reinforce the component's extremities, ensuring a precise component/component assembly interface. Figs. 9 and 10 illustrate the design and fabrication of the successive layers. The demonstrator was a four-meter-long, elliptical cross-section, tubular building component with widths ranging from 1.3/0.8 m at extremities to 0.6/0.4 m and a weight of approximately 80 Kg (Fig. 11).

Motion-related winding operations were automated, and material system preparations were manual. RCFW sequences were digitally and physically simulated before implementation; if needed, the KRL codes could be easily regenerated to match changing design requirements. The demonstrator's fabrication was a milestone for research and development. It experimentally verified RCFW was suitable for the fabrication of long-span composite building elements.

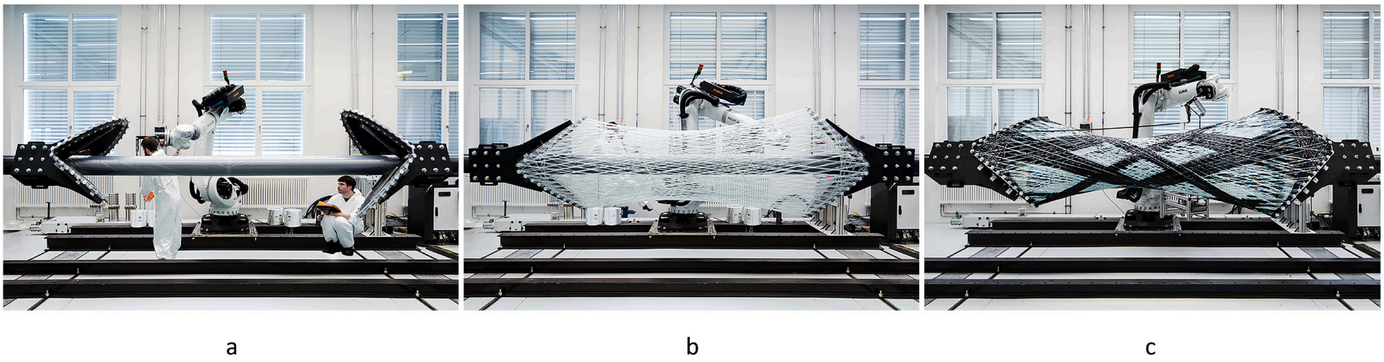


Fig. 10. The RCFW process: a. empty winding tool - calibration and preparation; b. winding of the GF elastic lattice; c. winding of the CF reinforcement slattices, (c) ICD

Fig. 11. RCFW demonstrator: G/CFRP composite element at 1:1 scale, (c) ICD.

4.2. *Industrial implementation: Fabrication of 68 load-adapted hyperboloid tubular building components*

RCFW opens up the possibility of *more geometry – less material* for composite construction. The proposed building system relies on components of relatively high internal curvature of their structural lattice. Hence, more voluminous structural components, compared to other pultruded CFRP or steel profiles.

4.2.1. *Industrial production*

The implementation of the developed RCFW process for industrial fabrication was conducted at FibR GmbH; for this, ICD and ITKE provided a complete fabrication data protocol.

The R&D process lasted for 18 months, including RCFW and industrial fabrication, assembly, installation, and building monitoring (Appx. 2 Table 10). Sixty percent of the project time was R&D. The project management overlapped with the entire Bundesgartenschau 2019(Federal Gardening Show) . Here, it can be seen that the timeframe allocated to industrial fabrication is relatively short, representing 17% of the project time.

Development and structural verification of the building component (months 10–18) concluded the project's R&D phase. This development was simultaneous with the last stages of component design. The 60 building components necessary for the loadbearing system were prefabricated in four months (Appx. 2 - Table 11). Two-component types simultaneously entered production, which ensured that while the first component type specimen was wound, the other could be tempered. It also meant that a single modular winding toolset was sufficient for fabricating all five components in a series, reducing equipment costs. After tempering, the winding tools were reused. The anisotropic G/CFRP material system utilized is described in Table 2.

Table 2
G/CFRP material system utilized in the RCFW process of the building demonstrator, (c) FibR GmbH.

Fiber		
Material	Brand	Product
GF	OCV	PS2300/2400
CF	Teijin	STS40 F13 48 K 3200tex CP

Matrix composition			
Function	Brand	Product	Ratio
Epoxy resin	Hexion	MGS LR 135	0.719
Hardener	Hexion	MGS LH 138	0.164
Hardener	Hexion	MGS LH 287	0.088
UV Protection	HP Textiles	BEL 91	0.029

The fabrication process (Fig. 14) started with the less loaded, bilaterally-symmetrical components of the dome apex C5 and C6 (Fig. 13, Fig. 16, Appx.2 Table 11). It ended with component types situated at the perimeter of the dome. These were the longest and most structurally loaded component types - C1.2 and C1.2m. Each component took only 24 h to fabricate temper and release from the winding tool (Appx.2 Table 11).

Table 3

RCFW dataset for component series C2 and C2m, raw data for each component in the series, (c) FibR GmbH.

C2	Production Time			C2m	Production Time		
Component no. per series	**Winding (H)**	**Ancillary Operations (H)**	**Total(H)**	**Component no. per series**	**Winding (H)**	**Ancillary Operations (H)**	**Total(H)**
1	7:16	1:29	**8:45**	**1**	4:47	1:23	**6:10**
2	6:21	1:56	**8:17**	**2**	3:34	1:00	**4:34**
3	4:34	1:00	**5:34**	**3**	2:44	2:59	**5:43**
4	4:19	1:26	**5:45**	**4**	3:36	2:19	**5:55**
5	6:16	0:43	**6:59**	**5**	5:18	0:52	**6:10**
Average	5:45	1:18	**7:04**	**Average**	3:59	1:42	**5:42**
		Total	**35:20:00**			**Total**	**28:32:00**

4.2.2. *Fabrication data set*

A fabrication-time breakdown is presented for component types, C2 and C2mirrored(C2m), relatively short and geometrically asymmetrical. Winding times, ancillary operation times, and total fabrication duration are presented in Table 3 and Fig. 15. Throughout the process, more than one hour was gained in fabrication time per component. This efficiency increase translated to 7 h between series C2 and C2m. Fabrication of each component series averaged one week.

5. Analysis, evaluation, and discussion

In total, 68 composite components of variable geometry and fiber structure, with an average weight of 80 Kg, were industrially fabricated (Fig. 14). Sixty components only weighing 7,6 Kg / m^2 were utilized in the loadbearing structure(C1.1-C6). The additional components comprised:

- two pre-series components (Pre_01, Pre_02)
- two components used in the assembly and structural test (NT_01, NT_02)
- three components utilized in destructive structural tests
- one exhibition component(E)

In total, more than 150,000 m of G/CFRP were wound for the BUGA Fibre Pavilion structure. As a result of the segmentation rationalization, the amount of component types has been significantly reduced. The geometric difference between the resulting 12 types lies in their symmetry/asymmetry variable length and fiber layup (Fig. 13).

5.1. *Trends in RCFW fabrication efficiency*

A survey of the industrial fabrication data is presented below. Fig. 16a indicates a decreasing trend in fabrication time between similar geometry components (C5-C6, C2-C2m). All component types, including the highly similar C5 and C6, follow that trend. The C5 series had the longest fabrication time. This fact can be explained by the fact that C5 was the first component type to enter production, which accounts for the increased fabrication time that included a measure of skill-building. Robot path length (Fig. 16b) is 9–11% longer than the fiber length because of travel and reorientation requirements. The fabrication process data presented below illustrates that fabrication efficiency increases inside each component series while more geometrically-complex components take longer to fabricate. No direct correlation could be found between the production time and the length of the fiber. Thus, we can infer that the components' overall size and fiber length influenced fabrication-time less than factors such as process and tooling robustness. Nevertheless, it is expected that fabrication time will become directly proportional to fiber length as the RCFW technology matures and the equipment's reliability increases.

5.2. *Benchmark of the fabricated composite components against the digital design model*

For quality control, a geometric survey was executed for one specimen of every series. This procedure enabled a benchmark against the digital design model. The component cross-section is elliptical. Thus, three physical measurements were performed per component at component cross-section: major radius (R2) of the component elliptical cross-section, minor radius (R1) of the elliptical component cross-section, and perimeter of the component cross-section(P). Deviation

Table 4

Benchmark of the fabricated composite components against the digital design model: R1 – cross-section radius 1; R2 – cross-section radius 2; P – cross-section ellipse perimeter; L – component length, (c) ICD.

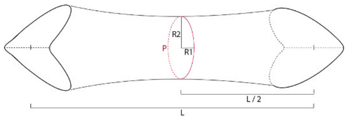
Component series						
	R1(m)		**R2(m)**		**P(m)**	
	simulated	measured	simulated	measured	simulated	measured
C5	0.24	0.23	0.29	0.3	1.7	1.7
C2	0.22	0.2	0.18	0.2	1.28	1.28
C6	0.24	0.2	0.29	0.3	1.68	1.68
C2m	0.22	0.2	0.18	0.2	1.28	1.28
C4	0.2	0.18	0.24	0.25	1.4	1.39
C3	0.2	0.19	0.22	0.23	1.33	1.33
C4m	0.2	0.18	0.24	0.25	1.4	1.39
C3m	0.2	0.19	0.22	0.23	1.33	1.33
C1.1	0.18	0.17	0.2	0.18	1.1	1.1
C1.1m	0.18	0.17	0.2	0.18	1.1	1.1
C1.2	0.18	0.17	0.2	0.18	1.1	1.1
C1.2m	0.18	0.17	0.2	0.18	1.1	1.1
Standard deviation	0.02		0.02		0.01	

Fig. 12. Top view of the RCFW building demonstrator on the Bundesgartenschau 2019 grounds, Heilbronn, Germany, (c)Roland Halbe.

from the mean was equal between horizontal and vertical radii of the cross-section (Table 4). The standard deviation between the measured and simulated lengths of the elliptical cross-section is well within building tolerances. Critical for the assembly of the composite components is the precision of the winding pin interfaces. The component circumference, while structurally significant, is not a construction tolerance constraint. We can thus conclude that tolerances between wound reality and the design models are acceptable. Nevertheless, future development is still needed towards a more precise and nuanced digital representation of the physical fiber lattice, including digitizing the surface through 3D scanning.

Concerning the fabrication method, the newly implemented features described in Section 3.4 improved the motion planning method's modularity. Syntax input was differentiated into spanning motions at adjustable intervals. The TCP proximity to the composite lattice is also adjustable based on the components' morphological features: geometry of the boundary conditions and local surface curvature.

Because existing composite building codes did not sufficiently cover the material system's application into a novel structural design, several structural proofs utilizing empirical tests were required under Eurocode 0 [65]. These were performed in collaboration with the German Building Authority. The capacity to accurately predict a coreless-wound composite component's form and structural behavior will simplify currently laborious benchmarking and testing procedures.

However, structural design and benchmarking exceed the current paper's scope, which is to report on the advances in RCFW fabrication methods.

Further validation occurred at building system assembly: the sixty components of the building system were easily lifted in position by a crane and precisely assembled without any permanent building scaffolding in just two weeks to create a 400 m^2 structure with a free span of 23 m (Appx.2 Table 10; Fig. 12 and Fig. 17).

5.3. Evaluation and discussion on the RCFW industrial fabrication process

Over the entire fabrication process, fabrication time and ancillary operations time decreased by over one hour per component type. Although fluctuating, the average production time could be reduced by more than two hours between the first and the last wound series (Fig. 16). An overall increase in productivity, correlated with a relative decrease in production time, was observed throughout every component series fabrication.

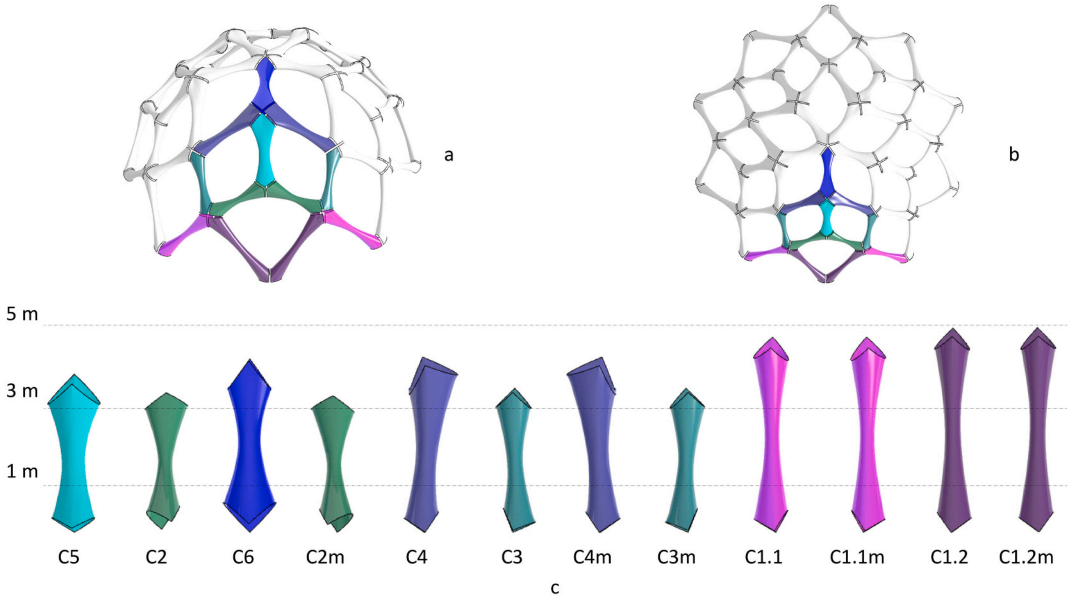


Fig. 13. RCFW industrial prefabrication of the 12 different component types: a. axonometric of the dome structure, ; b. horizontal projection of the dome structure; c. size and geometry comparison for the 12 different component types, in fabrication order , (c) ICD.

Fig. 14. The RCFW industrial application: The FibR factory floor, Stuttgart, Germany, (c)FibR GmbH.

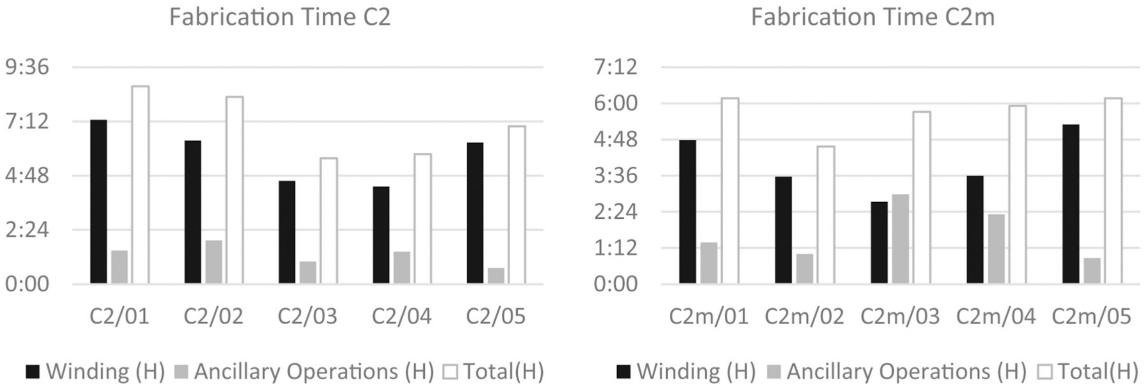


Fig. 15. RCFW dataset for component series C2 and C2m, data visualization: winding, ancillary operations and total fabrication time for individual elements of the 5-component series, (c)ICD

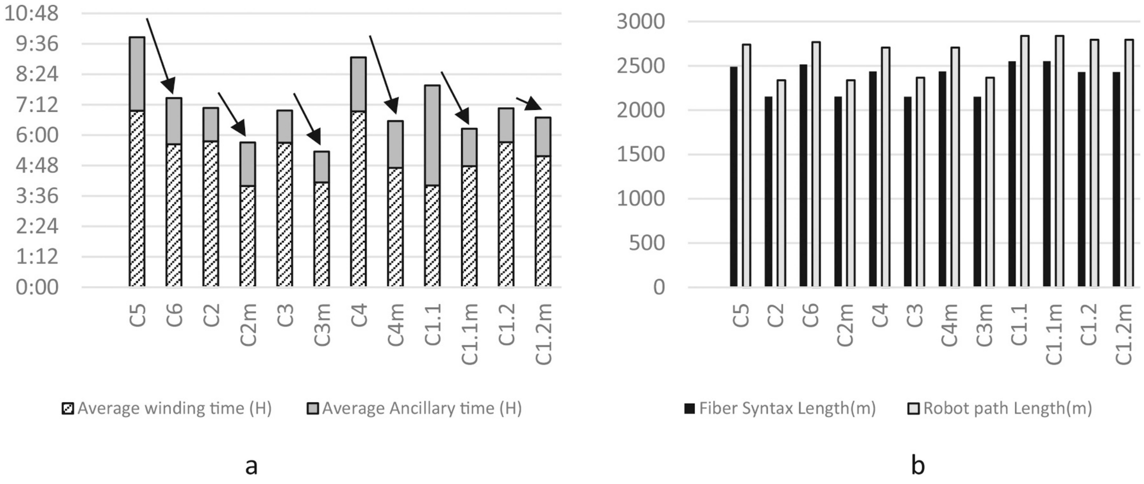


Fig. 16. Component geometry vs. component size, impact on production time, (c) ICD.

Fig. 17. Verification through assembly: the BUGA Fibre Pavilion loadbearing structure, Heilbronn, Germany, (c) ICD/ITKE.

Closer analysis of the fabrication data outliers (longer winding or ancillary operations times) could be attributed to human error or hardware malfunction. Although largely automated, the fabrication process included several manual ancillary operations. In RCFW technology, the industrial robot's integration and programming constitute the most technically challenging and time-consuming developments (Fig. 16). Similarly, the winding operation is the most time-consuming step in the fabrication process and requires high speed and precision.

Overall, the industrial process demonstrated robustness. Consequently, the production of fully customizable construction components is feasible utilizing the proposed RCFW application at high-quality standards and observing stringent certification procedures from the German Building Authority.

The significant fabrication time savings recorded during the process and the overall decreasing trend for the fabrication process duration suggest that substantial gains in efficiency can be obtained during R&D and even during industrial fabrication. This fact highlights the inherent potential of RCFW for reaching high productivity when industrialized and applied at scale.

6. Conclusion and outlook

In this paper, we first discussed the state of the art of composite fabrication methods in the industry and construction applications, highlighting the unique challenges and opportunities posed by composite construction through RCFW. Subsequently, we characterized a complete fabrication setup for RCFW. It was further illustrated how the motion planning and motion control methods were improved and automated to enable the transition to industrial prefabrication.

The research demonstrated that RCFW can be upscaled to the requirements of lightweight, long-span building construction. Thus, RCFW becomes the core of an industrial composite prefabrication process, enabling the realization of composite roof or dome structures out of individualized elements, previously very difficult to design or build. The BUGA Fibre Pavilion loadbearing structure was fabricated out of sixty composite components weighing only 7.6 Kg / m^2. The industrial fabrication process applied more than 150,000 m of composite materials. It demonstrated that RCFW can speed up building construction processes and timelines. Its success paves the way for further similar applications in long-span roofs or canopies. The ambitious R&D timeframe of two years was only feasible because of the flexible integration of industrial robotics and advanced composite manufacturing technology. Nevertheless, fabrication data analysis suggests the technology still holds significant potential for productivity and fabrication time gains.

Before a broader application of the RCFW technology in the industry, research needs to address several key areas. First, ancillary operations must be automated, leading to improved precision and reduced downtime. Second, the current pre-planned fabrication routines must transition towards cyber-physical winding strategies where path correction and sensor-guided motion directly adapt during execution. Third, cyber-physical RCFW will require new equipment for online monitoring and control of crucial fabrication parameters. Cyber-physical process-monitoring and quality-control are being investigated in the research project Additive Manufacturing Methods for Composite Structures [66] and the DFG Cluster of Excellence Integrative Computational Design and Construction at the University of Stuttgart [67], with further building-scale applications expected within the next three years. The automated acquisition of fabrication data sets, currently under implementation, will enable a deeper understanding of this fabrication process. Thus enhanced, RCFW will become more widely utilized in construction and further capitalize on its exploration of digital craft and automation, so characteristic for its authentic aesthetics.

While addressing some of the critical methodological and practical challenges posed by composite construction, we engaged in interdisciplinary academic research and industry cooperation. Coordinating our efforts with the industry, the planning community, and the public building authority proved essential to meeting certification, productivity, and scientific research goals. This synergy ultimately delivered results at building scale: as part of a new wave of robotically fabricated buildings, the BUGA Fibre Pavilion exemplifies an integrative mode of working, enabled by computational design and smart manufacturing. The development of its core technology, RCFW, accelerates the emergence of a more competitive and productive composite construction industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1. Industrial robot

Table 5
Specifications of the RCFW system: the industrial robotic manipulator, (c) ICD.

Robot - KR 210 R3100 Quantec Ultra	Specifications
Maximum reach	3095 mm
Rated payload	210 kg
Rated supplementary load, rotating column / link arm / arm	0 kg / 0 kg / 50 kg
Rated total load	260 kg
Pose repeatability (ISO 9283)	± 0.06 mm
Number of axes	6
Mounting position	Floor
Footprint	830 mm × 830 mm
Weight	approx. 1154 kg
Controller	KRC4

A.2. End-effector data

Table 6
Specifications of the RCFW system: the robotic end-effector, (c) ICD.

RCFW – Robot End effector	TCP data
X, Y, Z offset values for TCP coordinate system world coordinates CAD	{150, 50, 500}
A, B, C rotations of about the X, Y, Z axes at TCP	{90, 0, 90}

A.3. Positioner data

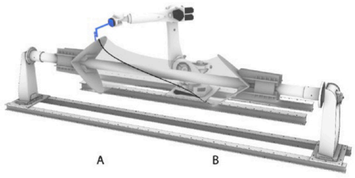
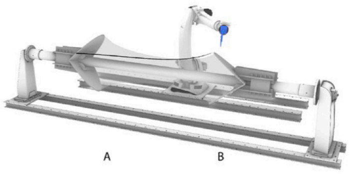
Table 7
Specifications of the RCFW system: the industrial positioners.

Positioner	Payload	Max. load torque A1	Moment of inertia A1
KP1-H1000	1000 kg	1472 Nm	719 kgm2

A.4. Fiber looping sequences

Impregnated fiber bundles are guided around winding pins in a motion termed looping [46]. Robotic looping is procedurally built around each winding pin and separately encoded for maximum adaptability. The geometric parameters of a pre-programmed motion sequence are altered to cater to local geometric constraints. A looping behavior composed, i.e., out of linear robotic(LIN) motions [68] requires five motions around the winding pin. These correspond to an entry/exit point and a minimum of four guiding points (Fig. 8:1,2). The procedure derives the optimal orientation of the winding targets and ensures that the robot can execute the entire motion sequence. Standard robot poses for winding tool extremities A and B are presented in Table 8(1;2) and Fig. 8.

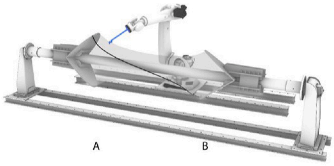
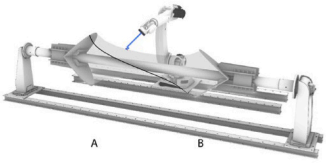
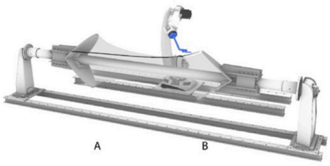
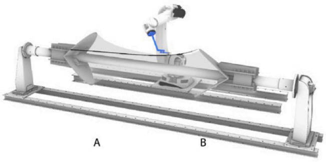
Table 8
RCFW characteristic fiber looping sequences 1: robot pose at winding tool A; 2: robot pose at winding tool B; A1-A6: axes of the industrial robot; Axes A1-A6 combination describes a robot pose, (c) ICD.

RCFW Event	Robot Pose – Axis values
1. 	[**A1**: 45°; **A2**: -85°; **A3**: 85°; **A4**: -75°; **A5**°: 30°; **A6**°: 90°]
2. 	[**A1**: -45°; **A2**: -85°; **A3**: 85°; **A4**: -75°; **A5**°: -30°; **A6**°: 90°]

A.5. Fiber winding sequences

Fiber winding sequences are designed to ensure that fibers are positioned in the correct orientations as they are added to complete the winding (Fig. 8:3). Since filaments in bundles are parallel, tailoring the fiber directionality is crucial for the composite's structural performance. Fiber directionality is defined as the relative angle at the winding pin, between the winding tool edge and the individual fiber bundle. Given the components' tubular geometry, cumulative fiber-bundle angles of a fiber circuit range 0–360°, a 180° cumulative angle define a half-turn helix curve around axis C while a 360° angle, a one-turn helix circuit. A computational method has been developed to define the robotic behaviors best suited for carrying out the traveling routines based on the design model's geometric inputs. In between looping sequences, the TCP follows the fiber syntax trajectory described in section 4.1.1. Depending on the syntax characteristics, points on opposite winding tool edges conditions(i) or the same edge(ii) must be wound. The two cases require different winding strategies:

Table 9
RCFW - characteristic spanning sequences: 1. Spanning position at start of fiber path A-B; 2. Spanning position on fiber path A-B; 3. Spanning position at start of fiber path B-A; 4. Spanning position on fiber path B-A; A1-A6: axes of the industrial robot; Axes A1-A6 combination describes a robot pose, (c) ICD.

RCFW Event	**Robot Pose – Axis values**
1. 	[**A1**: 15°; **A2**: -90°; **A3**: 90°; A4: 40°; A5: 40°; A6: 20°]
2. 	[**A1**: 0°; **A2**: -90°; **A3**: 90°; **A4**: 40°; **A5**:60°; **A6**: 5°]
3. 	[**A1**: -15°; **A2**: -90°; **A3**: 90°; **A4**: -40°; **A5**: 40°; **A6**: -20°]
4. 	[**A1**: 0°; **A2**: -90°; **A3**:90°; **A4**: -40°; **A5**:60°; **A6**: -5°]

i. Constitutes the most common winding motion sequence where the robot executes an ample motion consisting of two poses. At the end of this motion sequence, a reorientation allows the robot arm to approach the entry point of the looping motion optimally:

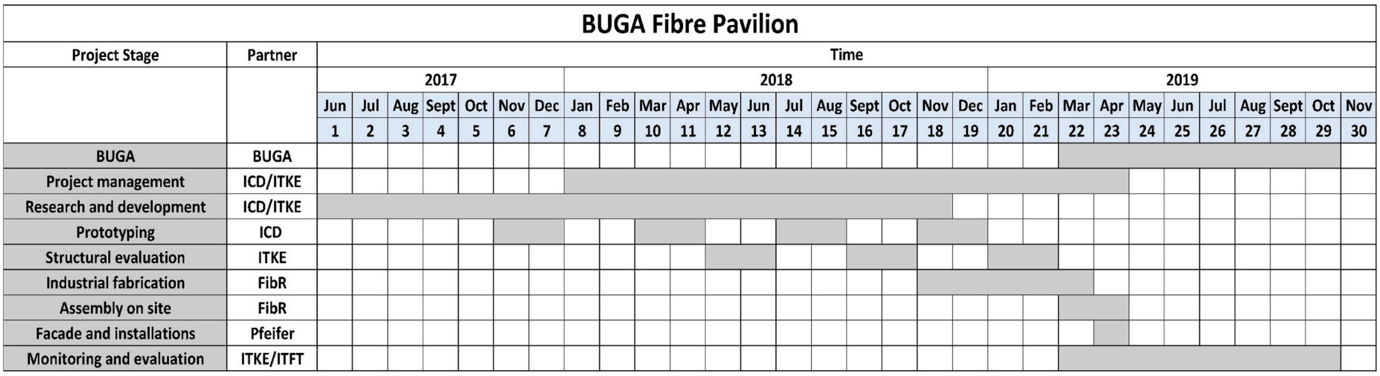
a. The poses described in Table8, 1;3 correspond to the arm being extended close to maximum reach, followed by an inclination of the end-effector such that the angle between fiber and the fiber guide tube is obtuse and tends to 180°.
b. The poses described in Table8, 2;4 correspond to the arm being retracted closest to the robot's vertical axis of symmetry. Here the robot positions the end-effector in configuration that avoids the Alpha5 [69] wrist singularity.

Traveling between points on the same side of the winding tool requires a reorientation step that allows an optimal approach of the next looping motion. The optimal robot reorientation pose is precalculated to minimize the inherent loss of tension associated with a short translational but increased rotational motion. Axes A4-A6 are set to 'rotational', thereby overriding the usual KUKA KR210 Quantec axes limitations [55] and allowing the axes to rotate continuously, a very useful feature when programming complex motion sequences. However, rotations of the robot wrist(A4-A6) of more than 360° would result in the tangling of the robot arm in the fiber. This situation is avoided through an integrated axis position check.

Appendix B

B.1. Schedule of the industrial fabrication

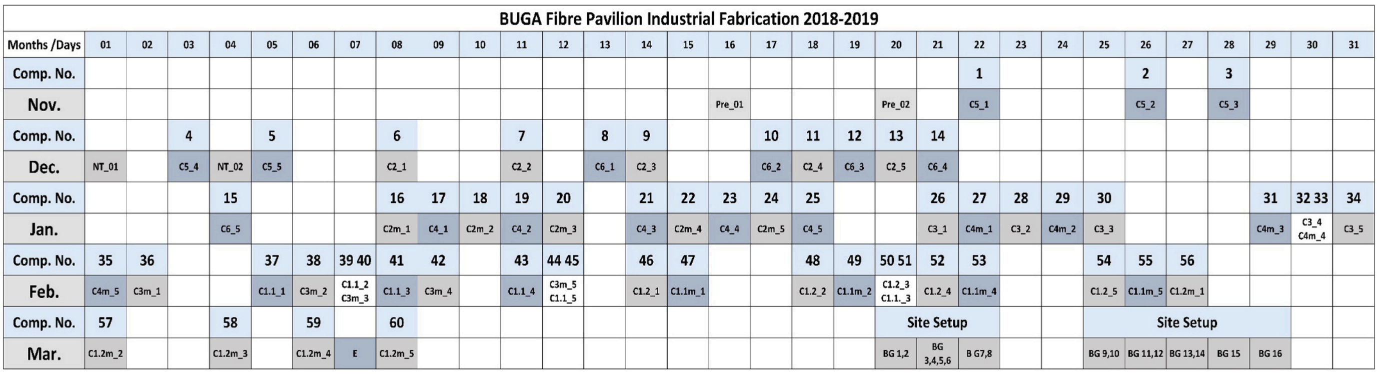
Table 10
BUGA Fibre Pavilion: project schedule, (c)ICD.



BUGA Fibre Pavilion

Project Stage	Partner	Time																													
		2017							2018												2019										
		Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
BUGA	BUGA																						▨	▨	▨	▨	▨	▨	▨	▨	
Project management	ICD/ITKE								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
Research and development	ICD/ITKE	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
Prototyping	ICD						▨	▨			▨	▨			▨	▨			▨	▨											
Structural evaluation	ITKE												▨	▨			▨	▨			▨	▨									
Industrial fabrication	FibR																		▨	▨	▨	▨	▨								
Assembly on site	FibR																						▨	▨							
Facade and installations	Pfeifer																							▨							
Monitoring and evaluation	ITKE/ITFT																						▨	▨	▨	▨	▨	▨	▨	▨	

Table 11
BUGA Fibre Pavilion: industrial fabrication schedule, (c)ICD.



BUGA Fibre Pavilion Industrial Fabrication 2018-2019

Months /Days	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Comp. No.																						1				2		3			
Nov.																Pre_01				Pre_02		C5_1				C5_2		C5_3			
Comp. No.			4		5			6			7		8	9			10	11	12	13	14										
Dec.	NT_01		C5_4	NT_02	C5_5			C2_1			C2_2		C6_1	C2_3			C6_2	C2_4	C6_3	C2_5	C6_4										
Comp. No.				15				16	17	18	19	20		21	22	23	24	25			26	27	28	29	30				31	32 33	34
Jan.				C6_5				C2m_1	C4_1	C2m_2	C4_2	C2m_3		C4_3	C2m_4	C4_4	C2m_5	C4_5			C3_1	C4m_1	C3_2	C4m_2	C3_3				C4m_3	C3_4 C4m_4	C3_5
Comp. No.	35	36			37	38	39 40	41	42		43	44 45		46	47			48	49	50 51	52	53			54	55	56				
Feb.	C4m_5	C3m_1			C1.1_1	C3m_2	C1.1_2 C3m_3	C1.1_3	C3m_4		C1.1_4	C3m_5 C1.1_5		C1.2_1	C1.1m_1			C1.2_2	C1.1m_2	C1.2_3 C1.1._3	C1.2_4	C1.1m_4			C1.2_5	C1.1m_5	C1.2m_1				
Comp. No.	57			58		59		60												Site Setup					Site Setup						
Mar.	C1.2m_2			C1.2m_3		C1.2m_4	E	C1.2m_5												BG 1,2	BG 3,4,5,6	B G7,8			BG 9,10	BG 11,12	BG 13,14	BG 15	BG 16		

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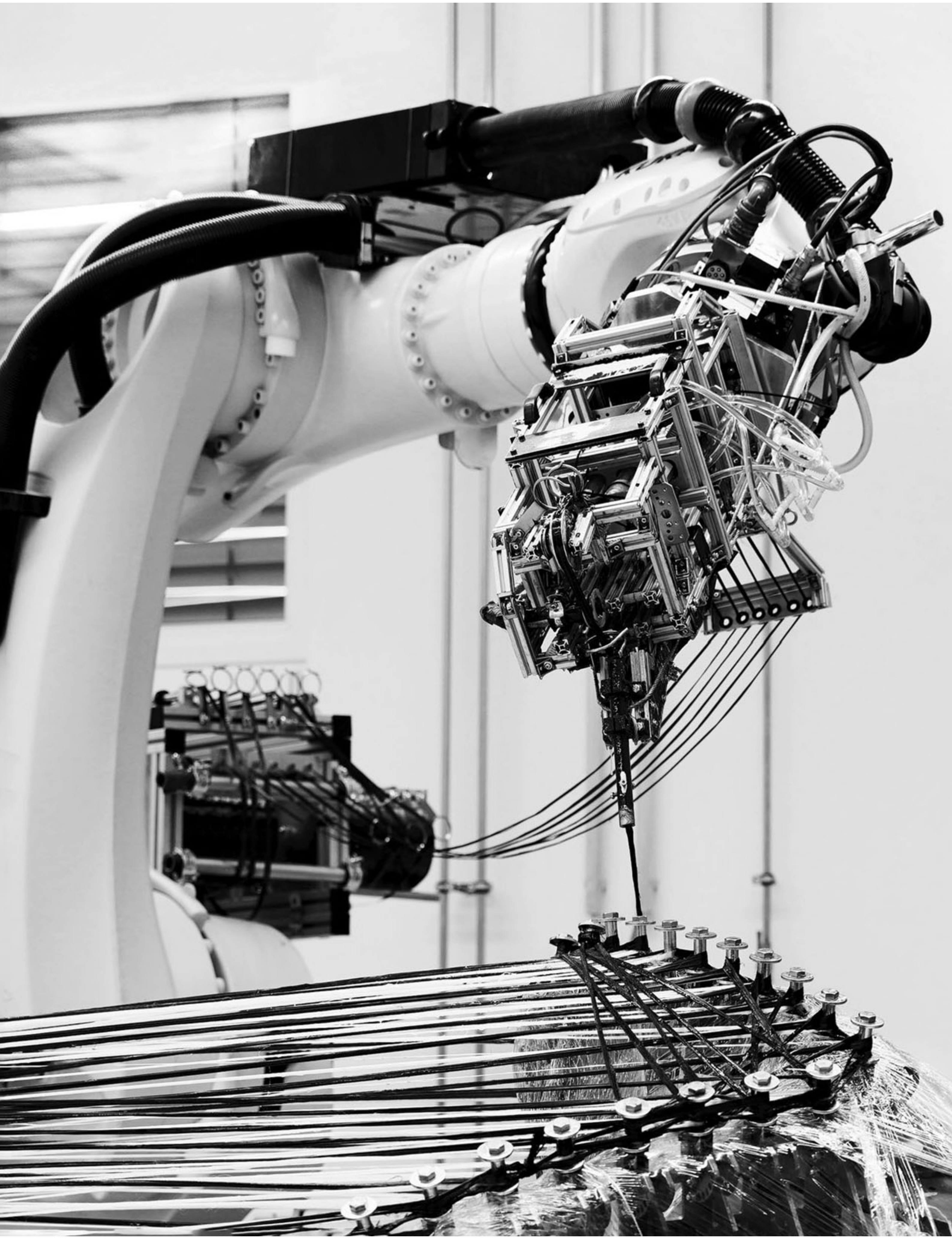
Article C: Additive Manufacturing of Large Coreless Filament Wound Composite Elements for Building Construction

S. Bodea, P. Mindermann, G. T. Gresser, and A. Menges, 2021. Additive Manufacturing of Large Coreless Filament Wound Composite Elements for Building Construction. 3D Printing and Additive Manufacturing [7]

The work presented in this article was conducted by S. Bodea, P. Mindermann, under the advising of G. T. Gresser and A. Menges. It builds upon prior research at the University of Stuttgart institutes ICD and ITKE and is complementary to published research by the authors [8; 7; 18]. The Journal article focuses on a cyber-physical RCFW fabrication method verified through the construction of a long-span tubular composite proof-of-concept element. The ICD researcher S. Bodea and the ITFT researcher P. Mindermann were in charge of research and development. The framework for collaboration was set by the ICD and ITFT. S. Bodea's contribution to the underlying research into CPRCFW is defined at the level of the conceptualization, design, implementation, and verification of the CPRCFW method with advising from A. Menges. S. Bodea also designed and operated the fabrication setup utilized in the fabrication of the long-span tubular composite proof-of-concept element. S. Bodea contributed to the design and implementation of the winding eye. Additionally, S. Bodea designed the fiber syntax for and fabricated the proof-of-concept composite element presented in this work. Additional assitance during fabrication was provided by P. Mindermann and B. Rongen with advising from A. Menges. As part of the underlying research presented in this publication, S. Bodea developed and implemented a fabrication data acquisition, analysis, and visualization methodology leading to the quantitative assessments presented in this publication, under advising from A. Menges. Research work conducted by S. Bodea closely aligns with the Additive Manufacturing of Large Fibre Composite Elements for Building Construction (AddFiberFab)" [61] research project let by ICD, University of Stuttgart.

The original research, scope definition, and organization of this journal publication originate from S. Bodea and P. Mindermann, under the advising of A. Menges and G.T.Gresser. The literature review for this publication covered the State of the art in cyber-physical production systems in the industry and in composite construction. The majority of the references were researched by S. Bodea, with additional references suggested by P. Mindermann and A. Menges. S. Bodea conceptualized the CPRCFW application, implemented the software and hardware necessary to realize the application, and characterized the feedback-based, sensor-informed application for process monitoring, fabrication data acquisition, and analysis presented in this publication. S. Bodea also formulated the prefabrication strategy for the research demonstrator, described the fabrication method's development, conducted, and systematized the experimental work included in this publication. P. Mindermann contributed original sections regarding the development of the material system, design and implementation of the experiments, design and implementation the the winding eye, and the fabrication of the demonstrator. A. Menges provided theoretical guidance and content revisions to crystalize the scope and highlight the original research contribution. S. Bodea developed the data acquisition methodology. S. Bodea and P. Mindermann developed the fabrication dataset analysis methodology. S. Bodea wrote the first draft and conducted the preparation of the manuscript with advising from A. Menges. All authors participated in revisions and responses to peer review.



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Additive Manufacturing of Large Coreless Filament Wound Composite Elements for Building Construction

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Abstract

Digitization and automation are essential tools to increase productivity and close significant added-value deficits in the building industry. Additive manufacturing (AM) is a process that promises to impact all aspects of building construction profoundly. Of special interest in AM is an in-depth understanding of material systems based on their isotropic or anisotropic properties. The presented research focuses on fiber-reinforced polymers, with anisotropic mechanical properties ideally suited for AM applications that include tailored structural reinforcement. This article presents a cyber-physical manufacturing process that enhances existing robotic coreless Filament Winding (FW) methods for glass and carbon fiber-reinforced polymers. Our main contribution is the complete characterization of a feedback-based, sensor-informed application for process monitoring and fabrication data acquisition and analysis. The proposed AM method is verified through the fabrication of a large-scale demonstrator. The main finding is that implementing AM in construction through cyber-physical robotic coreless FW leads to more autonomous prefabrication processes and unlocks upscaling potential. Overall, we conclude that material-system-aware communication and control are essential for the efficient automation and design of fiber-reinforced polymers in future construction.

Keywords: additive manufacturing, robotic coreless filament winding, fiber-reinforced polymers, fiber tension control, robotic fabrication, cyber-physical production system, robotic motion-control, automated construction

Introduction

THE BUILDING INDUSTRY represents 15% of global GDP[1] and is a leading employment sector,[2] yet it is one of the least digitized[3] and least productive[2] industrial sectors. Construction must close a productivity gap estimated in 2017 at 1.63 trillion dollars[2] and add more value to its core societal role. Automation and digitization can be leveraged for increased productivity. Digital fabrication research tackles these challenges while simultaneously addressing the rising demand for material-efficient construction through customized manufacturing.[4]

Additive manufacturing (AM) shifts the paradigm from mass-production to mass-customization in construction. The AM uses materials characterized by isotropic (concrete,[5–7] unreinforced plastics,[8] and metals[9,10]) or anisotropic (fiber-reinforced polymers [FRPs] with thermoplastic[11,12] or thermoset matrices[13]) material properties. These applications

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Opposite page: Cyber-physical robotic coreless filament winding in operation: robotic end-effector winding carbon fiber tows.
Image Credit: ICD / ITFT, University of Stuttgart.

profit from material science and industrial robotics advances, adapting their AM methods to construction-specific needs.[14]

The use of specific material systems must be application- and fabrication-process-aware. Long-span construction, for instance, demands lightweight, high-strength, and highly formable materials to achieve stiffness-through-form. The FRPs are materials that exhibit excellent strength-to-weight ratios under various loading conditions, making them ideal for such structures. Moreover, FRPs are well suited for AM processes as they inherently include reinforcement. For example, Branch Technology has demonstrated a robotic three-dimensional (3D) printing technology that solidifies a mixture of acrylonitrile butadiene styrene and carbon fiber (CF) that is able to create 3D-printed space-frames such as the One City Pavilion.[15,16] The CF 3D printing applications such those proposed by Kwon *et al.*[11,12] have offered evidence of CF added to 3D-printed structures as reinforcement. Both technologies are examples of customization but are slow and utilize thermoplastics, which may pose construction limitations. Although Branch Technology methods were verified at pavilion scale, their homolog at ETH is yet to be proven scalable.

The AM technology with the potential to integrate tailored reinforcement at a production speed suitable for construction is Filament Winding (FW) and its variant Coreless Filament Winding (CFW). The CFW drastically reduces the need for molds or mandrels, an advantage that makes it well suited for largescale and bespoke applications.

At the University of Stuttgart, the integration of industrial robots into CFW processes for technical fiber systems, glass fibers (GF), and CF composes the Robotic Coreless Filament Winding (RCFW) research stream.[17,18] The ongoing research yields novel industrialized production models exhibiting various automation, scalability, and efficiency.[13,17–22]

Continuing this line of research, we investigate material-aware automation strategies for RCFW adapted to the structural and functional needs of lightweight construction. The challenge to develop smarter RCFW construction methods extends our research scope beyond file-to-factory application, into the field of cyber-physical systems (CPS).[23]

State of the Art

Cyber-physical systems

The CPS are open systems of collaborating cyber-physical entities linked into data acquisition, processing, and sharing via information networks[23]; they are key enabler-technologies for ''Industry 4.0,''[23–25] the currently dominant industrial automation and data exchange paradigm. Their performance indicators are process stability, performance, reliability, and robustness, all of which are key to developing engineered systems integrating computation, communication, and control.[23,24] A comprehensive literature review on CPS is available from Wu *et al.*[25] whereas the terminology's development,[23] and evolution,[26] are described by Monostori *et al.*, Kim *et al.*, and Wu *et al.*, respectively.

The RCFW is an example of the sinuous development that many emerging technologies undergo, from initial conceptualization to large-scale construction. As pointed out by Monostori *et al.*[23] and Hack *et al.*,[27] research and development of construction-adapted CPS depend on information technology and market pressures and advances in manufacturing.[28] The RCFW is no exception. In reviewing the progress in the field contextualized by research conducted at the University of Stuttgart, Vasey and Menges[29] argue that the full potential of CPS in Architecture Engineering and Construction has not yet been reached. The authors provide evidence of the innovation and education interplay for developing CPS as part of academic research.

Toward construction-ready RCFW CPS

Recent research has sought to develop manufacturing methods and verify them at building scale, utilizing technology transfer from the composite industry to construction. Interesting for our work are several academia[13,17,19] and industry[30–32] applications that have adopted CFW to reduce the need for formwork in AM construction elements. With the reduction of formwork come limitations in the types of producible structures. Because it is dependent on the incremental deformation of free spanning fibers, CFW is currently limited to the production of lattices that approximate anticlastic surfaces,[19] 3D frames,[32] or truncated cone tubes.[30]

With the exception of processes described by Dawson[30] and Minsch *et al.*,[31] CFW methods still do not provide complete design, analysis, simulation, and fabrication solutions that are adaptable for construction.

Nevertheless, digital fabrication methods enable new architectural applications for composite material systems. The ICD/ITKE Research Pavilion 2013–14 was a collaborative robotics application that utilized two synchronized industrial arms to prefabricate Glass/Carbon Fiber Reinforced Polymers (G/CFRP) building components.[18] Automated process monitoring and quality control were outside its scope. This research laid the ground work for many of the future RCFW applications.[13,19,29,33] The ICD/ITKE Research Pavilion 2014–2015 developed the first CPS for tape laying pre-impregnated CF tows on an inflatable ETFE membrane. Here, the position of the end-effector on the membrane was controlled through feedback with the industrial robot.[33] Its advances in robot control were partially utilized for distributed robotic manufacturing processes demonstrated by the ICD/ITKE Research Demonstrator 2016–2017 with a high degree of automation and coordination of the collaborating robotic agents: two industrial robots and a drone for transferring the fiber.[34]

The precursor to our application was an RCFW method to fabricate elongated tubular composite elements.[35] The technology, developed at the University of Stuttgart and upscaled in collaboration with FibR GmbH, was verified in the prefabrication of the BUGA Fibre Pavilion's load-bearing structure.

Research gap

An analysis of state of the art reveals that all RCFW applications are interdisciplinary. They also span *in-situ*[33] and prefabrication[30,35] embodiments. Regarding CFW prefabrication, it is revealed that solutions are project-specific. This specificity has a limitative effect on RCFW control methods, tools, and solutions. The presented application, named Cyber-Physical Robotic Coreless Filament Winding (CPRCFW), aims at addressing a need for generality, versatility, and reusability of methods and tools demanded by novel building systems such as the BUGA Pavilion.[35] This research gap will be addressed through more general and extendable control methods, modular software and hardware tools, and clearly defined automation protocols. These principles will be embodied by a CPS consisting of feedback-driven, sensor-guided tension control and fiber impregnation methods embedded in an RCFW process. In addition, the application will address the upscaling potential of the CPRCFW methods and C/GFRP building structures as a direct result of the senor-informed fabrication method.

Materials and Methods

Owing to upscaling and digital control and monitoring, a re-characterization of the material system, fiber impregnation systems, and the kinematic system is required. The proposed system is pictured in Figure 1. Generally, the industry assesses that higher initial design effort and research investment in composite AM yields higher structural performance than is achievable by any individual component.[36,37] Thus, we expect similar returns in construction applications in similar R&D conditions. In describing the research methods, results and evaluations of the fiber tension will be interchangeably given in units of force (N) or equivalent mass (kg).

Properties and specifications for a CFW-adapted material system

A prerequisite for FRP applications throughout the industry is the development of lightweight materials that combine enhanced stiffness with high strength and toughness.[38,39] Grossman *et al.* explain that most synthetic materials cannot combine high strength with increased toughness, because the constituent chemical bonds cannot resist and facilitate stress-induced deformation.[40] The authors conclude that ''gains in toughness are normally accompanied by a reduction in strength and vice versa.'' However, this shortcoming can be mitigated through hierarchical composite architectures, as seen in many natural materials.[40]

We formulate a similar research question for composite manufacturing processes in construction: We need to reconcile seemingly contradictory demands, for high strength and toughness, through hierarchical composite architectures achievable through AM processes. It is well known that CF and GF materials have excellent mechanical properties.[38] Moreover, at fiber volume ratios of 35–50% the performance of the FRP significantly exceeds the performance of its constituent elements.[39] Further, owing to mechanical anisotropy, fibers can be engineered and precisely placed for high structural performance through FW[36,41] and CFW. The second major factor influencing performance is form. For example, Vasiliev *et al.* illustrate the structural characteristics of anisotropic grids and the interrelation between overall form and local structural properties.[42,43] In G/CFRP, fibers take tension, whereas the polymer matrix is mainly active in compression, distributing the force flow.[44] For our own work, the mechanical properties of the RCFW elongated fiber lattices are evaluated in Gil Pérez *et al.*[45] and for the specific application in domes composed of tubular elements, in Rongen *et al*.[46] At component and structural systems scale, safety factors have been adapted to the multiple load cases that determine the application.[47]

A distinct advantage of manufacturing through CFW compared with working with two-dimensional woven textiles[44] is the capacity to place every fiber bundle individually. In addition, the system retains its mechanical flexibility

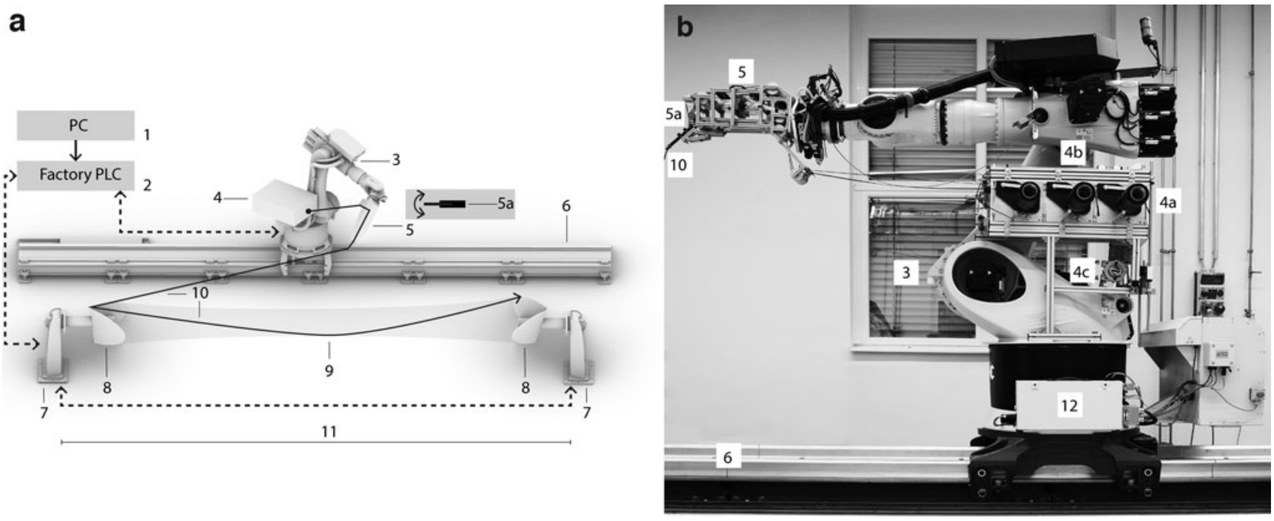


FIG. 1. CPRCFW system: **(a)** conceptual diagram; **(b)** implemented system. Components: 1. Computer; 2. ICD fabrication laboratory PLC; 3. Industrial robot (KR420); 4. Fiber guiding and impregnation system: 4a. CF/GF fiber creel, 4b. passive tensioning system (mechanical dancer bar), 4c. Peristaltic pump: Albin ALP 09-F connected to Polycarboxylic epoxy resin source; 5. Fiber impregnation end-effector; 5a. Tension sensor (Tensometric M-1191-KA); 6. Linear track, length 10 m; 7. Digitally synchronized 1-axis positioners (KP1), no core or mechanical synchronization needed; 8. Modular winding effectors, steel, weight 75 kg; 9. Multi-material G/CFRP composite; 10. Fiber bundle under pretension; fiber bundle on the composite body; 11. Adjustable distance between winding tools allows the AM of any component length in the 1 to 10-m range; 12. BEC Box: digital/analog sensors and actuators integration unit. CF, carbon fiber; CPRCFW, Cyber-Physical Robotic Coreless Filament Winding; G/CFRP, Glass/Carbon Fiber Reinforced Polymer; GF, glass fibers; PLC, Programmable Logic Controller.

Table 1. Fiber System: Material Properties of Glass Fibers and Carbon Fibers

Material	*Product*	*Tensile modulus (GPa)*	*Tensile strength (MPa)*	*Elongation at break (%)*
CF	Teijin Tenax-E STS40 F13 48K 3200tex	250	4300	1.7
GF	Owens Corning PipeStrand S2300 2400tex LS BP11 S CF A	81	3750	4.9

CF, carbon fiber; GF, glass fibers.

during fabrication because the open time of the thermoset resin can be precisely controlled. Tailoring the fiber orientation is essential: Even minor variations may lead to significant mechanical performance deviations.[48] An analysis of the impact of fiber morphology on robotically wound test specimens that reports excellent structural performance under axial compression and axial tension is presented in Gil-Pérez *et al.*[49]

Fiber system. A hybrid six-roving GF and CF system was selected for the application. The number of utilized fiber-rovings was influenced by the upscaled fabrication system. Roving sizing was correlated to impregnation-cartridge volume, as explained in Mindermann *et al.*[50] and as shown in Table 1.

Only CF reinforcement is considered load-bearing since Young's modulus (250 GPa/81 GPa $\approx$309%) and the tensile strength (4300 MPa/3750 MPa $\approx$115%) of CF are higher compared with those of GF, which are therefore used as an integrated elastic mold.

Matrix system. The chosen polycarboxylic[51] system (Table 2) consists of a resin sourced from renewable resources with an unlimited open time at 20°C and a viscosity of 450 MPa*s premixed with an activator. The low viscosity of the thermoset resin system was informed by emerging constraints arising from the fabrication method and setup upscale. This translated to:

- longer cycle times owing to larger components
- longer open times for the thermoset epoxy resin matrix

System for fiber guiding, tension measurement, and fiber impregnation

The implementation of the CPRCFW system consisted of two interlinked steps. First, sensing and evaluation methods for fiber tension were integrated into the RCFW procedure. Second, automatic, in-line fiber impregnation was added, to achieve a 50% fiber/volume ratio. The GF, CF, and epoxy matrix were housed on the robot arm, in a bespoke compact configuration consisting of:

- a two-row CF creel with a capacity of six textile bobbins (spool holders: TC200-14-110[52]; capacity max. 10 kg each; integrated adjustable brake), in a modular metallic construction attached to robot-axis 1 (Fig. 1b:4a).
- a passive tension-control mechanism (mechanical dancer-bar[53] with a 1.2-m stroke) housed above the CF fiber creel, consisting of six pulleys and adjustable counterbalance weight (Fig. 1b:4b).

The decentralized fiber impregnation system consisted of two main components:

- an industrial peristaltic pump (type: Albin ALP 09-F; capacity: 27–70l/h; max. pressure: 2 bar) mounted underneath the creel (Fig. 1b:4c), supplied with premixed resin through a 10-mm diameter glass-fiber-reinforced hose[54]
- a bespoke robotic end-effector[50].

The modular robotic end-effector served as a research platform. Its development was completed in two iterations (Fig. 2a and b). The device's structure, attached to robot-axis six, consisted of an aluminum frame stiffened with planar elements to withstand multidirectional dynamic loading of up to 600 N ($\sim$60 kg), see force distribution for GF and CF. The end-effector performs four integrated functions:

i. GF and CF fiber guiding from the fiber creel to the impregnation cartridges[50]
ii. impregnation of GF and CF fiber rovings with automatically dosed epoxy resin
iii. measurement of tension on the impregnated fiber roving
iv. guiding of fiber rovings around winding pins

Dry fiber rovings are separately routed to the impregnation cartridges connected through branching tubes to the resin pump (i–ii). After impregnation, the rovings are assembled in a single bundle before reaching the sensor roller where the fiber tension (iii) is measured (Fig. 2b). A sub-ensemble of mechanical joints was developed for the effector's front section (Fig. 2b:4). The hinged tool center point (TCP) sub-system (iv) integrates an orientation between 90° and 45° relative to robot axis 6. It was composed of a steel tubular profile (200 mm-long with a 10-mm diameter) of adjustable orientation. The end-effector tool direction was defined parallel to the tube's axis (Fig. 2a:4a, 2b:4a).

Integrated fiber tension measurement (iii) was implemented through an in-line yarn tension sensor (radial strain gauge; type: Tensometric M-1191-KA[55]; nominal load: 40 N; custom-fitted with a bearing axle). The unidirectional load cell was custom configured to register forces

Table 2. Matrix System: Material Properties of the PTP Resin (96 wt% Premixed Resin/Hardener, 4 wt% Accelerator)

Density (g/cm^3)	*Viscosity (MPa*s)*	*Flexural modulus (GPa)*	*Flexural strength (MPa)*	*Elongation at break (%)*	*Glass transition temperature (°C)*	*Pot life at 20° C*
1.075	450	2.1	80	3	115	∞

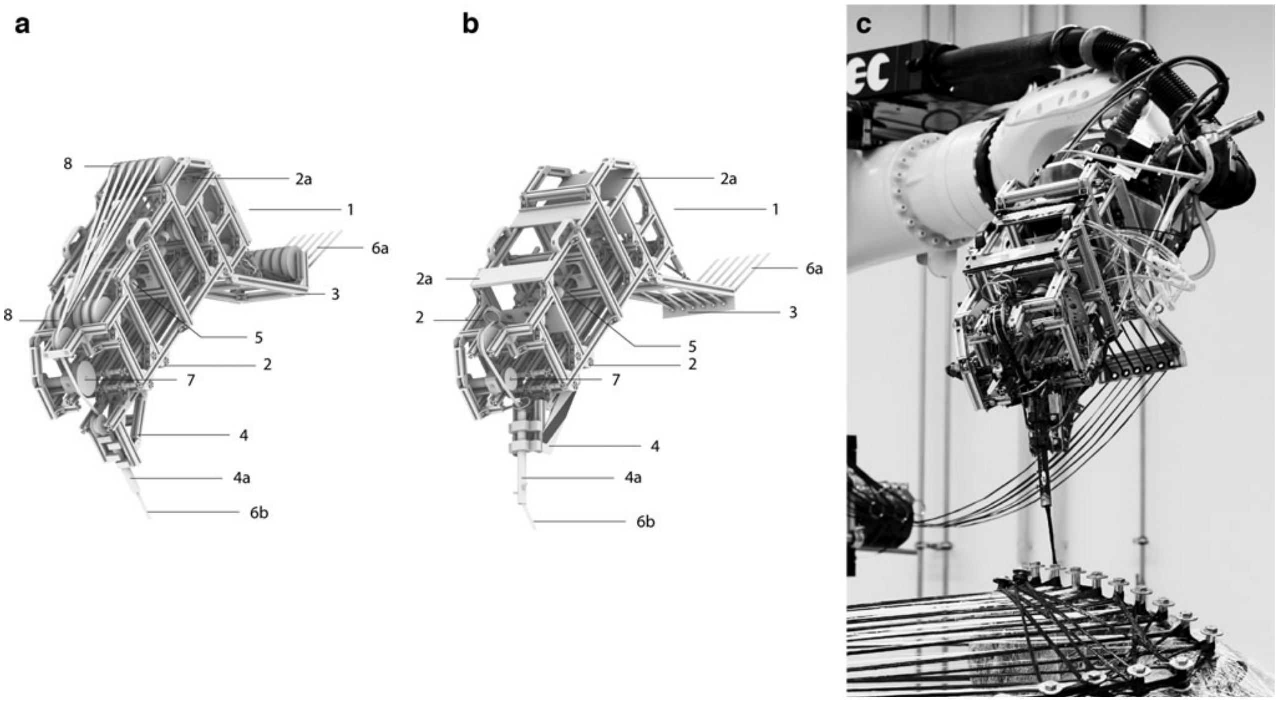


FIG. 2. Robotic fiber impregnation end-effector: **(a)** Development iteration 1—features a complex fiber routing subsystem, with multiple ceramic rollers to change fiber direction; **(b)** Development iteration 2—a simplified, more robust version, features stiffening plates, a redesigned TCP assembly and simpler fiber routing; **(c)**. Robotic end-effector, in operation: CF CPRCFW; Components: 1. Robot flange interface; 2. Modular aluminum-profile/ring steel guide structure; 3. On-board tension control arm; 4. TCP assembly; 5. Fiber impregnation cartridges; 6a. Dry, individually routed fiber tows; 6b. Impregnated, assembled fiber tows; 7. Tension sensor; 8. Ceramic roller guides. TCP, Tool Center Point.

up to 600 N by controlling the wrapping angle on the sensor roller. The device was mounted on the end-effector metal frame (Fig. 2b:7). The sensor measures the radial force acting on a ball-bearing roller. The measured values are amplified and the 16-bit integer output values calibrated to our application needs (forces of 600 N) by adjusting the offset and slope of a linear equation. The sensor was positioned as close as possible to the TCP (Figs. 1b:5a and 2b:7), ensuring accurate tension measurement before the fiber-deposition point. After force measurement, the analog signal is passed to a signal integration unit and via Ethernet to the Central Programmable Logic Controller (PLC) and the robot controller (see the Cyber Physical System Integration section).

The automatically controlled pump (see Table 3) is connected to the impregnation cartridges[50] and supports two operation modes:

- Manual operation: for testing, calibration, filling, and evacuating the epoxy resin
- Automatic operation: for CNC control through the pump PLC

Cyber-physical RCFW

We define CPRCFW by utilizing the communication and control criteria set out by Monostori *et al.*[23,56] and Cardin *et al.*,[26] adapting our development to the prefabrication of tubular fiber lattices for construction applications. The CPRCFW needs to integrate precision, speed, repeatability, and programmable logic control inherent to industrial robots, with the constraints imposed by an anisotropic G/CFRP material system.

Kinematic system. An industrial robot on a track was used as a starting point for the CPRCFW application. The KR420 fulfills the application's requirements regarding process forces from applied tension and robot end-effector weight (~10 kg). In the present implementation, two physically independent winding tools are digitally synchronized through the kinematic system. This now contains individually programmable rotational positioners at each end (Fig. 1a), suppressing a previously utilized metal synchronization axle weighing 50 kg/m, impractical for extended setup lengths. Each winding tool now only weighs 75 kg. The weight of the system is thus reduced from ~650 to 150 kg, whereas the setup's scalability is vastly improved. In combination with the existing 10-m track, our system can cover the complete winding range of 1 to 10 m without any change in tooling.

Offline robot programming. The robot programming model consisted of an adaptive simulation built in Grasshopper[57] and Rhinoceros.[58] The model contains multiple custom-built algorithms for robot motion-planning (Fig. 3a). The winding process is simulated with an inverse-kinematics solver from ''Virtual Robot,'' a plugin developed at ICD. The simulation provides a geometric representation of the CPS components, including the fiber syntaxes to be wound. The simulation also integrates physical system components such

Table 3. Peristaltic Pump Operation, Inputs/Outputs

Inputs	*Type*	*Description*
Run	Boolean	Pump is running
Fault	Boolean	Pump has a fault
Warning	Boolean	Pump has a warning
Ready	Boolean	Pump is ready to be controlled
FrReached	Boolean	Set frequency has been reached
Outputs	Type	Description
CW	Boolean	Run pump clockwise
CCW	Boolean	Run pump counterclockwise
FastStop	Boolean	Emergency stop
VoltageLock	Boolean	Enabling/disabling the DC link voltage on the inverter
FlowRate	Double (32 bits)	Flowrate target

CCW, counter clockwise; CW, clockwise.

as the hardware and the material systems, including the robotic end-effector, and peristaltic pump. All cyber-physical components of the system are integrated through KUKA WorkVisual.[59] The robotic motion and the functionality of the CPRCFW system are programmed through a custom-developed control algorithm developed around a'' Winder'' class in Python[60] that manages all fabrication-related information.

Cyber-physical system integration. The components of the nine-axis kinematic system are integrated by the primary PLC (Figs. 1 and 3a). The linear track and two positioners are controlled as external motion axes. The synchronization of the rotation and velocity of the two positioners was realized by using a primary-secondary control configuration where the offline-programmed fabrication module supplies the target positions and velocities and the robot controller calculates the actual position and velocities for the entire kinematic system. Communication between the CAD environment (offline system) and the robot controller (online system) is realized through Ethernet (Fig. 3a). During the execution, the robot is placed in automatic mode.

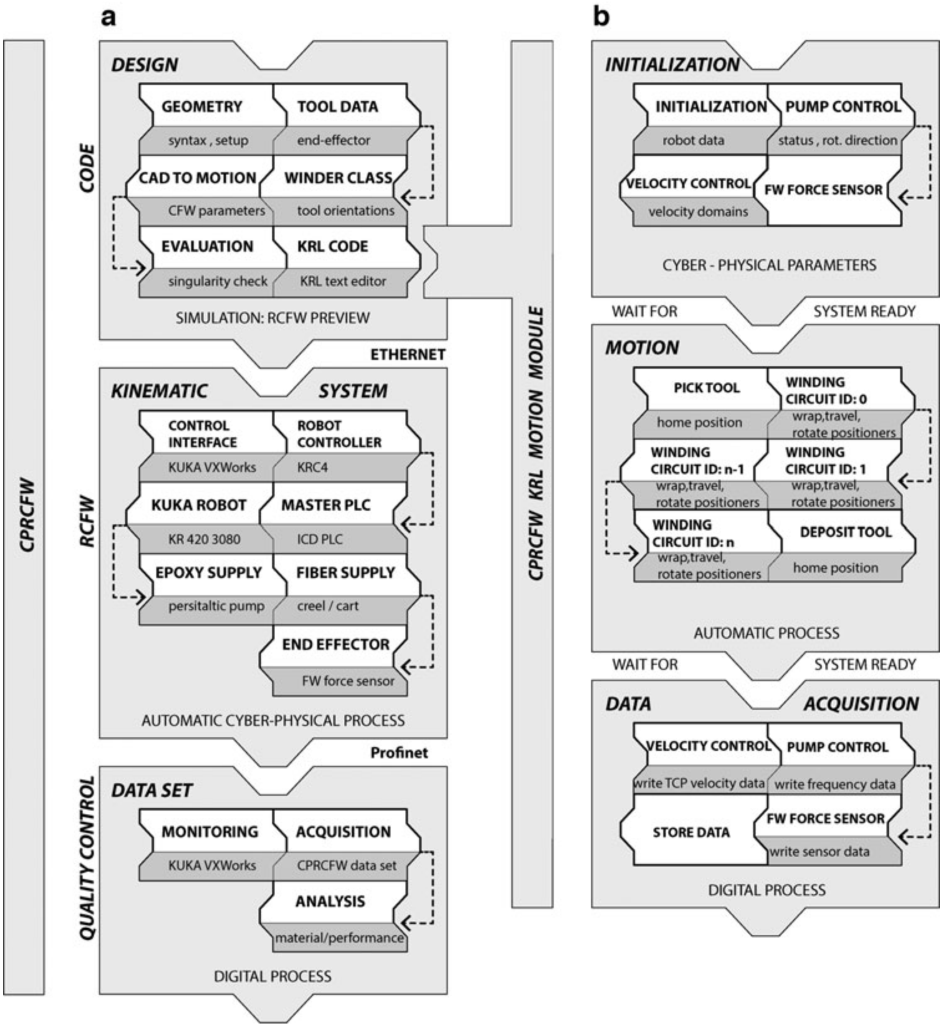


FIG. 3. Cyber-physical integration and robot control: **(a)** The Integration of the cyber-physical components of the fabrication system; **(b)** Robot code organization, structure of the CPRCFW control module.

The primary PLC receives the analog signal coming from the tension sensor amplifier and three signals from and to the peristaltic pump:

- a digital status signal;
- a first analog signal to the peristaltic pump, denoting the required revolutions per minute (RPM) value to be achieved;
- a second analog signal from the pump, denoting the actual RPM value achieved.

These signals are first passed to a unit for integrating digital/analog sensors and actuators (BEC Box,[61] Fig. 1b:12) and then to the master PLC and robot controller through Ethernet by using the PROFINET[62] protocol.

CPRCFW: real-time fiber tension and fiber impregnation control.

In previous applications,[13,17,18] the industrial robot executed a preprogrammed motion path with no feedback from the material system. To enhance those fabrication methods, we have introduced sensor-guided motion features complementary to the geometry-based motion planning methods described by Bodea *et al.*[35] The sensor-guided motion relies on force-feedback from sensors described in the System for Fiber Guiding, Tension Measurement, and Fiber Impregnation section. The implemented feedback loops are:

i. Negative feedback—between measured fiber tension and actual robot TCP-velocity and
ii. Positive feedback—between actual robot TCP-velocity and pump frequency.

Loop (i) is an example of negative feedback. The system maps the amplified 16-bit integer value from the force sensor invers-proportionately to a target velocity range (i.e., 0–250 mm/s). A force value reading above 600 N ($\sim$60 kg), experimentally evaluated as maximum allowable, results in an immediate stop of the robot and the notification of the operator. Values below 600 N are linearly mapped to velocities between 1 and 250 mm/s.

Crucially, because linear acceleration means increased tension, as a result of this negative feedback loop the tension-velocity system reaches equilibrium. The linear mapping (see Table 4) resulted in smooth winding operations, where correct functioning of the system leads to constant robot velocity averaging 145 mm/s for GF and 102 mm/s for CF (see Table 5).

From a given robot velocity and a targeted fiber/volume ratio, mass, and fiber length of a composite component we calculate a target average flow rate(F)[50] that the pump should maintain through linear regression of observation data. The desired pump frequency(f) can then be calculated (1), utilizing the F (parametrically linked to the actual robot TCP-velocity) and the slope of the regression line(s). The pump frequency is the variable that the robot controller sends to the pump. Loop (ii) is an example of positive feedback. Robot velocity is mapped to pump frequency.

$$f = \frac{F}{k}; \tag{1}$$

$$F = \begin{cases} v(g/m)/(3\rho), & \text{if}\, v < 0.06 \\ 2(g/s)/\rho, & \text{if}\, 0.06 \leq v \leq 0.12 \\ ((g/m)((3v/8) - 2.5(m/s)))/\rho, & \text{if}\, 0.12 < v < 0.2; \\ 5(g/s)/\rho, & \text{if}\, v \geq 0.2 \end{cases} \tag{2}$$

f = pump frequency (Hz); $k = 0.779\ (cm^3)$;

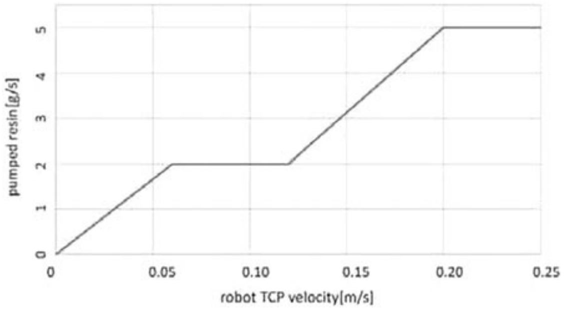
F = flow rate $(\mathrm{cm}^3/\mathrm{s})$; ρ = density of the resin $(\mathrm{g/cm}^3)$;

v = TCP velocity (m/s)

The CPRCFW motion planning is programmed by a "Winder" class (Fig. 3a). Once visual and procedural

TABLE 4. AUTOMATIC CONTROL OF THE PERISTALTIC PUMP

Inputs	*Unit*	*Value*	*Description*
Velocity variables GF			
rVelLimitLow	m/s	0.06	Robot velocity lower limit
rVelLimitHigh	m/s	0.12	Robot velocity upper limit
rVelLimitMax	m/s	0.25	Robot velocity maximum allowed
Resin system flow rate GF			
rFLowAverage	g/s	2.00	Target value for average flow rate
rFlowMax	g/s	5.00	Target value for maximum flow rate
xEnablePumpCtrl	Boolean	1	Triggers automatic control of the pump
Transfer function between TCP velocity and pump flow rate			



TCP, tool center point.

Table 5. Material Layup of the Demonstrator

Layup	*Iterations*	*Syntax*	*Fiber material: GF/CF*	*Syntax duration (s)*	*Average robot velocity (m/s)*	*Fiber path length (m)*	*Robot path length (m)*
GF layup							
1	1	GF_Scaffold_1	GF	3084	0.142	430	438
3	1	GF_Body_1	GF	2775	0.147	400	408
4	1	GF_Body_2	GF	5567	0.148	809	824
CF layup							
5	1	CF_Reinforcement_1	CF	3753	0.126	438	473
6	1	CF_Boundary_1	CF	1177	0.090	45	106
7	1	CF_Boundary_2	CF	1065	0.091	40	94

winding viability checks are completed the motion is simulated, and the CPRCFW module is automatically generated and passed to the robot controller. A CPRCFW module written in the KUKA Robot Language (KRL) controls the entire RCFW process. The composition of the control module is represented in Figure 3b.

Practically, the force sensor amplifier box and the peristaltic pump PLCs were connected to the I/O modules of the BEC Box. The Factory PLC (Fig. 1a:2) maps all signals to the robot controller, rendering them available for direct programming. The variables denoting the adjusted fiber tension (AFT), adjusted robot velocity (ARV), and adjusted pump frequency are set in two custom data modules defined in the robot controller:

- The Velocity Control(.dat) data module—contains initialization of the velocity control parameters
- The Pump Control(.dat) data module—contains initialization of the pump control parameters

These data modules are user-accessible and were configured with values specific to either GF or CF. Corresponding subprograms related to velocity and pump control are also defined in the robot controller.

- The Velocity Control(.sub) subprogram—performs all conversions from sensor output data to robot velocity and contains the velocity control logic describing the negative feedback loop described earlier
- The Pump Control(.sub) subprogram—performs all conversions from robot velocity to pump frequency and contains the pump control logic describing the positive feedback loop described earlier

In addition, a subprogram was written to manage the fabrication data acquisition:

- The Dataset(.sub) subprogram—opens a data file and creates a multidimensional array for a dataset that will contain fabrication time stamps, robot actual velocity values, tension sensor values, and pump RPM values. Two custom functions are also defined:
- AcquireData is defined inside Dataset.sub. It creates data arrays for the variables enumerated earlier. This function is called inside the winding module during the initialization steps of the executable winding module
- WriteData is also defined inside Dataset.sub. This function is called inside the winding module once all winding points have been wound. The function writes the stored data in a fabrication dataset (.txt) file inside the robot controller

The structure of the control modules mentioned earlier contributes to the system's modularity. The control code itself is modular, allowing the instructions to be efficiently regenerated on the fly. The main section integrates the cyber-physical components: the peristaltic pump and force sensor and initiates the custom velocity control loop. Each winding path is encapsulated in a fold that alternates ''wrapping'' and ''travel'' instructions, individually callable through a unique identifier. After executing the motion instructions, the components of the system are disabled and a fabrication dataset file is written as explained earlier. The CPRCFW system composition and control module are diagrammatically described in Figure 3.

Results

The CPRCFW methods were verified through the data acquisition, analysis (Fig. 4), and fabrication of a tubular hyperboloid fiber structure (Fig. 5). The design of the fiber layup utilized methods described in Zechmeister *et al.*[20] upscaled and adapted to the new fabrication and material system specifications.

The connectivity of the fiber strands is encoded in a polyline. Fiber rovings are initially wound straight and subsequently deform into a fiber lattice[63] that approximates an anticlastic surface. The fiber layup is composed of individually tailored *fiber syntax*es.[20] A CFW syntax is an ordered list of winding pin indices that describes how spatially arranged winding pins are connected through winding. They (Table 5) fulfill either a form-giving (GF) or reinforcement (CF) functions. The geometric instances of a fiber syntax are the primary input for the RCFW robot motion algorithm. In the CPRCFW process, epoxy-resin-impregnated fiber bundles are continuously spanned between the winding tools described in Bodea *et al.*,[19] with the crucial difference that, for the presented application, the tools are digitally synchronized (see the Offline Robot Programming section).

The fiber layup was composed of six syntaxes (Table 5). A form-giving fiber support surface was initially wound, totaling more than 7.2 km of GF. The CF reinforcement was wound next. In total, more than 3 km of CF fibers were wound in three different syntaxes. The resulting composite was

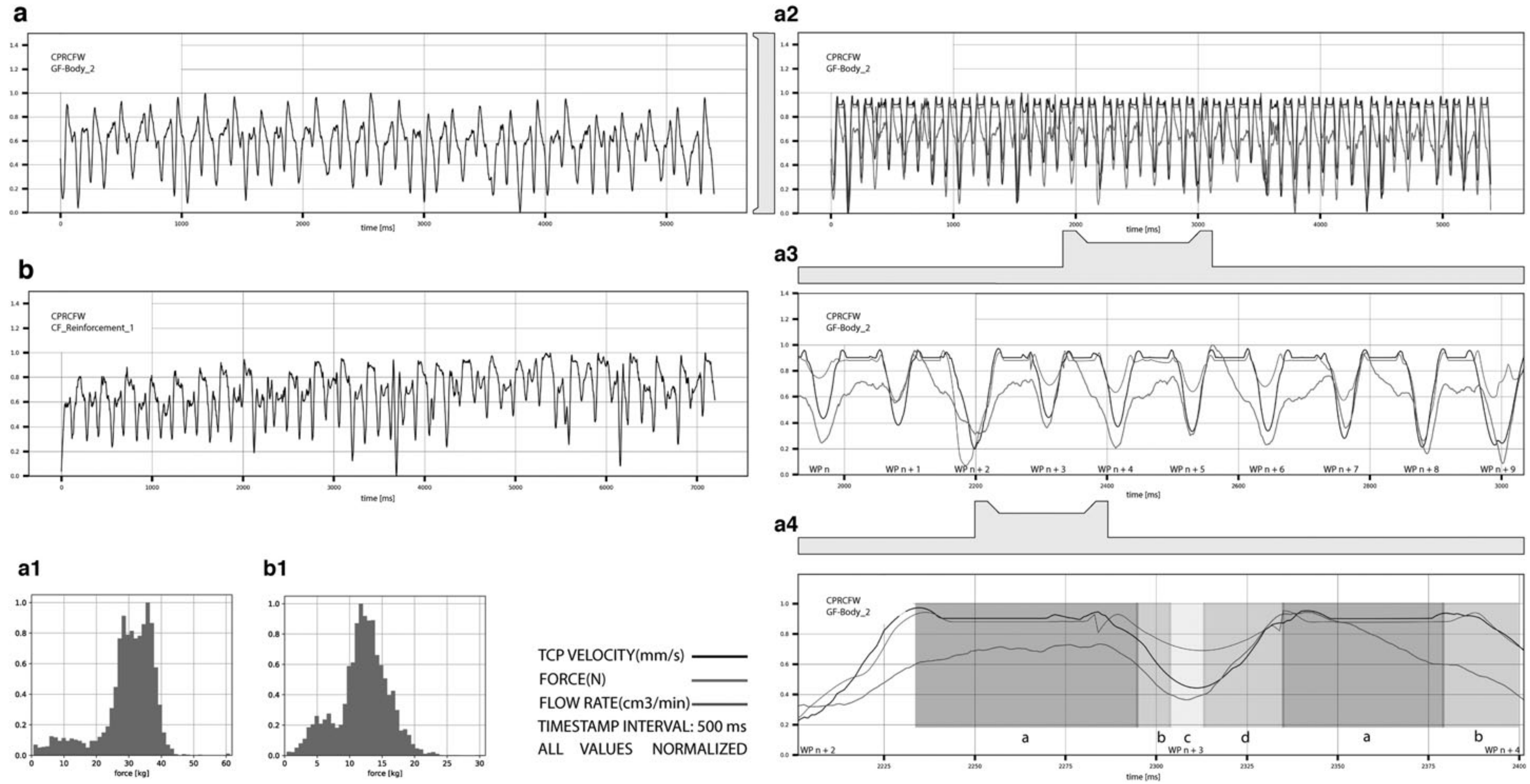


FIG. 4. CPRCFW fabrication data set: **(a)** fiber pretension data set Syntax GF-Body02; **(a1)** distribution of tension values for GF; **(b)** fiber pretension data set Syntax CF_Reinforcement_1; **(b1)** distribution of tension values for CF; **(a2)** Complete GF dataset Syntax GF-Body02, showing correlation of fiber pretension, TCP velocity, and epoxy pump flow rate; **(a3)** Zoom-in winding points $n+2$ to $n+4$; **(a4)** Analysis visualization of CPRCFW process parameters for winding point $n+3$: a—constant pretension sequence, b—decreasing tension sequence, c—low winding pretension at winding pin WP $n+3$; figure key: TCP velocity: *black line*, force (kg): magenta line, flow rate: *blue line*, timestamp interval: 500 ms, all values normalized.

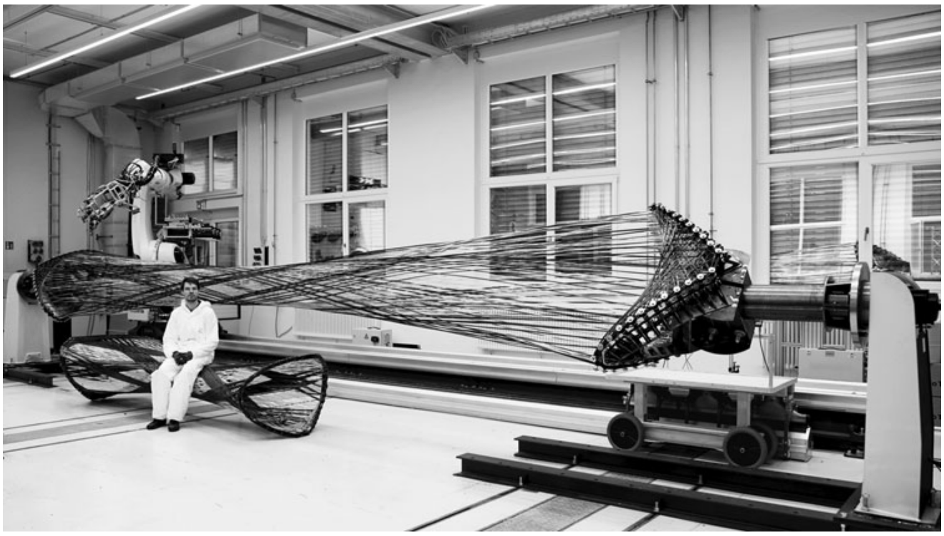


FIG. 5. CPRCFW G/CFRP proof-of-concept (on fabrication setup) next to RCFW G/CFRP component fabricated for the BUGA Fibre Pavilion (2019). Cyber-physical fabrication methods enable an enhanced fabrication workflow, resulting in enlarged design and solution spaces. RCFW, robotic coreless filament winding.

cured for 8 h at 100–120°C, resulting in a self-supporting fibrous artefact 9 m long and weighing 45 kg at an average weight of 2.3 kg/m^2.

Evaluation

However, it is important to note that this research did not aim at creating load-bearing construction components, which require significantly more material and suitable structural evaluation, but at demonstrating a new fabrication method. During CPRCFW, the robot executes self-similar motion sequences. Variation is induced by geometric parameters, depending on the syntax and position of the winding pins. A fabrication dataset was recorded and preprocessed for every syntax wound, following steps detailed in Appendix A1. It contained:

i. robot velocity at TCP;
ii. fiber tension;
iii. pump frequency values.

Figure 4 exemplifies a normalized data sample of syntax GF-Body_2 and CF_Reinforcement_1 (Table 5). Although the robot executes spanning winding motions, the pretension value is relatively stable (Fig. 4a:4a). Subsequently, due to a reorientation sequence before/after the fiber wrapping motion, two acceleration spikes are observed (Fig. 4a:4a). Although fluctuating, the tension values remain relatively stable with tension peaks/drops and velocity directly correlated. The fiber wrapping motion exhibits a deceleration (Fig. 4a:4b) followed by lower fiber tension while wrapping the fiber (Fig. 4a:4c). During the wrapping sequence, the fiber tension stays relatively constant at half its spanning value—30 kg. During the wrapping sequence (Fig. 4a:4c), the robot increases the tension and the TCP passes around the winding pin and the cycle repeats (Fig. 4a, b).

Initial CPRCFW tests on a 4 m setup indicated fiber tension levels of up to 10 kg; for our demonstrator, average tension levels reached 30–40 kg, with peak values up to 60 kg (Fig. 4a:1, b:1). Tension values higher than 600 kN ($\sim$60 kg) occurred due to faults in the winding effector (tangled fibers), or during missed hooking sequence. However, all mechanical faults were remedied and the system functioned robustly during the demonstrator's production phase. A tension fluctuation (Fig. 4a:4) of around 20% was experienced. This is unsurprising given the freeform geometry of the demonstrator. Due to a higher tension setting applied in the mechanical tensioning system, for CF the fiber tension levels recorded were higher than those experienced for GF (Fig. 4b:1, a:1). The characteristic tension values for different materials are presented in Table 6. The normalized datasets for GF and CF utilized for visualizing the force distributions are presented in Figure 4a:1 and 4b:1.

TABLE 6. CHARACTERISTIC TENSION VALUES FOR THE FABRICATION OF THE LARGE-SCALE DEMONSTRATOR

Syntax	*Material*	*During hooking*	*During traveling*
Body	GF	8 kg	19 kg
Reinforcement	CF	10 kg	28 kg
Corner	CF	7 kg	32 kg

Discussion

The initial phase of RCFW presented in Bodea *et al.* demonstrated that the technology could be applied to industrialized prefabrication. However, the fabrication data analysis suggested that the upscaling and productivity potential of the application could be further explored.[35]

An initial effect of the upscale are significantly higher process forces—30–40 kg versus 10 kg—in previous applications. Consequently, the tooling required added engineering robustness precision. The robot end-effector was designed to function at velocities up to 500 mm/s regardless of orientation.

During preparation and calibration, the end-effector's tensioning mechanism did not perform robustly. Frequent automatic interruptions were caused by abrupt drops in fiber tension, which prevented the system from reaching equilibrium in correlation with TCP velocity. It was determined that the tensioning subsystem integrated in the end-effector was generating increased fiber tension due to complex routing of the individual fiber rovings (Fig. 2a). As a solution, the internal tensioning mechanism and the routing of the rovings were rationalized (Fig. 2b).

A second upscaling consequence was a 10–20% tension fluctuation, owing to the complexity of the fiber syntax. Eliminating these fluctuations through mechanical compensation means is impractical, thus a future solution would need to include active fiber tension control for each fiber bobbin.

A third upscaling consequence was longer cycle times. The dynamically controlled robot velocity introduces unpredictability in the process. However, the presented development enables a comprehensive simulation of the fabrication process based exclusively on material properties, previously impossible due to a lack of fabrication data. Moreover, longer cycle times impacted the selection of a material system with a lower increase in viscosity over time and theoretically unlimited open time compared with a 5-h open time specified in Bodea *et al.*[35] As a result of added process complexity, the majority of R&D work addressed the integration and calibration of the CPRCFW system as opposed to intensive manual labor in previous applications. As a result, better impregnation quality and more precise fiber tension and robot velocity control could be achieved even for G/CFRP elements double the previously achievable length.

Overall, these features led to a reevaluation of the role of the human-in-the-loop, decreasing the specialization demanded from technicians and robot operators. The result was a more automated AM process, where many process parameters are derived from the internal state of the system and where humans are tasked with monitoring and control. Concurrently, programming of the system became simpler and more intuitive, owing to enhanced automation and integration.

An added contribution of this research is the potential enhancement of simulation methods for RCFW, and real-time response to material system constraints registered during CPRCFW. We next present some scenarios illustrating how simulation methods and online process adjustments will inform future interdisciplinary design-engineering methods.

In a first scenario, the acquired fabrication data contribute to an expanded computational design space. The existing design process[20] utilizes a simplified dynamic relaxation to approximate anisotropic material behavior. This method assumes that fiber tension remains constant during winding. This implies that some of the energy is dissipated through material stiffness whereas some accumulates, resulting in constantly increasing pretension. However, our fabrication dataset demonstrates that in RCFW fiber tension is variable, owing to complex geometry and robot motion. The presented dataset and processing methods can be directly utilized for a more informed dynamic relaxation simulation. Moreover, it was experimentally observed that the overall elasticity of the lattice decreases proportionally to the number of fibers wound, yet this decrease is not linear and has not yet been mathematically described owing to a lack of quantifiable fabrication data. In addition, the current dynamic relaxation model[20] does not predict the effects of increasing or decreasing fiber tension. The resulting design method is informed by anisotropic material properties combined with reciprocal deformation of the fibrous lattice effects. Consequently, the utilization of accurate fabrication data would aid the modeling of changes in fibrous lattice elasticity and provide a quantitative basis to quantify the design and structural benefits related to this material-system property.

Building on the more accurate simulation from the first scenario, in a second scenario, the fabrication data inform an enhanced structural simulation to more accurately predict the form of the structural lattice, translating to a precise structural evaluation of the amount of pretension induced.

These scenarios allow us to conceptualize adequate post/during-fabrication-measures to respond to emerging structural or building system constraints. Postfabrication measures trigger changes in computational models to adjust material amount, impacting the fiber syntax topology and component geometry. These adjustments would affect the design of subsequent components. During-fabrication-measures include procedurally added, topological, or geometric changes in syntax layup as well as procedurally AFT with a direct impact on fiber lattice morphology during the winding process.

Conclusion and Outlook

This article discussed the opportunities and challenges presented by CFW for the building industry. The core contributions were an increase in automation for RCFW coupled, with a significant upscale of the process. The emerging demand for more general, versatile, and reusable RCFW methods and tools was addressed by a CPRCFW method proposing an abstraction of control methods, physical and software tool-modularity, and clearer automation protocols. The methods were embodied by online sensor-informed tools for process monitoring and control.

In addition, this article exemplified the upscaling potential of the technology, resulting in larger building components. The CPRCFW application was verified through the fabrication of a 9 m long composite element consisting of a bespoke G/CFRP fiber layup tailored to the specifications of the prefabrication setup. The automated process demonstrated robustness and reliability, reflected by the fabrication dataset analysis, which showed close correlation between the fabrication parameters of robot winding velocity and fiber tension.

The importance of online controlled fabrication through sensor feedback for future more informed design-engineering-fabrication methods was discussed in several discipline-relevant development scenarios.

The realized demonstrator suggests that the linear scalability of the chosen component typology is well supported by the fabrication method. In practical terms, this translates to the capacity to cover more than $1200\,m^2$ with a 14 m high structure, triple the area and double the height achieved by the BUGA Fibre Pavilion[35] with a similar building system, utilizing our tooling, control methods, and automation protocols while incurring minimal added automation/production costs.

A wide-ranging interdisciplinary investigation aiming at disentangling design and solution space limitations, with profound implications for composite architecture applications, is underway in the context of the DFG Cluster of Excellence Integrative Computational Design and Construction.[64] This initiative is planned to yield novel research advancements and construction-scale results within the next 2 to 3 years.

Our investigations represent incremental research toward more autonomous prefabrication environments through CPRCFW. Our goal was to expand the range of fibrous morphologies and material systems compatible with its construction application. Although currently calibrated for two types of fibers, GF and CF, we estimate that this technology is applicable to many other material systems, including those sourced from renewable resources such as composites utilizing plant-based or basalt fibers and ecologically competitive resin systems.

Presently, several technologies involving robotic AM and bespoke CPS including CFW find themselves in a knowledge-transfer relationship with the construction industry. However, efficient robotized production still requires incremental advancement in material and building system-aware communication and control. This constitutes a proving ground for technologies, such as CPRCFW, trying to solve the challenges of automation and AM in construction.

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Author Contribution Statements

S.B.: Conceptualization; Investigation; Methodology; Programming and software development; Hardware development; Experimental work; Design and execution of the demonstrator; Data acquisition, processing, and analysis; Writing—Original draft of sections: Introduction, State of the Art, Materials and Methods (System for fiber guiding, tension measurement, and fiber impregnation, Cyber-physical RCFW), Results, Evaluation, Discussion, and Conclusion and Outlook; Visualization—Figures: 1–5; Tables: 3–5; Writing—Review and Editing; Research project management.

P.M.: Conceptualization; Investigation; Methodology; Hardware development and calibration; Design of the Experimental work; Design and execution of the demonstrator; Data acquisition, processing, and analysis; Writing—Original draft of sections: Materials and Methods (Properties and specifications for a CFW-adapted material system, System for fiber guiding, tension measurement), Results, Evaluation; Visualization—Figures: 2, 4a1, and 4b1; Tables: 1, 2, 5, and 6; Writing—Review and Editing. G.T.G.: Research supervision; Funding acquisition of the research project; Writing—Review and Editing of the article.

A.M.: Principal investigator of the research; Research supervision; Research Project management; Funding acquisition of the research project; Writing—Review and Editing of the article.

Author Disclosure Statement

S.B., P.M., G.T.G., and A.M. declare that they have no known competing interests, competing financial interests, funding interests, employment interests, personal relationships, or other competing interests that could have appeared to influence the work reported in this article.

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(*Appendix follows* →)

Appendix

Appendix 1. Data Preprocessing Steps

The fabrication dataset was preprocessed according to the following steps:

- Prolonged periods of downtime—when the robot velocity was 0.00, they were filtered out. They signify a mechanical/hardware or software fault that had to be remedied
- The tension sensor values are amplified by direct multiplication with a sensitivity coefficient to reflect the physical orientation sensor
- The tension sensor values are subsequently remapped to the metric system kg unit of measurement
- Peristaltic pump values are converted from revolutions per minute to a flow rate to better reflect epoxy resin consumption
- Tension sensor data, robot velocity at tool center point data, and flow rate data are then normalized by remapping the values from their respective units of measurement and domains to a [0,1] domain
- The digital filter Savitzky–Golay[65] (data range 51, polynomial order 2) is applied to the data, with the purpose of smoothing and increasing the precision of the data points without affecting the signal tendency

8

Glossary

anisotropy

“In physics, the quality of exhibiting properties with different values when measured along axes in different directions”[28]

automation

“The application of machines to tasks once performed by human beings or, increasingly, to tasks that would otherwise be impossible”[29]

biomimetics / bionics

“Science of constructing artificial systems that have some of the characteristics of living systems. Bionics is not a specialized science but an interscience discipline”[30]. “The transfer of ideas and analogues from biology to technology”[133]

circuit

“One complete traverse back and forth of the fiber-feed mechanism of a winding machine”[94]

composite material

"A combination of two or more materials (reinforcing elements, fillers, and composite matrix binder) differing in form or composition on a macro scale. The constituents retain their identities: They do not dissolve or merge completely into one another, although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another"[94]

coreless filament winding

An industrial manufacturing process that drastically reduces the need for support structures. If the defining feature of FW is the presence of a mandrel or core, CFW eliminates such elements in favor of spatially-positioned winding pins. Another defining trait of the process is a more constrained design space of anticlastic geometries resultant from the reciprocal deformation of free-spanning fibers under controlled pretension.

creel

"A device for holding the required number of roving balls or supply packages in a desired position for unwinding onto the mandrel"[94]

curing

"To irreversibly change the properties of a thermosetting resin by chemical reaction (that is, condensation, ring closure, or addition). Cure may be accomplished by addition of curing (cross-linking) agents, with or without heat and pressure"[94]

cyber physical system

[The] "integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa"[102]

design space

Type of solution space that "contains all systems that a group of engineers are able to explore given their knowledge and skill limitations"[108]

digitalization

"The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business"[46]

fiber

"A general term used to refer to filamentary materials. Often, fiber is used interchangeably with filament. It is a general term for a filament with a finite length that is at least 100 times its diameter, which is typically 0.004 to 0.005 in. (0.10 to 0.13 mm). (In most cases, it is prepared by drawing from a molten bath, spinning, or deposition on a substrate. Fibers can be continuous or specific short lengths, that is, discontinuous, normally no less than $1/8$ in., or 3.2 mm)"[94]

fiber layup

The physical manifestation of one or multiple winding syntaxes - usually defined by the result of the reciprocal deformation of free-spanning fibers.

fiber-volume fraction / ratio

"The ratio of the volume of fibers present to the total volume of the layer"[104]

filament winding

A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape, or other), previously impregnated with a matrix material or impregnated during the winding, are placed over a rotating and removable form or mandrel in a previously prescribed way to meet certain stress conditions. Generally, the shape is a surface of revolution and may or may not include end closures. When the correct number of layers is applied, the wound form is cured and the mandrel removed. [94]

genotype

[The] "genetic constitution of an organism. The genotype determines the hereditary potentials and limitations of an individual from embryonic formation through adulthood"[32]

geodesic

"The shortest distance between two points on a surface"[94]

industrial robot

"[A] reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks"[34]

mandrel

"The form (usually cylindrical) around which resin-impregnated fiber is wound to form pipes, tubes, or vessels"[94]

morphogenesis

"The shaping of an organism by embryological processes of differentiation of cells, tissues, and organs and the development of organ systems according to the genetic "blueprint" of the potential organism and environmental conditions"[31]

object oriented programming

"A style of programming characterized by the identification of classes of objects closely linked with the methods (functions) with which they are associated. It also includes ideas of inheritance of attributes and methods. It is a technique based on a mathematical discipline, called "abstract data types," for storing data with the procedures needed to process that data. OOP offers the potential to evolve programming to a higher level of abstraction"[46]

phenotype

"All the observable characteristics of an organism that result from the interaction of its genotype (total genetic inheritance) with the environment"[32]

reciprocal deformation of free-spanning fibers

[In CFW], "the fiber rovings start out laying straight between their supports (slightly deformed under self-weight). They are iteratively deformed as new rovings are added on top under controlled pre-tension"[8; 138]

resin

"A solid, semisolid, or pseudosolid organic material that has a variable (often high) molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. Most resins are polymers. In reinforced plastics, the material used to bind together the reinforcement material; the matrix"[94]

robot, robotics

“Any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a humanlike manner. By extension, robotics is the engineering discipline dealing with the design, construction, and operation of robots”[33]

roving

“A collection of bundles of continuous filaments either as untwisted strands or as twisted yarns. Rovings may be lightly twisted, but they generally are wound as bands or tapes with as little twist as possible”[94]

solution space

“The space of all potential solutions for a problem”[59]. In engineering, the main objective of any investigation is exploring a solution space to find an adequate solution to a problem.[108]

strain gauge

device for measuring the changes in distances between points in solid bodies that occur when the body is deformed[35]

tow

An untwisted bundle of continuous filaments. They are commonly referred to as artificial fibers, mainly carbon and graphite and glass and aramid. A tow designated as 140 has 140,000 filaments.

TRIZ

“Teoriya Resheniya Izobretatelskikh Zadatch” “Method for inventive problem solving [that] identified systematic means of transferring knowledge between different scientific and engineering disciplines” [35]

winding angle

“The angle at which the roving band is laid with respect to the mandrel axis of rotation, circumferential winding being approximately 90°”[94]

(robotic) winding end-effector

See *winding eye* .

(robotic) winding eye

The tool mounted on the standard robotic manipulator flange which has the role to guide the fiber during the winding process. The equivalent of the delivery eye in FW, the winding effector, is configured as a robot tool part of the robotic kinematic system and defines a precise physical location for the robot TCP.

winding frame

See *winding scaffold* .

winding pattern

"A recurring pattern of the filament path"[94]. Unlike in FW, in CFW, complete revolutions around the winding axis are not a prerequisite for completing a winding pattern, and the direction of revolution can be reversed. Also, see Winding Syntax.

winding pin

The usually modular, physical infrastructure that provides the interface between the composite material being wound and the Winding Tool. Winding pins are composed of a washer-sleeve (metal tube)-bolt assembly in the presented applications. The sleeve acts like a spacer housing the fiber bundle, while the bolt and sleeve secure the Winding Pin on the Winding Tool. In the presented applications, the metal sleeve stays embedded into the composite material, thus serving as the exact interface for the mechanical assembly of the prefabricated components or interfacing with building subsystems such as foundations and facades.

winding scaffold

The modular, physical infrastructure holds the Winding Pins in space. It is calibrated in coordination with the robotic Kinematic System. The Winding Tool is configured as part of the robotic kinematic system and is manipulated synchronously to the robot TCP.

winding syntax

A list of ordered Cartesian positions representing a continuous fiber path between winding pins[8; 138]. Also, see Winding Pattern.

winding tension

“The amount of tension on the reinforcement as it makes contact with the mandrel. Winding tension can influence resin content, propensity to slip at a specific wind angle, and residual stress, among others”[94]

winding tool

See *winding scaffold* .

yarn

“An assemblage of twisted filaments, fibers, or strands, either natural or manufactured, to form a continuous length that is suitable for use in weaving or interweaving into textile materials”[94]

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Curriculum Vitae

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Work experience

Postdoctoral Resercher 1/08/2021 - Present	Flexible Formworks, The Block Research Group, Institute of Technology in Architecture, Swiss Federal Institute of Technology(ETH), Zurich, Switzerland
Doctoral Researcher 1/03/2017 - 01/07/2021	Fibrous Morphology, Institute for Computational Design and Construction(ICD), University of Stuttgart, Germany
Researcher and Tutor 1/09/2014 - 1/02/2017	Robotic Building, Hyperbody Research Group Delft University of Technology(TU Delft),The Architecture faculty, The Netherlands

Architecture and Design

1/04/2016 - 1/07/2016	Front-end wed developer - Body Chair APP and web-site development Form/Matter and ONL collaboration, Rotterdam, NL Team: S. Bodea, A. Anton, T. Verkerk, B. Molendijk
1/09/2015 -01/03/2016	Motion Design: Robot in Residence, deployable robotic fabrication systems, NL Team: S. Bodea, A. Anton, T. Verkerk, B. Molendijk
1/07/2015 -01/07/2016	Motion Design: Machining Emotion - Robotic Painting Project Team: I. Lenard, A. Anton, S. Bodea, K. Oosterhuis
1/03/2015 -01/07/2015	Computational Design analyst: Compliant Exoskeleton design on human body Skel-ex, Delft, NL
1/09/2014 - 1/01/2017	Computational Designer: Form/Matter, design and dissemination platform Team: S. Bodea, A. Anton
1/11/2014 - 30/06/2015	Research Assistant: Robotic Building, Design to Robotic Production Architecture Faculty,TU Delft, NL
1/05/2013 - 31/08/2013	Computational Design analyst- Back-end development, Python programming White Lioness Technologies, Amsterdam, NL
Architecture Student Internship	Computational Design analyst: TV Tower Design Comptetition Information Based Architecture, Amsterdam, NL
1/01/2011 - 30/06/2011	Architectural Design Assistant Intenship Architectural and Urban Design KCAP Architects and Planners, Zürich, CH

Teaching

ETH Zurich - D-Arch 24/02/2022 - 19/05/2022	Computational Structural Design II: Structurally-informed Materialisation

ITECH Masters Degree in Architecture	
01/10/2019 - 01/04/2020	Advanced fabrication Design Studio: Coreless Filament winding of naturally-sourced fibrous material
	Advanced fabrication Seminar: Coreless Filament winding of naturally-sourced fibrous material
01/10/2018 - 01/10/2019	Performative Morphologies Design Studio Class of 2020 Resistant Filigrees Master Thesis
01/10/2018 - 01/06/2019	
Hyperbody Master of Science, Architecture Faculty, TU Delft	
	Game Set and Match
10/02/2016 - 30/06/2016	Rotterdam Expo 2025
7/10/2015 - 30/01/2016	Robotic Environments, D2RP
10/02/2015 - 30/06/2015	M4H Vertical Studio
7/10/2014 - 30/01/2015	
International Workshops	
01/11/2018	Design and Automation for Coreless Composite Filament Winding, ITECH, University of Stuttgart, Stuttgart, Germany
	Introduction to Grasshopper, Hyperbody, Architecture Faculty,TU Delft, NL
19/09/2016	Digital Methods, Industrial Design Faculty, TU Delft, NL
30/10/2015 - 2/11/2015	Interactive Environments, Industrial Design Faculty, TU Delft, NL
7/10/2015 - 9/10/2015	Informed Porosity, Hyperbody, Architecture Faculty,TU Delft, NL
4/10/2015 - 30/11/2015	Seamless Variation for D2RP, The International Association for Shells and Spatial Structures: Future Visions,
15/08/2015 - 16/08/2015	Amsterdam, NL
	Continuous Variation for D2RP, International Design Seminar: InDeSem ReCraft, TU Delft, NL
29/05/2015 - 5/06/2015	Design to Robotic Production, Hyperbody, Architecture Faculty,TU Delft, NL
6/09/2014 - 24/09/2014	
Selected Peer Reviewed Publications	
Journal Publication Automation in Construction	S. Bodea, C. Zechmeister, N. Dambrosio, M. Dörstelmann, A. Menges, 2021. Robotic coreless filament winding for hyperboloid tubular composite components in construction. Automation in Construction 126, 103649. https://doi.org/10.1016/j.autcon.2021.103649.
Journal Publication 3D Printing and Additive Manufacturing	Bodea S., Mindermann P., Gresser T., Menges A.: 2021, Additive Manufacturing of Large Coreless Filament Wound Composite Elements for Building Construction, 3D Pinting and Additive Manufacturing, Mary Ann Liebert, Inc. Publishers. https://doi.org/10.1089/3dp.2020.0346
Journal Publication MDPI Processes	Mindermann P., Bodea S., Menges A., Gresser T.: 2021, Development of an Impregnation End-Effector with FiberTension Monitoring for Robotic Coreless Filament Winding, Processes, Molecular Diversity Preservation International(MDPI). DOI: 10.3390/pr9050806
Advances in Architectural Geometry, Paris, 2020	Christie, J., Bodea, S., Solly, J., Menges, A., Knippers, J.: 2020, Filigree Shell Slabs, Material and Fabrication-aware Shape Optimisation for CFRP, Coreless-wound slab components: Advances in Architectural geometry, Advances in Architectural Geometry(AAG2020). DOI: 10.13140/RG.2.2.16871.98727
Fabricate, London, 2020	Bodea, S., Dambrosio, N., Zechmeister, C., Gil Perez, M., Koslowski, V. Rongen, B., Doerstelmann, M., Kyjanek, O., Knippers, J., Menges, A.: 2020, BUGA Fibre Pavilion: Towards Robotically-Fabricated Composite Building Structures, in Burry, J., Sabin, J., Sheil, B., Skavara, M., (eds.), Fabricate 2020: Making Resilient Architecture, UCL Press, London, pp. 234-243. (ISBN: 9781787358119)
ACADIA, Austin, TX, 2019	Dambrosio, N., Zechmeister, C., Bodea, S., Koslowski, V., Gil-Pérez, M., Rongen, B., Knippers, J., Menges, A.: 2019, Towards an architectural application of novel fiber composite building systems – The BUGA Fibre Pavilion. in ACADIA – Ubiquity and Autonomy [Proceedings of the ACADIA Conference 2019]. The University of Texas, Austin. (ISBN 978-0-578-59179-7)
Design Modelling Symposium, Berlin, 2019	Zechmeister, C., Bodea, S., Dambrosio, N., Menges, A.: 2020, Design for Long-Span Core-Less Wound, Structural Composite Building Elements, in Gengnagel, C., Baverel, O., Burry, J., Ramsgaard Thomsen, M., Weinzierl, S. (Eds.), Impact: Design With All Senses [Proceedings of the Design Modelling Symposium 2019], Springer International Publishing, Cham, pp. 401-415. (doi: 10.1007/978-3-030-29829-6 32)

Book Chapter	Bier H., Liu Cheng A., Mostafavi S., Anton A., Bodea S.: 2018, Robotic Building as Integration of Design-to-Robotic-Production and -Operation, in Springer Series in Adaptive Environments, Robotic Building, H. Bier, Ed., Cham: Springer International Publishing, pp. 97–120.(https://doi.org/10.1007/978-3-319-70866-9_10)
eCAADe, Viena, 2015	Mostafavi S., Bier H., Bodea S., Anton A.: 2015, Informed Design to Robotic Production Systems, Developing Robotic 3D Printing System for Informed Material Deposition, in Martens B., Ed., eCAADe 2015: Proceedings of the 33rd International Conference on Education and Research in Computer Aided Architectural Design in Europe, 2015, Vienna, Austria, 1st ed. Vienna: eCAADe; Faculty of Architecture and Regional Planning.
Lectures and Reviews	
19/05/2021	BUGA Fibre Pavilion: Towards Robotically-Fabricated Composite Building Structures Fibrous tectonics: Applying lessons from biology and technology on lightweight composite building systems in architecture, Robotic Building TUDelft, Delft, Netherlands(online).
11/09/2020	BUGA Fibre Pavilion: Towards Robotically-Fabricated Composite Building Structures, Lecture and Project presentation at FABRICATE 2020: Making Resilient Architecture, UCL, Bartlett, London, United Kingdom (online).
27/06/2019	Research and teaching in ITECH Master Studio – Lecture, Faculty of Architecture, University of Stuttgart, Stuttgart, Germany.
10/10/2019	The BUGA Fibre Pavilion – Lecture, PARAMATERIA Academia - Industry Event, University of Stuttgart, Stuttgart, Germany
20/12/2019	Fibrous Tectonics in Architecture, Lecture and Review for Concrete Calligraphy, Master in Advanced Studies (MAS) ETH Zürich, Zürich, Switzerland.
27/06/2019	Fibrous Tectonics in Architecture: BUGA Fibre Pavilion. Lecture, DIA Dessau, Germany.
27/06/2019	DARS - Master in Architecture. Masters Project Reviews, DIA Dessau, Germany.
10/10/2017	Composite Architecture. Lecture, Norman Foster Foundation Robotics Atelier – Lecture at the Norman Foster Foundation, Madrid, Spain.
10/11/2016	Design to Robotic Production. Lecture, Game Set & Match 3, International Symposium, Robotic Building Session, Architecture Faculty, TU Delft, Delft, Netherlands.
Awards	
2019	German Design Award, BUGA Fibre Pavilion 2019. [Online]. Available: https://www.german-design-award.com/en/the-winners/gallery/detail/28394-buga-fibre-pavilion-2019.html
2019	Iconic Wold, BUGA FIBER PAVILION 2019. [Online]. Available: https://www.iconic-world.de/directory/buga-fibre-pavilion-2019
2019	Land der Ideen, Beyond Bauhaus – prototyping the future Award 2019 for BUGA Fiber Pavilion Heilbronn. [Online]. Available: https://land-der-ideen.de/en/competitions/beyond-bauhaus/award-winners/buga-fibre-pavilion
2020	Detail Prize for students and architecture schools 2020, The BUGA Fiber Pavilion 2019 Heilbronn. [Online]. Available: https://www.detail-online.com/article/houses-made-of-carbon-detail-prize-for-students-and-architecture-schools-2020-goes-to-the-buga-fibre-pavilion/
Exhibits and demos	
BUGA Fibre Pavilion 16/08/2019 - 01/09/2019	Land der Ideen, Beyond Bauhaus – prototyping the future Exhibition, Belin, DE
1/11/2016 - 11/11/2016	Game Set & Match 3, Exhibition, BK Expo, Architecture Faculty, TU Delft, NL
27/06/2016 - 15/09/2016	ARGUS Expo, BK Expo, Architecture Faculty, TU Delft, NL
15/03/2016 - 19/03/2016	Movie: “Continuous Variation – Informed Robotic 3D Printing”, ROB|ARCH Conference, (2016), Sidney, AU
17/03/2016 - 19/03/2016	Movie: “Informed Porosity”, ROB|ARCH Conference, (2016), Sidney, AU

Machining Emotion	Robotic Painting
3/06/2016	Future Flux Festival, Rotterdam, NL
08/05/2016 - 17/06/2016	Up Memory Lane (Part I), Ram Gallery, Rotterdam, NL
15/03/2016 - 19/03/2016	Movie:“Machining Emotion-Robotic Painting”, ROB|ARCH Conference, (2016), Sidney, AU
26/10/2015 - 31/10/2015	Dubai Design Week, Dubai, UAE
17/10/2015 - 25/10/2015	Dutch Design Week, Eindhoven, NL
Design to Robotic Production	Robotic Environments, Hyperbody MSc. 2 Design Studio
2/07/2015 - 4/07/2015	V2 Institute for Unstable Media, Rotterdam, NL
26/11/2015 - 18/12/2015	Exposition Synthetic, Le Mans, FR
Scalable Porosity	Robotic Clay 3D Printing
15/03/2017 - 19/06/2017	Movie: “Scalable Porosity”, Imprimer le Monde Exhibition, part of Mutations/Creations, Centre Pompidou, Paris, FR
9/02/2015 - 13/02/2015	Week van de Bouw, Utrecht , NL
18/05/2015	Beurs-World Trade Center, Rotterdam, NL
Robowtie	
20/04/2014 - 26/05/2014	Ram Gallery, Rotterdam, NL
28/11/2013 - 15/02/2014	Blauwhoed Event , Delfshaven, Rotterdam, NL
7/07/2013 - 31/07/2013	Bridges, Enschede, NL
SPACEPLAY	
26/09/2010 - 11/10/2010	The Romanian Pavilion, ShanghaiExpo2010, Shanghai, CN
Education	
Doctorate in Architecture	University of Stuttgart, Faculty of Architecture and Urban Planning, Institute for Computational Design and Construction
01/03/2017-21/09/2022	Magna Cum Laude
	Architecture Faculty, TU Delft, NL
Architect, Master of Science	Architect(Ir.), Cum Laude
1/09/2012 - 30/06/2014	Ion Mincu - Architecture and Urban Planning, Architecture Faculty, Bucharest, RO
Integrated Master Diploma in Architecture	Architect
1/10/2005 - 30/06/2012	
Languages	English(Proficient), German (Proficient), French (Proficient), Dutch(Beginner), Romanian (Native)
Computer Skills	
Programming Languages	Python, C#
CAD	COMPAS Framework for AEC, Rhinoceros+Grasshopper, 3DSMax, Revit, ABB RobotStudio, KUKA Sim, KUKA Work Visual
Image processing	Adobe Suite
Computational Fabrication	
Additive and Subtractive Robotic Fabrication	Coreless filament winding (CFW) Multimateial 3D printing (3DP) Milling Hot wire cutting (HWC)
Hobbies	Science communication, SF Literature, Trail Running, Alpine climbing, Cycling, Football