Fortschritte im kernlosen Wickeln für eine digitale Prozesscharakterisierung

Advancements in coreless filament winding towards a digital process characterization

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My parents are always there for me when I need them. I would like to include my other family members and friends on a similar note.

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Pascal Mindermann

Abstract

Coreless filament winding is an emerging additive manufacturing process for generating fiber-reinforced thermoset composite structures. An impregnated fiber bundle is spanned freely between spatially arranged point-like anchors, defining the lattice geometry of the fabricated components. This design freedom, combined with the automation of the process, marks coreless filament winding as a valuable contribution to the spectrum of lightweight manufacturing technologies. However, coreless filament winding still requires several advancements to deliver its potential to mechanical engineering and architectural applications. Mechanical engineering demands efficiency to meet climate neutrality and high-performance structures driven by technical innovation. In conjunction to the challenges, architecture faces an increasing need for building floor space caused by population growth, while productivity stagnates due to missing digitalization.

The adoption of coreless filament winding is held back by inherent variations in the parameters describing the process and the fabricated structures. Process parameter fluctuations combine with material deviations. Safety factors and resource consumption increase as these variations translate into uncertainties in the design process.

Therefore, this thesis aims to improve the characterization of the coreless filament winding process. An enhanced digital representation realized this characterization, as the primary objective was to improve the consistency between the digital model and the physical counterpart. The primary objective was achieved by implementing adjustments in the physical as well as in the digital domain. In parallel, this thesis also realized advancements in the quality of the fabricated structures and the efficiency of the process. Furthermore, the process capabilities were extended to new features and applications. Coreless filament winding was considered holistically based on four research approaches as follows: fabrication system, the material system, the load induction, and the computational infrastructure.

The cumulative advancement extracted from the comprised academic contributions, distributed across the research approaches, confirms the overarching improvement of the considered process evaluation criteria through a consistent digital characterization. Moreover, the improved understanding of the peculiarities of coreless filament winding allows for more effective management of specific requirements in the future by simplifying the decision-making during the design process, covering all process aspects.

Kurzfassung

Das kernlose Wickeln ist ein aufstrebendes additives Fertigungsverfahren zur Herstellung von duroplastischen Faserverbundstrukturen. Ein imprägniertes Faserbündel wird frei zwischen räumlich angeordneten punktförmigen Ankern frei aufgespannt, wodurch die Geometrie der herzustellenden gitterförmigen Bauteile definiert wird. In Verbindung mit der Automatisierung des Prozesses kennzeichnet diese Gestaltungsfreiheit das kernlose Wickeln als relevant unter den verfügbaren Leichtbautechnologien. Allerdings bedarf es noch mehrerer Weiterentwicklungen, um das Potenzial des kernlosen Wickelns für den Maschinenbau und die Architektur nutzbar zu machen. Im Maschinenbau werden effiziente Strukturen zur Erreichung der Klimaneutralität und hoch-leistungsfähige Strukturen für technische Innovationen benötigt. Hingegen besteht im Bauwesen aufgrund des Bevölkerungswachstums ein ansteigender Bedarf nach Gebäudeflächen, während die Produktivität jedoch infolge mangelnder Digitalisierung stagniert.

Die technologische Verbreitung des kernlosen Wickelns wird durch die inhärenten Streuungen in Prozess- und Strukturparametern verlangsamt. Abweichungen im Material und Schwankungen in den Prozessparametern führen zu Unsicherheiten im Auslegungsprozess, welche durch eine Erhöhung der Sicherheitsfaktoren und des Ressourcenverbrauchs kompensiert werden.

Daher ist die Aufgabe dieser Arbeit die Verbesserung der Charakterisierung des kernlosen Wickelprozesses. Dies wurde durch eine Weiterentwicklung der Methoden zur digitalen Erfassung umgesetzt, wobei das primäre Ziel in der Vergrößerung der Übereinstimmung zwischen dem digitalen Modell und dem physischen Gegenstück bestand. Durch die Implementierung von physikalischen und digitalen Anpassungen wurde das primäre Ziel erreicht. Zugleich wurden im Rahmen dieser Arbeit auch Fortschritte in der Bauteilqualität und der Prozesseffizienz gemacht. Darüber hinaus wurde das Verfahren auf neue Funktionen und Anwendungen erweitert. Das kernlose Wickeln wurde ganzheitlich anhand von vier Forschungsansätzen betrachtet, welche auf das Fertigungssystem, das Materialsystem, die Lasteinleitung und die Datenverarbeitungsinfrastruktur ausgerichtet sind.

Der kumulative Entwicklungsfortschritt, welcher anhand der Forschungsansätze aus den eingebundenen wissenschaftlichen Beiträgen gewonnen wurde, zeigt aufgrund der konsistenten digitalen Charakterisierung eine übergreifende Verbesserung in den Prozessbewertungskriterien. Zudem ermöglicht das vermehrte Verständnis über die Eigenheiten des kernlosen Wickelns eine effektivere Handhabung von zukünftigen spezifischen Anforderungen, indem die Entscheidungsfindung während des Auslegungsprozesses in allen Prozessaspekten vereinfacht wird.

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Abbreviations

AI	artificial intelligence
CAD	computer-aided design
CDR	critical design review
CFRP	carbon fiber-reinforced plastics
CFW	coreless filament winding
CLT	classical laminate theory
CNC	computerized numerical control
DSC	differential scanning calorimetry
FEA	finite element analysis
FMR	fiber mass ratio
FOS	fiber-optical sensor
FVR	fiber volume ratio
LAB	CIELAB color space
LED	light-emitting diode
PDR	preliminary design review
RMR	resin mass ratio
RVR	resin volume ratio
SEM	scanning electron microscope
UV	ultraviolet
VOC	volatile organic compounds
VVR	void volume ratio

1. Introduction

1.1 Historical Background

With the introduction of the first artificial resins in the late 19th century, the modern era of engineering composites began [1]. When continuous glass fibers [2] were created in the 1930s for the first time, their combination with resins improved the neat plastics' mechanical properties opening up new prospects. Later in that decade, other resins, such as epoxy [3] and polyester [4], were patented. Based on these innovations, the technological utilization of fiber-reinforced plastics was initiated and rapidly grew by including further applications and processes until the 1950s ended [5]. Especially for some lightweight applications in aerospace, such composites successfully displaced metal-based material systems because of their advantageous mechanical properties [6]. Moreover, with other distinctive properties (a.o., non-corrosive, non-magnetic) and a fundamentally different design language (e.g., flexible before curing, forming/bonding instead of separating), this prospect delivered new manufacturing processes, such as pultrusion or vacuum infusion techniques.

In the 1960s, carbon fibers [7] were introduced, and the deployment of filament winding [8] was promoted by producing large-scale propellant tanks for space exploration [9]. In the following decades, the composites industry matured as innovation was driven by enhancing material properties to expand composite applications. For example, aramid [10] was launched on the market in the late 1960s. Hereafter, servo technology replaced controlling filament winding machines by adjusting mechanical elements, such as gears or belts [11]. By the 1970s, the composite market for automotive surpassed that for marine applications [5]. The lightweight potential of lattice structures was recognized and patented in the second half of the 1970s as isogrid structures [12] executed in metal and fiber composite. Isogrid structures can be manufactured by filament winding using a mandrel with grooves that receive the fibers [13]. Through increasing computer technology, the first CNC filament winding machines (Figure 1.1) were available in the early 1980s, as the control technology was adapted from metal cutting [14]. Only later the application of filament winding was extended from cylindrical to more complex shapes [15]. Automated tape laying began to focus on aircraft structures in the late 1980s and was improved throughout the 1990s [16]. With onset in the 2000s, nanotechnological products were combined with fibrous composites [17].

State-of-the-art filament winding machines contain 2–8 axis, multiple spindles, and work with rovings and tapes [14]. From this, coreless filament winding (CFW) was derived in the early 2010s in an academic architectural context by replacing the spindle/mandrel with point-like anchors on a frame and the winding machine with an industrial robot. Before the end of that decade, several research-orientated building demonstrators for CFW were realized [18]. However, CFW shows substantial unlocked potential, especially for lightweight lattice structures, compared to other manufacturing processes, as it is still an emerging technology. This thesis centers around CFW, set in mechanical engineering and architectural application context.

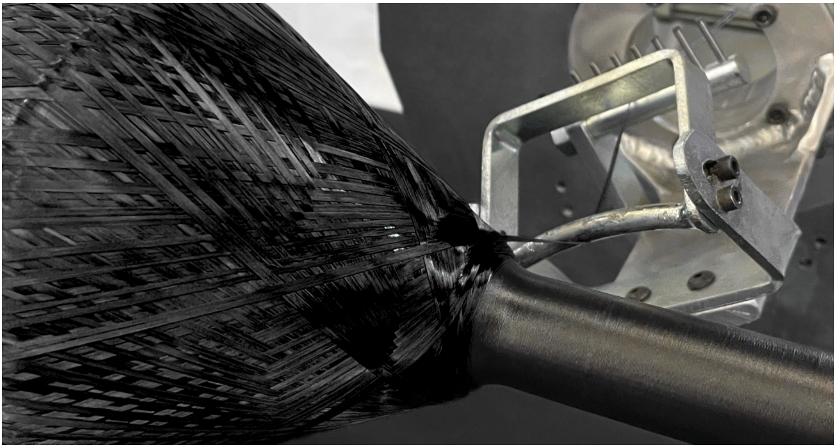


Figure 1.1 CNC-controlled filament winding machine using a conical mandrel.

Nowadays, various advanced composite manufacturing processes and materials are present across the industry. They are critical in lightweight-oriented applications, such as aerospace, automotive, marine, and energy, and enter other branches, such as construction, robotics, and medical technology. However, CFW is currently not at the level to gain a considerable presence in the industry. The global market [19] for fiber-reinforced plastics is expected to reach USD 118 billion by 2027, with a growth rate of over 8% until then, which highlights the increasing demand for lightweight structures, while current research trends focus on sustainability.

1.2 Definition of Coreless Filament Winding

CFW is an additive manufacturing process in which an impregnated fiber bundle is spanned between point-like anchors for generating thermoset fiber-reinforced composite structures (Figure 1.2). The anchors are spatially arranged, defining the component shape as the fiber bundle connects them in a specific sequence. The stepwise evolving lattice structure is geometrically best described by nodes connected by edges and becomes load-bearing after curing the resin. As a result of eliminating the mandrel in filament winding, fiber–fiber interactions commonly influence the resulting component shape in CFW. In contrast, if external surfaces of molds or fixtures also interact with the composite, the process is referred to as hybrid CFW.

1.3 Technological Advantages

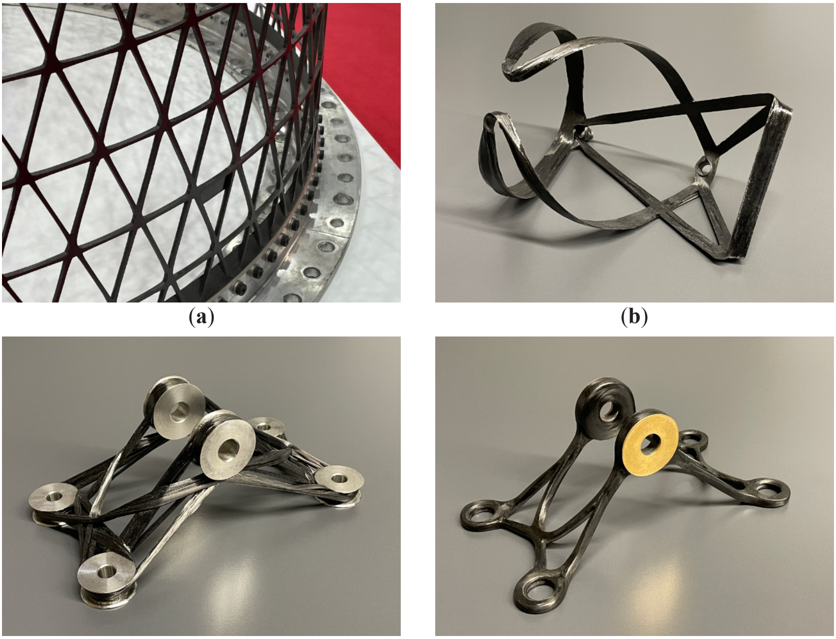
Fiber-reinforced composites include several advantages over conventionally used material systems that justify their deployment. High-performance fibers express higher mass-specific stiffness and strength than metal-based material systems [20]. Composites also offer properties that are helpful in specific applications, such as excellent chemical and corrosive resistance (marine and outdoor applications), low thermal expansion (antenna mounts and cameras), non-magneticity (satellite booms and medical applications), and radiolucency (radomes) [21, 22]. Reducing the part count is possible when applying an integral construction method. CFW inherits all those material-related advantages.

Figure 1.2 Nozzle (left) of a winding head spanning an impregnated glass fiber bundle after hooking it to a winding pin (right), illustrating the CFW process.

1.4 Mechanical Engineering Applications

Engineering disciplines are of fundamental significance to mankind as they amplify technical capabilities. The state of civilization is, among others, indicated by technological innovations addressing problems in every aspect of human life. A current challenge of central importance in engineering is reaching climate neutrality. Similar to other nations, Europe [23] and USA [24] target to achieve it no later than 2050 while reducing emissions significantly before the 2030s. Chinese emissions are expected to peak at that time and from then on to reduce to net-zero by 2060 [25]. These climate agreements create the demand for efficient structures in the mechanical engineering sector. To highlight one example: The transportation sector requires an efficiency increase, while vehicle mass constantly rises with new features [26]. Another motivation lies in scientific and technical innovations that demand peak-performing structures. For example, the importance of such lightweight structures is easily recognizable from the launch cost of USD 3000–14000 per kg for low-earth orbit [27]. Furthermore, reducing structural mass increases the payload or mission range especially needed for potential future interplanetary manned space flight. Another example is robotics, where inert masses limit productivity and increase energy consumption.

Current technology appears insufficient to meet these challenges. This motivates harnessing the full potential of CFW through research. In the form of lattice truss structures [28] integrally fabricated from carbon fibers and topologically optimized for their specific application, CFW might combine efficiency with high performance for mechanical engineering. In addition, automation could allow scaling productivity. In mechanical engineering applications, CFW competes with fiber-reinforced 3D printing, which is already fully digitalized. However, CFW could achieve higher process speeds in a larger build volume while realizing an uninterrupted fiber path. CFW could be particularly suitable for the production of local reinforcements or as connecting elements with complex load cases or geometries. At present, there are only isolated CFW structures that are utilized industrially in mechanical engineering. The utilization of isogrid-like structures is more common, especially in aerospace engineering [29]. Nonetheless, there are technology demonstrators (Figure 1.3).



(**a**) (**b**)

(**c**) (**d**)

Figure 1.3 State-of-the-art wound structures in engineering. (**a**) isogrid structure made by conventional filament winding, (**b**) bottle holder made by hybrid CFW, (**c**) bracket made by CFW, component kindly provided by Automotive Management Consulting GmbH, (**d**) consolidated bracket made by hybrid CFW, component kindly provided by LASSO Ingenieurgesellschaft mbH.

1.5 Architectural Applications

Alongside mechanical engineering, also architecture is of central importance as humans spend 87% of their lives in buildings [30]. Due to population growth, new residential units for 2.5 billion people and a corresponding number of commercial and public buildings will need to be erected until 2050 [31]. However, construction productivity has stagnated since the 1990s [32] and currently only meets 65% of the demand [33]. The primary reason for this is a lack of digitalization [34]. Comprehensive automation to increase productivity requires such digital planning tools. Moreover, the construction sector is responsible for a considerable share of global resource consumption [35]. The overuse of some construction materials has led to a global shortage, such as reinforced concrete requiring sand [36]. Also, timber shows a deficiency of availability currently [37].

These currently unsolvable issues motivate the development of fabrication technology generating efficient structures on an architectural scale, something that CFW could provide. Sparing material use and sustainable materials could mitigate possible material shortages. In addition, CFW could provide lightweight long-span building systems facilitating stock extension addressing the increasing urbanization. On-site fabrication could reduce logistics. Apart from technical advantages, CFW could also contribute design freedom and individualizable components without the extensive framework. In recent years, several research-motivated architectural CFW demonstrators have been presented (Figure 1.4).

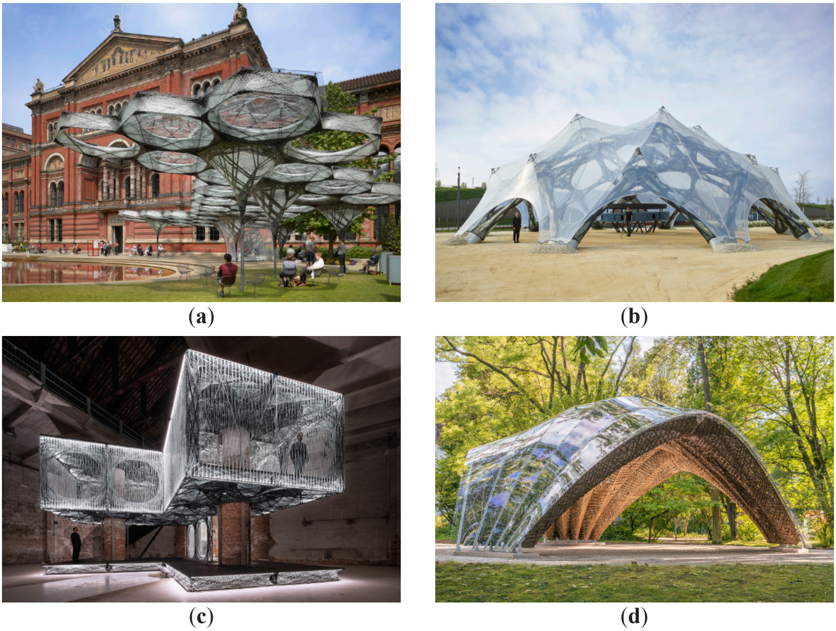


Figure 1.4 State-of-the-art wound structures in architecture. (**a**) Elytra Filament Pavilion 2016, (**b**) BUGA Fibre Pavilion 2019, (**c**) Maison Fibre 2021, (**d**) LivMatS Pavilion 2021.
© Roland Halbe for (a) and (b),
© ICD/ITKE/IntCDC University of Stuttgart for (c) and (d).

1.6 Technological Disadvantages

Despite the mentioned potential, CFW and fiber composites have significant drawbacks. Some of which are addressed by the work conducted within this thesis. Although fiber composite processing often relies heavily on craftsmanship [38], deviations in the fabricated structures are the main drawback of CFW. Variations are inherent in the composite material system [39] and even amplified by CFW process parameter fluctuations. Both influences translate into significant variations in the fabricated structures' mesoscopic geometry and material composition causing uncertainties in mechanical performance and limiting predictability in the design processes. As a result, safety factors and material consumption are increased [40]. Moreover, extensive non-standardized testing [41] is required to individually qualify the CFW structures in retrospect. Those disadvantages affect both application contexts equally. In architectural applications, the diversity between components is more frequent, building codes are missing for non-standard building systems, and testing becomes more elaborate on a larger scale. So, for both application contexts, the variations in the fabricated structures are the central issue to be solved for CFW. Consequently, improving the process characterization is the only solution to this challenge.

Other material disadvantages also directly translate to CFW, such as adversities in repair [42] and recycling [43], limitations in shelf and pot lives, and the material's brittleness [44], which hinders internal load redistribution. The spectrum of non-destructive quality control inspections is quite limited [45]. Usually, subsequent machining operations are unfavorable to the component performance as fibers are cut [46]. Furthermore, the precise balancing of load cases, structures' aversion to punctual load induction, composite components' more pronounced interfaces, and the material's anisotropy complicate the design. A notable distinction from other composite manufacturing processes is that fiber orientation and component geometry are directly entangled in CFW. Matching the fiber orientation and force flow is impossible by changing laminate patterns without altering component geometry, further complicating the design. Only digital methods are powerful enough to approach these challenges, so the before-mentioned characterization for CFW must happen digitally. Besides establishing a digital infrastructure, further aspects of the CFW process also need to be improved.

1.7 Process Target Metrics

The process target metrics [47] indicate the maturity of a manufacturing process. Unused potential can be identified by evaluating the process based on all target metrics, which are the following:

- **effectivity** – achieving the desired result without errors
- **efficiency** – requiring minimal resources
- **determinism** – predicting the (repeatable) process results
- **controllability** – knowing the consequences of control inputs
- **robustness** – stabilizing against fluctuations and errors
- **atomicity** – operating on the smallest unit (material or information)
- **side/after-effect absence** – limiting of process interdependencies
- **documentation** – acquiring the actual process execution
- **flexibility** – adapting to changed requirements
- **improvability** – enhancing the process attributes

Productivity, often used in economic considerations, is the arithmetic product of effectivity and efficiency [48]. This thesis will evaluate the process enhancements by applying these ten target metrics as criteria.

1.8 Process Facets

Where the target metrics prescribe the direction of needed improvements, the process facets represent all contributing entities that can be manipulated to enhance the process. In general, a manufacturing process can be divided into three information-containing facets: resource, process, and product [49]. However, adopting this theory to CFW requires a rearrangement. The resource facet contains equipment resources and raw material resources. Equipment and processing can be joined together due to their strong interdependence. The same applies to the raw material and product. In parallel, data handling is extracted from each of the general facets and treated separately due to its importance in CFW. Hence, three facets describe the CFW manufacturing process:

- **Equipment and Processing** – These operating resources directly participate in value-adding. In CFW, this includes the manufacturing setup and the fabrication instruction execution.
- **Product** – The product of CFW is the load-bearing structure, which can be a sample, a component, or an assembly of multiple components. This facet also includes the required material resources.
- **Data Handling** – It refers to the data produced during all process phases (design, fabrication, quality assurance) and might be extended until the end of life as object monitoring and in the other direction by considering the input raw materials.

All three process facets need to be considered during optimizing the process as they all interrelate. In addition, depending on the configuration of the CFW process, it might involve auxiliary processes, such as conventional manufacturing techniques and material systems.

1.9 Hypothesis

This thesis will argue that

> *a consistent digital characterization covering all process facets is required to establish coreless filament winding as a manufacturing process with improved target metrics.*

Following this hypothesis, several advancements will be incorporated into CFW by focusing on its main drawback. The digital characterization will then be presented as an improved computational representation of the process and the fabricated structures, reducing variations and thus uncertainties. This thesis will answer how such a digital characterization must be composed in order to provide the fundamental expertise for a subsequent more accurate design of CFW structures.

2. State of the Art – Coreless Filament Winding

Coreless filament winding is a manufacturing process for thermoset fiber-reinforced plastics, in which an impregnated fiber bundle stepwise connects point-like anchors. The spatial arrangement of these anchors defines the component's shape. CFW has evolved from conventional filament winding [50] by substituting the mandrel with anchors. In contrast to manual winding, in robotic CFW [51], an industrial robot spans the fiber bundle. In hybrid CFW external surfaces also interact with the places fiber bundles [52]. The process classifies under additive manufacturing as fibers are added in layers in a specific sequence, called winding syntax [53]. The hooking syntax specifies the fiber arrangement for each anchor and step. Nodes connected by edges best represent the fabricated structures (Figure 2.1). Hence, they categorize as lattices [54] or shells [55].

	Winding Plan								
Winding Step	0	1	2	3	4	5	6	7	8
Winding Syntax	0	1	2	3	1	3	2	1	-1
Hooking Syntax	-	U	U	U	U	X	X	U	-

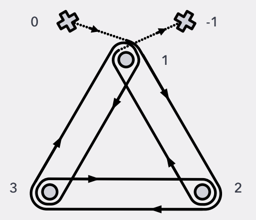


Figure 2.1 Example of a winding plan. Winding anchors (1, 2, 3), fixation points (0, -1), placement direction of the fiber (arrows), cut-off segments (dotted line), hooking steps with self-overlapping (X) and without (U). This illustration ignores the order of layers.

2.1 Distinctions from Related Processes

In comparison to other processes, CFW offers unique traits. CFW does not entail the downsides of mandrels or molds used in, for instance, conventional filament winding and automatic tape laying [56]. Such shortcomings are high investment cost, sensitive mold surfaces, small tolerances, use of release agents, need for additional load induction elements, and fiber net design restrictions. Removing the mandrel or mold makes the fiber-supporting surface missing, resulting in fiber–fiber interactions significantly affecting the component shape in CFW. This influence becomes more pronounced when minimizing the number of anchors.

CFW is not limited to flat or low curvature applications compared to **automated tape laying**, also exhibiting lower production speeds and cutting of fibers. Moreover, overlaps or gaps between tapes must be mitigated, especially with complex components [57]. Nevertheless, tape laying allows the automated production of flat components with high precision in fiber orientation, high component shape accuracy, and repeatability. In contrast, conventional filament winding achieves the same attributes for rotational shapes under constant fiber tension.

Pultrusion is a cost-effective and fast process for producing continuous profiles with accurate cross-sectional contours. Truss structures similar to CFW can be assembled from pultruded profiles [58] or fabricated by a combination of pultrusion and filament winding [59]. The key difference is that with CFW, the component is formed from an uninterrupted fiber bundle and does not require connectors between the segments. Joining the pultruded rods reduces the load capacity and raises the workload.

Continuous fiber-reinforced 3D printing combines the high mechanical properties of fibers with the design freedom of thermoplastic 3D printing. The process chain from CAD to fabrication is digitized end-to-end and thus user-friendly [60]. In contrast, CFW can produce components faster and on a larger scale. CFW also uses thermosets instead of thermoplastics, covering more operational areas. In 3D printing, the fibers are embedded in isolated layers, usually with a low fiber volume ratio (FVR). Contrariwise, CFW achieves an uninterrupted fiber path in all spatial directions. The fiber orientation primarily depends on the object orientation during printing, whereas in CFW, it is entangled with the component geometry.

2.2 Setup and Equipment

The robotic CFW setup (Figure 2.2) represents a robotic cell with the corresponding safety devices and regulations. Preferably, the facility is climate-controlled in terms of temperature and humidity. When operating autonomously in a single workspace, the CFW system can support on-site fabrication. The equipment includes fiber and resin sources, a robotic system, and a winding fixture with mounted anchors. The most straightforward robotic system utilizes a single industrial robot. During winding, material flows from the fiber source via the resin source to robotics and ends at the fixture.

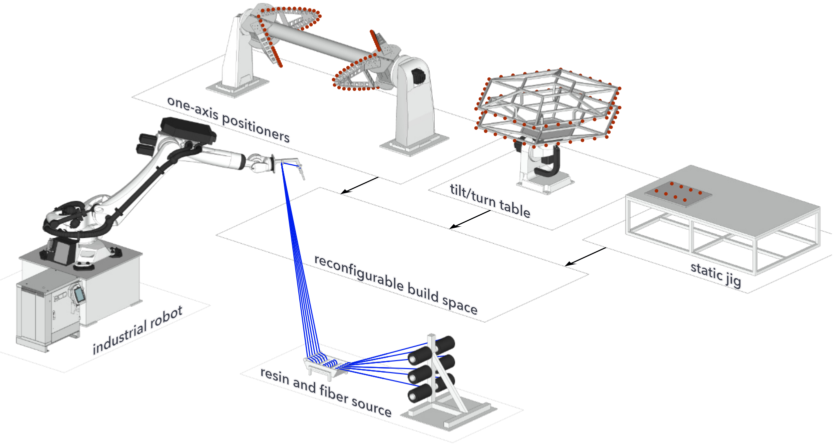


Figure 2.2 Conceptual illustration of a robotic CFW setup with different possible configurations for fixtures and additional robotic axes. Fiber path indicated in blue and winding anchors in red.

According to the state of the art, the fiber and resin sources are stationary units on the ground. Fibers are pulled through the system purely by the shaping movements of the robotic end-effector's tool center point (TCP) following the winding trajectory. In this way, the dry fibers travel from the creel to the resin source. It is a resin bath impregnating by immersion [61] or by a drum [62] and can include a passive fiber tension control (Figure 2.3a). In its simplest form an adjustable friction-based mechanism is located at the spool holders or at the resin bath's egress. The latter mechanism also regulates the amount of resin remaining in the fiber bundle. Alternatively, a dancer arm is located between the creel and the robot. Fiber and resin sources are located sideways or opposite to the robot on the setup's perimeter, depending on the fixture configuration and its interaction with the robot. After leaving the stationary resin source, the impregnated fiber bundle span freely through the setup and meet the dynamically moving robot's end-effector. Hence, substantial fiber tension variations [63].

The 6-axis industrial robot usually operates from an elevated position on the floor. The robot's reach can be extended by additional robotic axes or arm extensions, depending on the fixture configuration. Due to investment costs or motion restrictions, especially during hooking, CFW setup configurations with overhead-mounted robots [64] or static tools [65] are rarely used.

(a) (b)

Figure 2.3 State-of-the-art CFW equipment. (**a**) drum resin bath with passive tension control and fibers traveling from left to right, (**b**) winding head with fibers traveling from bottom to left. © ICD/ITKE University of Stuttgart.

The industrial robot carries a rudimentary end-effector with two fiber guiding elements (Figure 2.3b). The one closer to the robot flange collects the fibers and has larger fillets, requiring more space. The fibers run from there to the second tubular fiber guiding element. The center of its egress opening represents the TCP, whose eccentricity avoids singularities. The tube's end section contains a spring for collision avoidance with anchor elements. The tube's small diameter must fit between two anchors, while the tube's length exposes the TCP from the winding head.

In conventional filament winding, the TCP's trajectory results from the geodesic fiber path [66] on or above the mandrel's surface as circumferential, helical, or polar winding [14]. In CFW, the robot trajectories are more complex and thus pre-computed by algorithms based on a CAD of the setup and the component to be manufactured. Then, the trajectory is translated into robot code, transmitted to the robotic system, and finally executed in the full-speed manual test operating mode of the robot. Cartesian points and corresponding tool orientations connected by linear motions define the trajectory. Point-to-point motions are only used outside the component's winding trajectory. Robot programming by teaching is common only for short trajectories.

The winding head places the fiber bundle around the anchors of the winding fixture. The anchors are almost always designed as winding pins. These metallic pins are either lathed from a solid part [67] or assembled from a metallic sleeve between two washers lined up on a bolt (Figure 2.4a). Besides cost, the advantage of such a sleeve/washer winding pin is that its metallic interface can later be used in assembly for bolt connections. In some cases, the pins connect to the support structure of the winding fixture via individually adjustable adapters (Figure 2.4b). However, the major drawback of winding pins is the coupling in orientation between the pin and the attaching fiber bundles. Moreover, in some scenarios they require adaptors to be connected to each other [68]. The winding fixture's supporting structure is usually made from metal or timber and designed as a frame or monolithic block. Such, winding fixtures are usually removable, disassemblable, and reconfigurable [69]. In some cases, they remain in the CFW component as a structurally active constituent [64]. Pins anchored in single-use milled foam fixtures are suitable, especially for low fiber tensions and complex free-form geometries [70]. The fixture design defines the range of anchor reconfigurability. Designs beyond that range require the manufacturing of a new fixture. The winding fixture can be stationary or mounted on one or more additional robotic axes. Single-axis rotary positioners or turn-tilt positioners are usually used to manipulate the winding fixture. Counter bearings are coupled mechanically [71]. Additional axes are integrated into the robot controller for synchronizing.

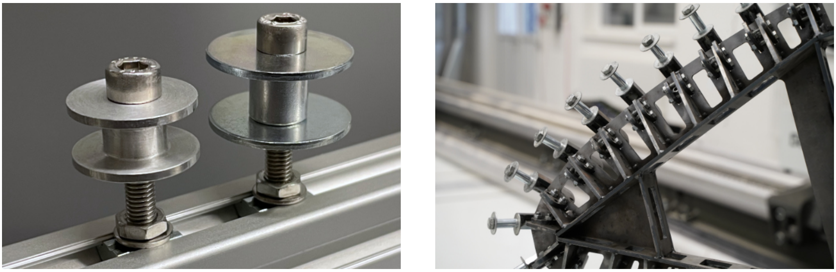

(**a**) (**b**)

Figure 2.4 Winding pins and fixture. (**a**) lathed winding pin (left) and sleeve/washer winding pin (right) mounted to an aluminum profile, (**b**) winding fixture designed as a reconfigurable metallic frame with adjustable adapters to hold the winding pins in place.

As alternative to an industrial robot, cartesian 3-axis kinematics, like from a milling machine, can also be used to place fibers. However, this lack of axes leads to noticeable limitations in trajectory creation, restricting the fabrication capability of such a system to flat or low-curvature components. In manual winding, neither robots nor additional axes are used. Instead, the fibers are placed directly by hand or using a handheld fiber-guiding device.

In some cases, this device (e.g., resin-filled syringe) covers the impregnation function of the resin bath. After depositing the fibers, the last instrument needed is an oven for tempering the resin. After curing, the dimensionally stable component is removed from the fixture, clearing the setup for the next winding session.

2.3 Fabrication Workflow

The workflow consists of three phases, whereby post-processing and especially preparation can substantially outweigh the duration of the actual winding session, depending on various process specifics, such as the component size in relation to the average material throughput.

The workflow begins with preparing the setup by adjusting the equipment to the component to be manufactured. For robotic setups, this phase includes matching the digital model with its physical counterpart, which is essential if the model is used to create control inputs. In addition, the robotic tool and the anchors must be calibrated to check their coordinates and orientations when updating the model. After completing the fabrication instructions (winding plan or robot code), the fibers are threaded, and an optional dry winding for testing is performed.

The resin is mixed and filled into the resin bath in the next step. The fiber bundle is pulled through and then knotted or taped to the start position. It is located outside the component and prevents non-impregnated fibers from entering the component. The winding session begins with executing the fabrication instructions. These contain the winding and hooking syntax for each winding step in a structured manner, including loops, jumps, and subdivisions based on the sub syntaxes. The winding syntax lists the identifiers of the anchors in the sequence the fiber bundle connects them. The identifiers are usually integer numbers. The hooking syntax specifies how fibers are attached to the anchor. According to the state of the art, the description of the hooking syntax was premature as only two rudimentary fiber arrangement patterns were distinguished (Figure 2.1). In the case of robotic winding, fabrication instructions extend to the computational description of the trajectories as points, orientations, speeds, and robot postures. If necessary, winding sessions are interrupted to refill fibers or resin sources. Temperature and humidity are recorded during the winding.

After fully executing the fabrication instructions, the fiber is cut and fixed in the same manner as at the beginning of the process outside the component without changing the fiber tension. The component remains on the fixture until it is self-supporting and is removed by unbolting the winding pins or disassembling the fixture. It may require curing or tempering in an oven. The post-processing includes cleaning the equipment, removing the protruding fiber ends, brushing, weighing, and measuring the finished component.

2.4 Composite Material System

The CFW process is intended for producing fiber-reinforced plastic composite structures using for instance carbon and glass fibers with epoxy resins (Figure 2.5). A clear conceptualization of the material system [72], which extends beyond the material constituents and their micro-mechanical interactions, is paramount in CFW to control the numerous structural interfaces. Unfortunately, there is no uniformly accepted definition of the material system notion across all disciplines.

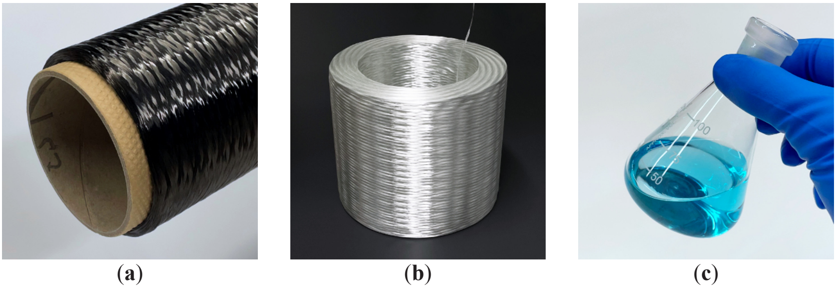


Figure 2.5 Fiber–polymer composite raw materials. (**a**) carbon fiber, (**b**) glass fiber, (**c**) epoxy resin.

Carbon fibers have been placed as reinforcements due to their high mass-specific stiffness onto a glass fiber substrate, which provides a high mass- and cost-specific strength [73]. The process's fiber deposition quality describes the fiber bundles' error-free positioning in the component with appropriate tension and without slipping or damage. Other fiber systems, such as flax or sisal, have only recently been transferred to CFW [74]. Epoxy resins are nearly exclusively deployed in CFW due to their excellent mechanical properties and high fiber-matrix adhesion [75]. In addition, they exhibit higher temperature and chemical resistance compared to other thermosets. Compared to other composite manufacturing processes, a characteristic feature of CFW is the relatively low fiber volume ratio. This high quantity of resin is required for functional resin bridges between rovings, especially at crossing points.

The definition of CFW also includes other material variations. CFW can process alternative technical fibers and thermoset resins, requiring no or at most minor adjustments. However, integrating thermoplastics would require significant adjustments, so much that it would be questionable to call it still CFW because such a process would transition into fiber-reinforced 3D printing. Moreover, thermoset CFW structures are also over-molded with thermoplastics [76]. In general, thermoplastics exhibit lower thermal stability and are susceptible to certain chemicals [77] and creep [78].

Using fiber-reinforced plastics can only be justified if their anisotropic material properties are exploited. A clear differentiation of the load paths is required for this. The load paths depend on the load scenario and the component shape. As mentioned previously, there is a coupling of fiber orientation and component geometry in CFW. As a general concept, more quasi-isotropic fiber orientations and a lower FVR drastically reduce the mechanical properties one could expect from the unprocessed dry fiber datasheet values. This weakening clarifies that composites must be adequately designed to excel against other material types.

2.5 Morphology of the Fiber Net

According to the design language of CFW, structures can be represented by straight connections between nodes, preferably resulting in sparse lattice structures. Within these fiber nets, three morphological primitives can be distinguished (Figure 2.6):

- **Segments** – The fiber bundle is placed within the segments without deflections or twists. This undisturbed fiber orientation results in a strongly pronounced local anisotropy. Idealized, the segments are under tension or compression.
- **Nodes** – At nodes, the fiber bundle wraps around the anchor to transfer loads from the anchor to the composite material. The local anisotropy is at its minimum as the fiber orientation becomes ambiguous and the bundle's cross-section deforms. The load induction is considered punctual at the component level, which is problematic for composites.
- **Crossings** – Crossings are fiber net intersections remote from anchors. Here, the composite behaves like a mixture of the other two primitives, depending on the intensity of fiber deformation. Anchors and other fibers can deflect the fiber. The properties of the connecting resin bridge characterize a crossing point and decrease the local FVR. The number of fiber orientation changes between the layers at a crossing point must be considered in the syntax design since an alternating layer arrangement can result in a separation between fiber bundles. In contrast, a blockwise arrangement provides only one resin bridge to transfer loads.

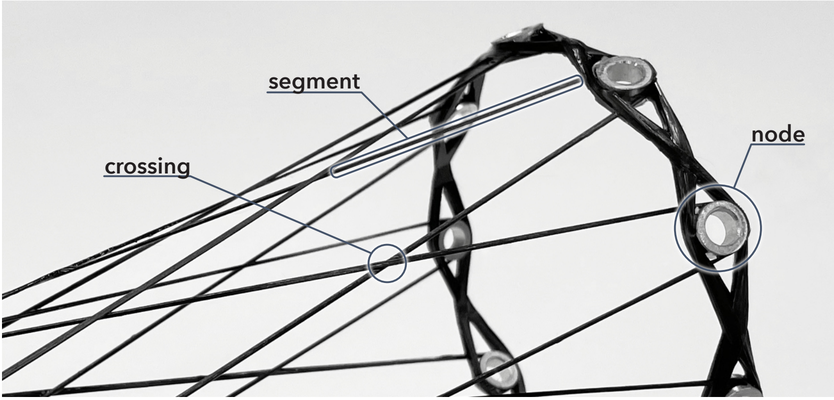


Figure 2.6 Fiber net primitives illustrated on a generic CFW sample.

A generally valid statement cannot be made for the FVR in the segments or nodes due to the substantial variations resulting from the process parameters. The nodes resemble the weak points in the structure due to their rather quasi-isotropic laminate configuration. Since CFW structures can only be loaded at nodes, this serial connection can lead to problems obtaining structural information about the central component sections, especially with simple CFW structures.

2.6 Structural Analysis

Due to the difficulty in defining the fiber orientation at the nodes and the often missing thin-walled attribute of the structure of its parts, the classical laminate theory (CLT) is rarely helpful for CFW [79]. Therefore, finite element analysis (FEA) tools are essential in the structural design process of the fiber net. However, CLT-related methods [80] are appropriate when material usages increase so that the lattice appearance transitions into a solid shell. Due to the geometric complexity of CFW and the anisotropic nature of the material, calculations are subject to uncertainties. Variations in the object's parameters intensify these uncertainties. Therefore, full-scale mechanical failure testing is necessary to calibrate FEA results [81]. Besides fiber and resin properties and component geometry, the FVR is most relevant and can be measured destructively by thermogravimetry [82].

2.7 Engineering Design Processes

The CFW design process is analogous to a general engineering design process [83] with the addition of a dedicated conceptualization phase. While global and component designs are strongly interconnected, the design process aims to define the fiber net shape and fiber path, as this determines the overall structural behavior. The design process also outputs the fabrication instruction. The design process divides into several phases, which are iteratively passed:

- **Requirements** – Initially, the mass and volume budgets of the structure are defined. Then, the available interfaces are described, and possible load induction points are identified. These points are candidates for the initial anchor positions. Next, restrictions for the center of gravity and inertia parameters of the structure are set. Finally, the load scenarios required later for the load path analysis are characterized.
- **Feasibility** – This phase may be included when the requirements might exceed the current capabilities of the CFW to determine if the design can reach the next phase. In this phase, uncertainties about the capabilities of the manufacturing system (process variations) are a hindrance.
- **Conceptualization** – The phase explores the global and component design. The designs on the global and component level are strongly interlinked. While the global design focuses on the segmentation and component assembly, the component design explores different topologies of the building system. Conventional volumetric methods, pretending isotropic material properties, can be used to generate initial topologies. The previously defined design requirements are mapped from the global to the component level. Especially geometrical variations in the components create uncertainties in this phase. Concepts for the components are coordinated with the available manufacturing setup and winding modes: planar, low curvature, hyperboloid tubular, or truss structures.
- **Preliminary Design** – The selected design solution is further developed in this phase to define the fiber net. The challenge is the vastness of possible fiber net configurations.

The load path is determined based on the volumetric material distribution in the build volume. From this analysis, nodes and segments of the fiber net are isolated. FRPs are most performative under pure tension. Nevertheless, it is usually impossible to design the fiber net so that no segments are in compression. In this phase, FEMs transition to anisotropic material properties. When creating such more accurate FEMs, material variations present uncertainties. Unlike other textile processes, such as braiding or weaving, each fiber placement is considered individually in CFW. This phase also sets which nodes provide load induction (high wrap angle) or only shape the fiber net (small wrap angle). This phase ends with the preliminary design review (PDR).

- **Detailed Design** – This design phase defines the component geometry fully. The aim is to derive the winding and hooking syntax from the fiber net. Achieving a continuous fiber path throughout the entire component complicates this design phase. The fiber path specifies the material distribution in the fiber net. The final geometry, including the accumulated uncertainties, is communicated by CAD, and based on this model, the final versions of the FEA are run. This phase is concluded by the critical design review (CDR).
- **Fabrication Instruction** – This final phase translates the final design into a winding plan or robot code. The planning of the trajectories and the definition of the details of the fabrication setup happen. The winding and hooking syntaxes may be divided into sub-syntaxes. For CFW, also this phase relies on human decision-making on a detail level due to the many degrees of freedom. In contrast, 3D printing is an example where this phase is fully automized by digital tools converting the CAD into fabrication instruction with the engineering only interacting in high-level decisions.

During production, the previously unknown specifications of the individual variations are fixed at an exact value. This deviation can subsequently be measured up to a particular accuracy, leaving a residual uncertainty. After the fabrication, the product definition is completed so that the following phases (qualification/ certification, utilization, and disposal) are not discussed in detail. This traditional design technique is a decision-making process that relies heavily on human experience and intuition. Especially after the PDR and CDR iterations in the design workflow become necessary. Improvements to this rather linear process are concurrent design and co-design strategies. Both require immediate communication and interaction between several involved factors in the design process.

With the concurrent design [84] strategy, the design challenge is approached by dividing the system to be developed into its subsystems (structures, mechanisms, power, thermal, command, communication, propulsion, attitude control, and eventually environmental control and life support system). Then, the above-described design process is undergone simultaneously involving all subsystem specialists. This direct feedback between the subsystems speeds up the design process and enables the most complex designs [85]. As a result, the concurrent design strategy is state of the art in spacecraft and its mission design.

Co-design [86] is another design strategy, rethinking the engineering design process from an architectural perspective. Since the structure subsystem is the primary relevant one in architecture, co-design does not focus on immediate feedback between subsystems but between design and engineering methods, fabrication and construction processes, as well as material and building systems. Co-design develops the interlocking of these areas further by replacing human communication with digitalized data-related interactions. This strategy minimizes the arbitrary human impact on the design by transferring the human experience and intuition into algorithms representing the interrelations in a physics-based and objective manner. A fully functional co-design software tool would allow the designer to go through the development process similar to the fully automated creation of manufacturing instruction for 3D printing. Co-design aims to effectively bring digital design together with automated manufacturing to reduce iterations and gain full control over process outcomes early.

Intuitive artificial intelligence (AI) design [87] strategies are another approach that will become more relevant in engineering design in the following decades. Such an AI tool can perform tasked beyond its training sets. AI can also create digital products which are not directly bound to physical laws. Nonetheless, there are already isolated demonstrations of intuitive AI design methods for technical products [88, 89]. Intuitive AI tools go beyond today's generative design [90] or deep-learning methods [91] as they are the first active tool augmenting the human designer. Before, the designers had to orchestrate passive tools to manifest their will before. An intuitive AI tool requires learning and pattern recognition leading to reasoned decision-making. Applying these strategies in the future to load-bearing structures would require the AI to acquire the fundamental interrelations between all aspects sufficiently, which would mimic a functional co-design. As the physical laws of nature would bind the intuitive AI, optimized solutions will look similar to biological designs driven by evolution principles. Both would require additive manufacturing to realize the complexity of the designs, a task to which CFW could be contributing. Finally, the AI tool would not only provide several valid solutions based on the design requirements but output a nearly optimal solution to the formulated requirements. A designer team augmented by such intuitive AI tools could be able to solve problems that are beyond human capability or that require years of research [92].

2.8 Parameter Variations

A prerequisite for co-design is a digitalization of the process, which requires a digital representation of CFW with sufficient accuracy. Such a digital twin of CFW would enable rapid analyses based on real-world data to facilitate decision-making. In addition, the virtual representation would eliminate the need to create physical breadboard models and prototypes. As mentioned before, the variations in CFW are the main drawback to overcome for acquiring a digital twin. Several types of variations are addressed in this thesis:

- **Process Parameters** – fiber tension, curing, trajectories, resin supply
- **Material Parameters** – impregnation quality, fiber damage, material properties (especially notable in natural fibers)
- **Geometrical Parameters** – fiber bundle geometry, resin bridges, fiber–fiber interaction, curvature, consolidation

3. Objective and Approach

As presented in the previous chapter, the disadvantages of CFW revolve primarily around inherent variations in the parameters describing the process and the fabricated structures. These variations translate into uncertainties in the structural design, and significantly higher safety factors are needed to compensate for this, resulting in avoidable higher resource consumption. The targeted improved characterization of CFW aims to substantially reduce uncertainties by advancing the equipment, process, produced structures, and digital representation. These advancements will lead to a CFW process with improved target metrics such as efficiency, controllability, and robustness. The objectives of this thesis derive from this motivation and are structured into primary and secondary objectives.

3.1 Primary Objective

The primary objective is to improve the digital characterization of coreless filament winding.

A digital process characterization enables reliable analyses and predictive modifications of objects in the digital domain without physical prototyping and validation testing. Its requirement is a close match between the digital model and the actual object and process. As in the case of structural design, variations in the parameters are also limiting the characterization. In order to achieve the primary goal, adjustments in the physical and digital domains are necessary. Two sub-objectives can be defined:

A) **Adjustments in the Physical Domain** – These actions reduce the variations in the manufacturing process or the fabricated structures to make them more similar to the digital model.

B) **Adjustments in the Digital Domain** – This includes the development of digital methods and the increase in accuracy of digital models. The latter can be done by sensor-based measurements or by including the different levels of detail in the modeling. These actions will make the digital model more similar to the physical counterpart.

A characterization achieved in this manner makes CFW more deterministic and controllable, which increases its robustness and also helps in documenting the fabricated structures. Such target metrics are essential for the transition of CFW from research to industry.

3.2 Secondary Objective

The secondary objective is to improve other target metrics of the coreless filament winding process apart from its digital characterization.

The relevance of the secondary objective arises from the fact that besides the primary objective, further significant improvements are required simultaneously. For example, an exact characterization is irrelevant if the process exhibits reduced productivity or the fabricated structures are less performative. The process enhancements which were implemented in this thesis fall into the following categories:

C) Quality – These include all actions enhancing the quality characteristics of the fabricated structures, such as mechanical performance, sustainability, material efficiency, reproducibility, and external appearance. High-quality products are easier to establish on the market or are a prerequisite for some applications.

D) Efficiency – All measures that improve the efficiency of the CFW process execution are integral to this sub-objective, such as more precise fabrication instructions or comprehensive automation. Factual and temporal process sequences may be simplified or accelerated. Reducing offcuts and waste contributes also to this sub-objective. Economic efficiency is not considered exhaustively in this thesis. However, only an efficient process has the potential to diffuse in the industry.

E) Extension – This sub-objective includes either removing limitations of the CFW process or implementing new features. Examples are extending the design solution space by supporting new geometries, incorporating customizations, improving geometrical tolerances, reducing health hazards, and adding machinability. In addition, such process extensions allow for opening new applications for CFW.

Also, for the secondary objective, the different sub-objectives link to the target metrics of the process. Where sub-objective (C) targets increasing the effectivity of CFW, sub-objective (D) focuses on improving efficiency and eliminating side/after-effects. Sub-objective (E) maintains the flexibility of the process and allows for consistent improvements. Each advancement presented in the papers can be assigned to the five sub-objectives labeled (A) to (E). Figure 3.1 summarizes the objectives of this thesis.

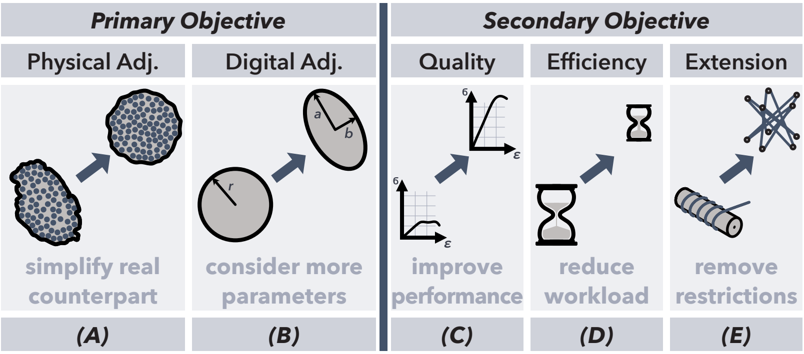


Figure 3.1 Exemplary illustrations of the thesis' sub-objectives. (**A**) making the fiber bundle cross-section smoother and more circular, (**B**) increasing the precision of the cross-section description, (**C**) increasing mechanical performance, (**D**) shortening required time of process steps, (**E**) enhancing design freedom of components.

3.3 Research Approaches

The research approaches derive from the general facets needed to describe manufacturing processes: equipment, processing, product, and data handling. Where "equipment" and "processing" converge to "fabrication system" and "data handling" translates to "computational infrastructure", a subdivision of the "product" facet is helpful for the CFW characterization. This is because CFW structures include two different morphological types. A distinction is made between straight segments, which are best represented by the material, and areas at anchors, which define the load induction behavior. The accomplishment of the described objectives is pursued by following four research approaches:

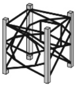
1) **Adjustments to the fabrication system** (equipment and process)
   This approach includes modifications to the winding setup equipment (hard- and software) and adjustments to the process steps or their sequence.
2) **Characterization of the material system** (segments of the fiber net)
   As application-oriented requirements of the fabricated structures almost entirely determine the material selection, this approach focuses on improving the description of the fiber composite in its most undisturbed form at straight segments of the fiber net.
3) **Configuration of the load induction** (nodes of the fiber net)
   Since the load induction areas behave differently from the segments and crucially determine the mechanical performance, an individual approach is devoted to rethinking and configuring the anchor system at the nodes of the fiber net.
4) **Establishment of computational infrastructure** (data-related methods)
   This research approach involves developing software tools tailored toward CFW that entail novel data-related methods to enhance the digital object representation (digital twin). A beneficial interpretation of different data sets is possible through clear structuring, analysis, and visualization. Such extensive and diverse data sets originate from structural design, sensor-supported measurements, and fabrication protocols.

3.4 Scope

The academic contributions of this thesis are limited to a variety of advancements listed in the next chapter. However, the overlaps between set research objectives and the identified approaches outline what exceeds the scope, such as methodical developments for the structural design, enhancement of finite element analysis methods, improvement of the robotic system on itself, or development of new materials. Also, running numerical simulations to quantify the impact of the found advancements on safety factors or material consumption is out of scope. Furthermore, combining all advancements in a single process is not purposeful, as different applications require individual solutions.

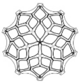
4. Publications

The following academic contributions feature the realized advancements to achieve the research objectives. The order in which the papers appear matches the order of the research approaches, while the primary focus of each paper assigns it to one approach. Yet, the research aspects included in each paper are not limited to its main focus.

1. 
   Robotic 3D Deposition of Impregnated Carbon Rovings with Gradient Properties for Primary Structures
   PM, GTG
   IAF – Proceedings of the 69th International Astronautical Congress

2. 
   Additive Manufacturing of Large Coreless Filament Wound Composite Elements for Building Construction
   SB, **PM**, GTG, AM
   Mary Ann Liebert – 3D Printing and Additive Manufacturing

3. 
   Development of an Impregnation End-Effector with Fiber Tension Monitoring for Robotic Coreless Filament Winding
   PM, SB, AM, GTG
   MDPI – Processes

4. 
   Material Monitoring of a Composite Dome Pavilion Made by Robotic Coreless Filament Winding
   PM, BS, DG, JK, GTG
   MDPI – Materials

5. 
   Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding
   PM, MGP, JK, GTG
   MDPI – Materials

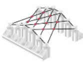
6. 
   Pultrusion-Winding: A Novel Fabrication Method for Coreless Wound Fiber-Reinforced Thermoset Composites with Distinct Cross-Section
   PM, MUW, GTG
   Elsevier – Composites Part A

7. 
   Investigation of Different Load Transmission Concepts for Coreless Filament Wound Structures
   PM, PK, LM, LF, PG, UH, GTG
   Elsevier – Composite Structures

8. 
   Adaptive Winding Pin and Hooking Capacity Model for Coreless Filament Winding
   PM, GTG
   Sage – Journal of Reinforced Plastics and Composites

9. 
   Implementation of Fiber-Optical Sensors into Coreless Filament-Wound Composite Structures
   PM, MGP, NK, JK, GTG
   Elsevier – Composite Structures

10. 
    Design of Fiber-Composite/Metal–Hybrid Structures Made by Multi-Stage Coreless Filament Winding
    PM, RM, ED, CO, RK, MM, GTG
    MDPI – Applied Sciences

11. 
    Computational Co-Design Framework for Coreless Wound Fibre–Polymer Composite Structures
    MGP, CZ, FK, **PM**, LB, YG, SH, AG, DF, MB, CT, PM, VS, GTG, AM, JK
    Oxford – Journal of Computational Design and Engineering

The first three papers address the fabrication system. The first paper realizes a winding fixture made by additive manufacturing to explore different winding syntaxes cost-effectively. It also demonstrates how small-scale compression testing could replace stiffness evaluation with full-scale eigenfrequency measurements and benchmarks the results against conventional metal structures. The second paper presents how a robotic CFW setup, including sensor-informed feedback loops, was upscaled by a digital coupling between additional robotic axes. In this context, the first two papers concentrate on adjustments in the digital domain. In contrast, the third paper focuses more on the physical domain adjustments by continuing the second paper's topic while discussing the winding head and its subsystems in detail. Besides, it post-processes the obtained sensor data.

The following three papers concern the material system. Paper number four monitors the behavior of the composite material in a large-scale demonstrator subjected to outdoor weathering and probes the inner composition of the CFW composite material. Methods describing this composition were further developed in the next paper and applied to natural fibers. In addition, this paper evaluates more sustainable material systems regarding structural performance and fabrication suitability. The sixth paper introduces a new fabrication method that defines the cross-sectional shape of wound fiber bundles by implementing direct curing within the winding head. Where papers four and five contribute primarily to the sub-objective regarding the digital domain, this paper contains adjustments to the physical and digital domain.

Then, the emphasis lies on load induction configuration for the subsequent three papers. The seventh paper structurally investigates numerous fiber arrangements at the winding pin and quantifies the impact of consolidation. Hereafter, the next paper complements this by creating a winding pin redesign and a predictive algorithm for the pin occupancy. The last paper following this research approach presents fiber-optical sensor integration, data handling, and analysis methods, which inform about the load induction distribution and the behavior of CFW structures. While paper number seven addresses physical adjustments, the eighth and ninth papers include both kinds of adjustments.

Finally, the last two papers focus on the computational infrastructure. While the tenth paper introduces an object model for form-finding, the final paper deploys a similar one to find interrelations between various process domains. In association with these digital adjustments, case studies validated both interoperable object models. In the context of the tenth paper case study, the CFW process incorporated further physical adjustments.

How each paper connects to the primary (physical and digital adjustments) and secondary objective (quality, efficiency, and extension) can be seen in Figure 4.1.

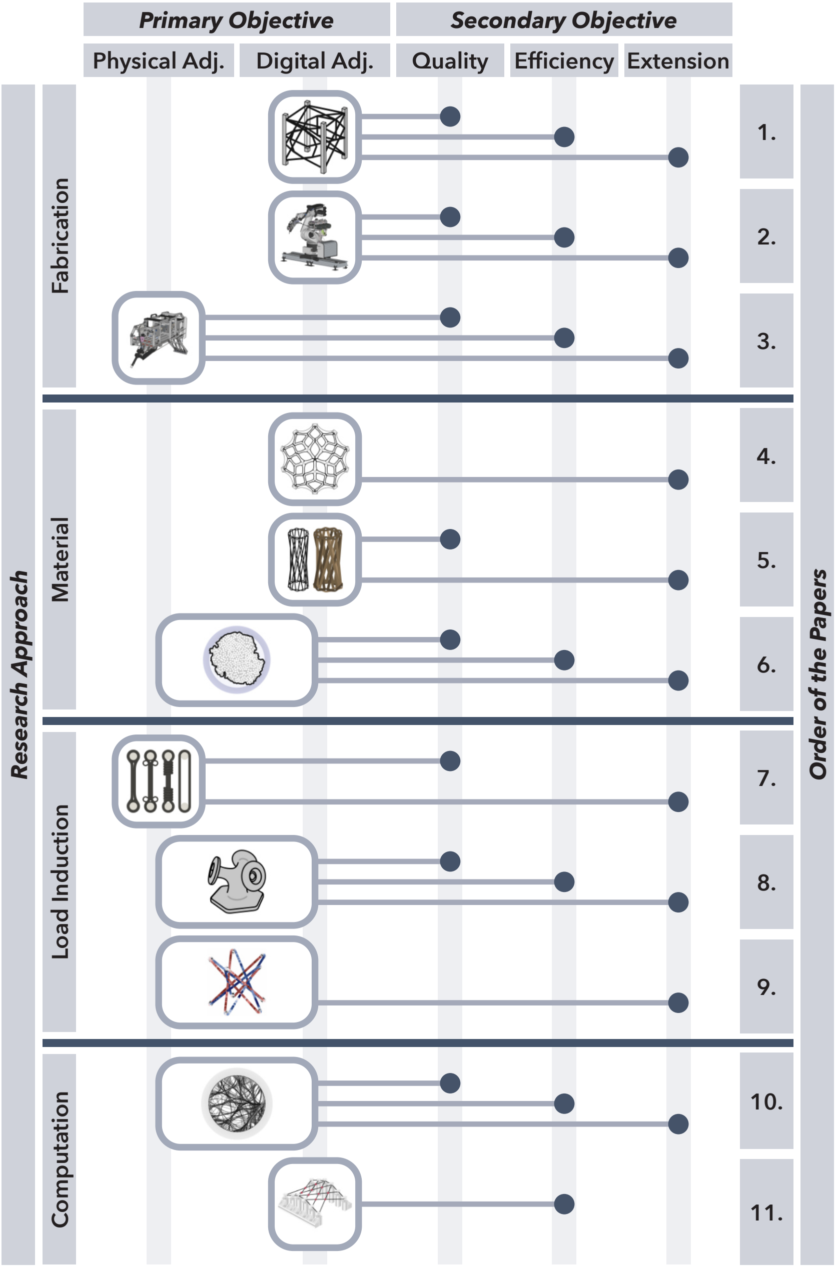


Figure 4.1 Assignment of the papers to their intended sub-objectives and research approaches.

The papers were sorted by application context and winding technique to understand how each contribution interrelates (Figure 4.2). After grouping them by the research approaches, it can be observed what combination of topics this thesis covers well. Fabrication-related issues on robotic winding were addressed for both engineering and architecture applications. The material characterization also contains both application fields. Advancements in the load induction were stirred towards manual winding in engineering, whereas the developed computation infrastructure covers all areas.

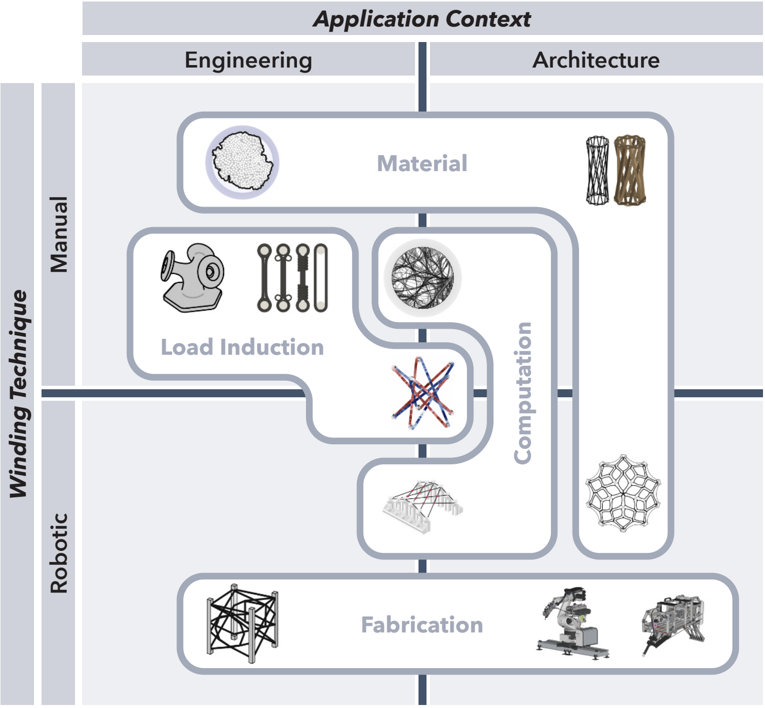


Figure 4.2 Papers organized by application context and winding technique. Grouping represents the research approaches.

As previously mentioned, each paper addresses various research aspects apart from its main focus. Moreover, the presented contributions utilized several research methods. Table 4.1 indicates which papers cover certain topics. This overview emphasizes their interconnectedness and helps navigate the contents. In the following, the papers are presented as originally published.

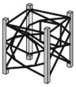
Table 4.1 Recurring research aspects and methods covered in papers. Blue markers indicate occurrence.

Research Aspects											
Impregnation Head	■	□	■	□	■	■	□	□	■	□	■
Fixture	■	□	□	□	■	□	□	■	□	■	□
Anchors	■	□	□	□	□	□	■	■	□	■	□
Robotics	□	■	□	□	□	□	□	□	□	□	■
Trajectory	■	■	□	□	□	■	□	□	■	□	■
Winding Syntax	■	■	□	□	□	□	□	□	□	■	■
Hooking Syntax	■	□	□	□	□	■	■	■	□	□	□
Composite Selection	□	■	■	■	■	■	□	□	□	■	■
Composite Composition	■	□	■	■	■	■	□	□	■	■	■
Cross-section / Contour	□	□	□	■	■	■	■	□	■	■	■
Consolidation	■	□	□	■	□	■	■	□	■	■	□
Curing	■	■	■	□	□	■	□	□	□	■	□
Sustainable Materials	□	■	■	□	■	□	□	□	□	□	□
Hybrid Material Systems	■	□	□	□	□	□	□	■	□	■	□
Performance Benchmark	■	□	□	□	■	■	■	□	□	■	□
Sensor Monitoring	□	■	■	■	□	□	□	□	■	□	■
Object Data Collection	□	□	□	□	□	□	□	□	■	■	■
Research Methods											
Algorithm / Software	□	■	■	□	□	■	□	■	■	■	■
Analytic Geometry	□	□	□	□	□	■	□	■	□	□	□
Engineering Design	■	■	■	□	■	■	□	■	■	□	□
3D Printing	■	□	□	□	□	□	□	■	□	■	□
Experimental Design	■	□	□	■	■	■	■	■	■	■	■
Material Selection	■	■	■	□	■	■	□	□	□	■	□
Sensor Integration	□	■	■	□	□	□	□	□	■	□	■
Structural Simulation	■	□	□	□	□	□	□	□	■	■	■
Structural Testing	■	□	□	□	■	■	■	□	■	■	■
Microscopy	□	□	□	■	■	■	□	□	■	■	□
Visual Inspection	□	□	□	■	□	■	□	□	□	□	■
Thermogravimetry	□	□	■	■	□	■	■	■	□	□	■
DSC	□	□	■	■	□	■	□	□	□	□	□
Mass / Dimensions	■	□	□	□	■	■	■	□	■	■	■

Selection of several downsized specimens after winding and before removing the winding fixture.

4.1 Robotic 3D Deposition of Impregnated Carbon Rovings with Gradient Properties for Primary Structures

Pascal Mindermann, Götz T. Gresser



Proceedings of the 69th International Astronautical Congress
1 – 5 October 2018, Bremen, Germany, IAC-18-C2.9.1, 42747
submitted: 2018-9-15 – published: 2018-10-01 – presented: 2018-10-05
https://iafastro.directory/iac/paper/id/42747/summary/

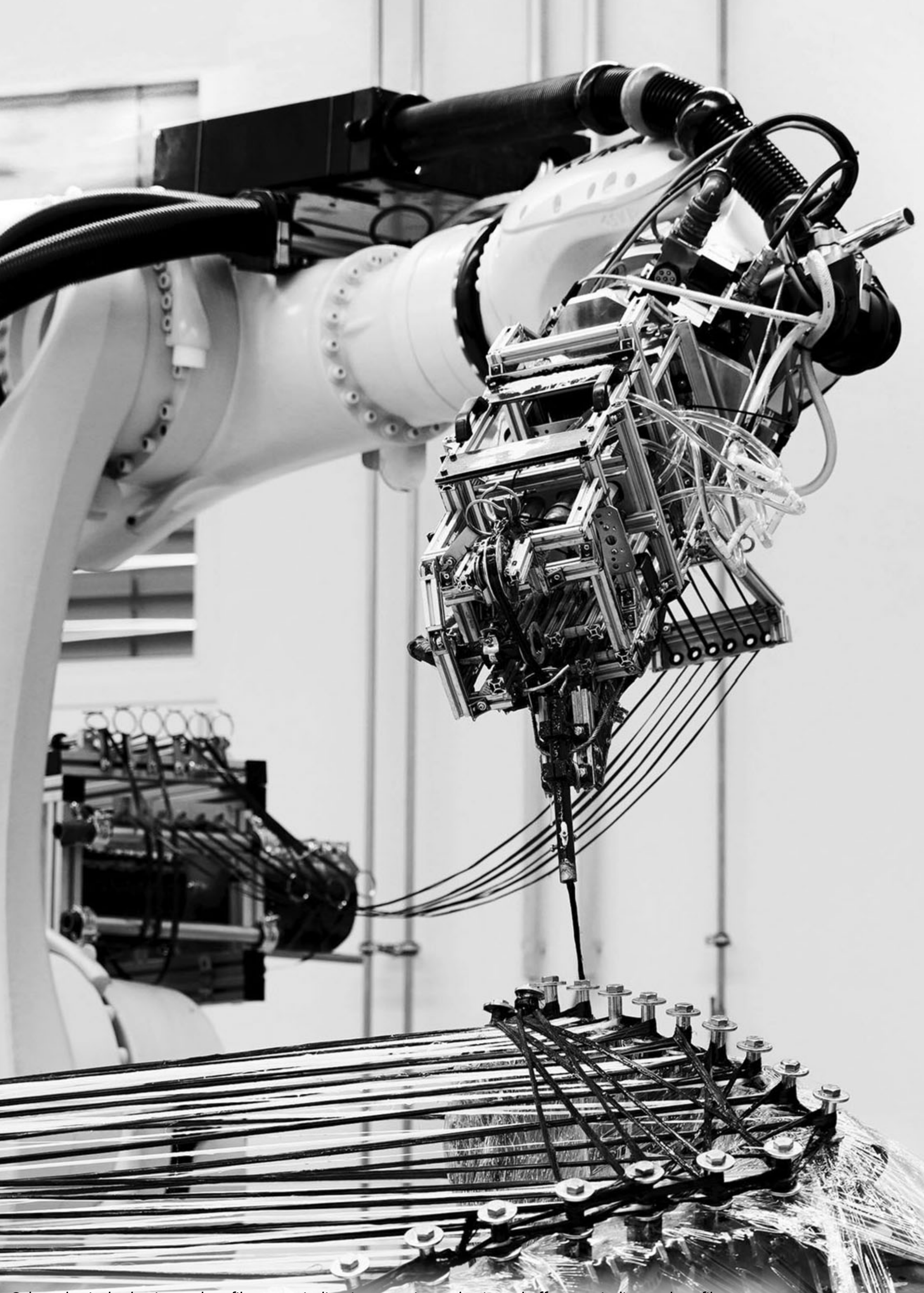
This paper resumes the research work presented at the 69th IAC in 2018, which introduced water-soluble highly-adjustable winding fixtures made by additive manufacturing to robotic hybrid CFW. For the manufacturing of samples, a two-resin-chamber robotic winding head was realized. Moreover, it was shown that the compression testing of downscaled samples correlates with the structural performance of full-scale demonstrators in terms of their eigenfrequency responses.

For the full-scale samples production in a hybrid CFW process, winding fixtures were 3D-printed using a water-soluble polymer. Hereafter, winding pins were directly bolted into the plastic and installed in the winding setup using a custom adapter. The realized winding head allows the production of gradient structures by utilizing two separate resin chambers and features an internal spool and passive tension control system. The FVR is predicted depending on the equipment, material, and process parameters. Three winding syntaxes were digitally planned and selected for the mechanical evaluation based on the application-orientated requirements. Compression testing was conducted on downscaled samples for each syntax, and the failure behavior was analyzed according to the load induction concept. Different full-scale demonstrators were fabricated, and their eigenfrequencies, as measured by laser Doppler vibrometry, were related to the compression testing. Finally, in a comparative evaluation of the new fabrication method for state-of-the-art components, the mass budgets of the demonstrators were computed according to the material system.

This paper contributes a relative description of the hooking syntax and initial methods for FVR calculation to the thesis's primary objective.

Author's Contribution

The author contributed substantially to all aspects of this paper.



Cyber-physical robotic coreless filament winding in operation: robotic end-effector winding carbon fiber tows.

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

Serban Bodea, Pascal Mindermann, Götz T. Gresser, Achim Menges

Mary Ann Liebert – 3D Printing and Additive Manufacturing, 9(3), 145–160
submitted: 2020-12-29 – accepted: 2021-06-19 – published: 2021-08-11
https://doi.org/10.1089/3dp.2020.0346

This paper presents the research outcome of upscaling robotic CFW and its characterization to achieve a more autonomous fabrication through feedback-based and sensor-informed process monitoring. The fabrication data acquisition allows an immediate analysis and response. The development led to the construction of a full-scale demonstrator.

The computational control of the winding process was adapted to the large-scale fabrication and material system selection. The state-of-the-art robotic winding setup was extended for the upscaled fabrication by replacing a mechanical with a digital coupling of two rotary positioners. The upscaling leads to more sustainable structures. In addition, a robot on an additional linear axis was deployed because of the limited reach of a stationary one. This configuration required the integration of all subsystems, such as creel, pump, control cabinets, resin supply, and passive tension control onto the robotic platform. The robot trajectory separated in hooking and spanning motions is digitally planned and checked for collisions prior to production. The recorded fiber tension measured in the winding head is evaluated in a real-time feedback loop to autonomously adjust the winding speed of the robotic system and adapt the power setting of the peristaltic pump to achieve a constant resin flow. These feedback loops were implemented as formal relations in the robot code, and they interrupt the process before potential failures embed into the component. Their data sets are recorded synchronized with the fabrication parameters for subsequent analysis. From these data sets, time-independent characteristic tension values for CFW were extracted.

The introduction of cyber-physical robot control, including sensor-informed feedback loops, is this paper's main contribution to the primary objective of the thesis.

Author's Contribution

The author developed, realized, and integrated the textile equipment. He selected the composite material and performed the fiber tension data analysis. He also supported the development of the robot code by providing the formal relations for the tension sensor and pump. He significantly participated in the demonstrator's manufacturing and supported the configuration of the robotic winding setup.

Cyber-physical robotic coreless filament winding in operation: robotic end-effector winding glass fiber tows.

4.3 Development of an Impregnation End-Effector with Fiber Tension Monitoring for Robotic Coreless Filament Winding

Pascal Mindermann, Serban Bodea, Achim Menges, Götz T. Gresser

MDPI – Processes, 9(5), 806
submitted: 2021-04-17 – accepted: 2021-04-30 – published: 2021-05-04
https://doi.org/10.3390/pr9050806

This paper features the technical development of a winding head and robot-system-integrated peripheral textile equipment for robotic CFW and a detailed time-resolved analysis of the gathered fiber tension monitoring data. The winding head includes an impregnation unit for a controlled resin supply and a sensor unit for fiber tension monitoring. Both were validated in a research-orientated large-scale demonstrator production.

The textile equipment was mechanically, electronically, and computationally integrated into the robotic winding setup based on the required configuration and process parameters for large-scale fabrication. A material system was selected to meet the specific requirements of large-scale manufacturing. Defrosting premixed resin shortened the preparation time. Theoretically, the used resin has an unlimited pot life but requires thermal curing. For this purpose, a custom-built oven was installed around the demonstrator in the winding setup. The winding head was designed as a configurable modular platform to house the impregnation and sensor units. The impregnation unit allows the separate and efficient impregnation of six rovings without limiting the winding head orientation. A peristaltic pump supplies it via a tube placed along the robot arm. The sensor unit monitors the fiber tension and allows sensor-supported control through feedback loops. Recording the fiber tension during winding allows a subsequential time-depended analysis of process-related tension and pump data to identify regular patterns.

The paper's main contribution to the primary objective is that process parameter variations can be quantified by sensor monitoring.

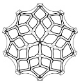
Author's Contribution

The author's work entails developing, realizing, and integrating the textile equipment, testing the impregnation and sensor monitoring principle, selecting the composite material, and data analysis. Furthermore, he significantly participated in the demonstrator's manufacturing and supported the configuration of the robotic winding setup.

Lattice carbon-fiber reinforcement pattern of a fiber pavilion component showing the layerwise fiber deposition process.

4.4 Material Monitoring of a Composite Dome Pavilion Made by Robotic Coreless Filament Winding

Pascal Mindermann, Bas Rongen, Drilon Gubetini, Jan Knippers,
Götz T. Gresser



MDPI – Materials, 14(19), 5509
submitted: 2021-08-28 – accepted: 2021-09-21– published: 2021-09-23
https://doi.org/10.3390/ma14195509

This paper addresses the material monitoring of the coreless-wound composite dome pavilion over 130 days, focusing on the deployed methods, the on-site monitoring results, and complementary laboratory material tests. In particular, the thermal behavior of the pavilion was investigated, the resin color change was measured, and bundle cross-sections were microscopically analyzed. The results will facilitate the creation of regulations for such non-standard building systems and inform future designs.

An analysis of the composite dome pavilion and its material system led to a selection of inspection methods and appointments. Assisted by temperature and rainfall recordings by a weather station, the on-site monitoring activity entailed in situ measurements such as local air temperature and humidity, both inside and outside the pavilion. The surface temperatures of the two different composite materials were measured on the pavilion's interior and exterior and in shadow and direct sunlight. The temperature distribution of the pavilion's supporting structure was monitored using a thermal imaging camera. Moreover, the resin color change in the glass fiber bundles was measured in the LAB color space. Off-site measurements include the fiber volume determination on retaining samples and SEM scans of fiber bundle cross-sections to estimate the void content and identify resin bridges. Both methods reveal the inner composition of the composite material to characterize the missing consolidation of the fabrication method.

The paper's main contributions are characterizing material aging and composition for CFW.

Author's Contribution

The author conceptualized the monitoring program and significantly participated in the on-site monitoring sessions. He also performed substantial parts of the analysis on the curated data sets and provided the off-site laboratory tests.

Comparison of samples made of carbon (left) and hemp fibers (right) highlighting the parameter fluctuations in natural fibers.

4.5 Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding

Pascal Mindermann*, Marta Gil Pérez*, Jan Knippers, Götz T. Gresser
* equal first author contribution

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submitted: 2022-04-04 – accepted: 2022-04-29 – published: 2022-05-01
https://doi.org/10.3390/ma15093260

This paper includes a structural performance assessment of several alternatives to carbon and glass fibers under the consideration of two sustainability markers. The impact of a bio-based epoxy was also identified, and adjustments were introduced to the fabrication equipment and process to evaluate the fabrication suitability of the alternative materials.

Based on the literature, several fiber materials were selected for the structural testing: Carbon and E-glass as a benchmark, S-glass, basalt, aramid, stainless steel, viscose, flax, hemp, and jute. The fibers are present as roving, yarn, tape, or crocheted card sliver, depending on the product. A bio-based resin with a significantly lower ecological impact was selected. Hereafter, the CFW fabrication system and process were adapted to consider the characteristics of this material spectrum. The fabrication suitability of the different materials was tested during the fabrication of generic cylindrical CFW samples. Four-point bending samples were produced in a hybrid CFW process using a half-open mold to limit geometric variations. The composition and geometry of those samples were comprehensively investigated and used in the subsequent sustainability analysis. Based on comparing the spring stiffness and flexural strength of these samples to the range described in the literature, the impact of the CFW fabrication process was characterized. The mass-specific mechanical performance was calculated. The embodied energy and global warming potential for samples normalized for stiffness and strength were compared in the final step. The impact was differentiated between fiber and resin. Finally, alternative fiber materials were ranked.

The holistic composite composition analysis, also applied to natural fibers, is the main contribution of this paper to the primary objective.

Author's Contribution

The author contributed all aspects regarding the fabrication system, process adjustments, the sample design, production, measurement, and structural testing. Moreover, he supported the data analysis on a conceptual level.

LED array of a UV lamp.

4.6 Pultrusion-Winding: A Novel Fabrication Method for Coreless Wound Fiber-Reinforced Thermoset Composites with Distinct Cross-Section

Pascal Mindermann, Martin-Uwe Witt, Götz T. Gresser

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submitted: 2021-05-01 – accepted: 2021-12-06 – published: 2021-12-09
https://doi.org/10.1016/j.compositesa.2021.106763

This paper introduces a fabrication process that combines pultrusion and CFW to reduce the fiber structure's geometrical uncertainties without limiting the use of molds. The method was validated on the laboratory scale utilizing intermittent ultraviolet curing, for which two UV-triggered resin systems with different reactivity were developed. In addition, the boundary conditions for a new winding trajectory creation method were mathematically defined in this context.

A robotic winding head was conceptualized to integrate the novel process, and a hand-held model was realized for the process validation. Due to the implementation of the UV radiation source and impregnation unit, pultrusion-winding heads are more voluminous than conventional ones. This attribute necessitated modifications to the winding trajectory creation method based on process-related criteria. The new method was defined by six conditions described by geometrical relations between the winding head, fixture, and fiber. By adopting all six conditions, the fiber deposition quality can be increased even with conventional winding. A radical and a cationic polymerizing resin were developed for UV-triggered curing. Both were photometrically evaluated and tested by DSC. An initial characterization of the process parameters was conducted, investigating the maximum wall thickness, color change as a curing indicator, cross-sectional shape accuracy, and FVR. In a bending test, pultrusion-wound fiber segments were compared with coreless-wound segments revealing higher performance due to the increased structural depth.

This paper's main contributions to the thesis's primary objective are reducing geometrical and material parameter variations of the fiber net's segments and introducing a novel trajectory creation method.

Author's Contribution

The author's contribution covers the idea of the fabrication principle and the development of the pultrusion-winding equipment and process. Moreover, he defined the new winding trajectory creation method. From a conceptional to an investigational level, he was involved in all aspects of the process characterization. Finally, he also supported the development of the resin systems.

Loop specimen after failure exhibiting fiber fracture, delamination, and detachment from the sleeve.

4.7 Investigation of Different Load Transmission Concepts for Coreless Filament Wound Structures

Pascal Mindermann, Patrick Kaiser, Lena Müller, Lisa Fischer,
Philipp Gebhardt, Ulrich Hindenlang, Götz T. Gresser

Elsevier – Composite Structure, 303, 116287
submitted: 2021-08-28 – accepted: 2022-09-28 – published: 2022-10-04
https://doi.org/10.1016/j.compstruct.2022.116287

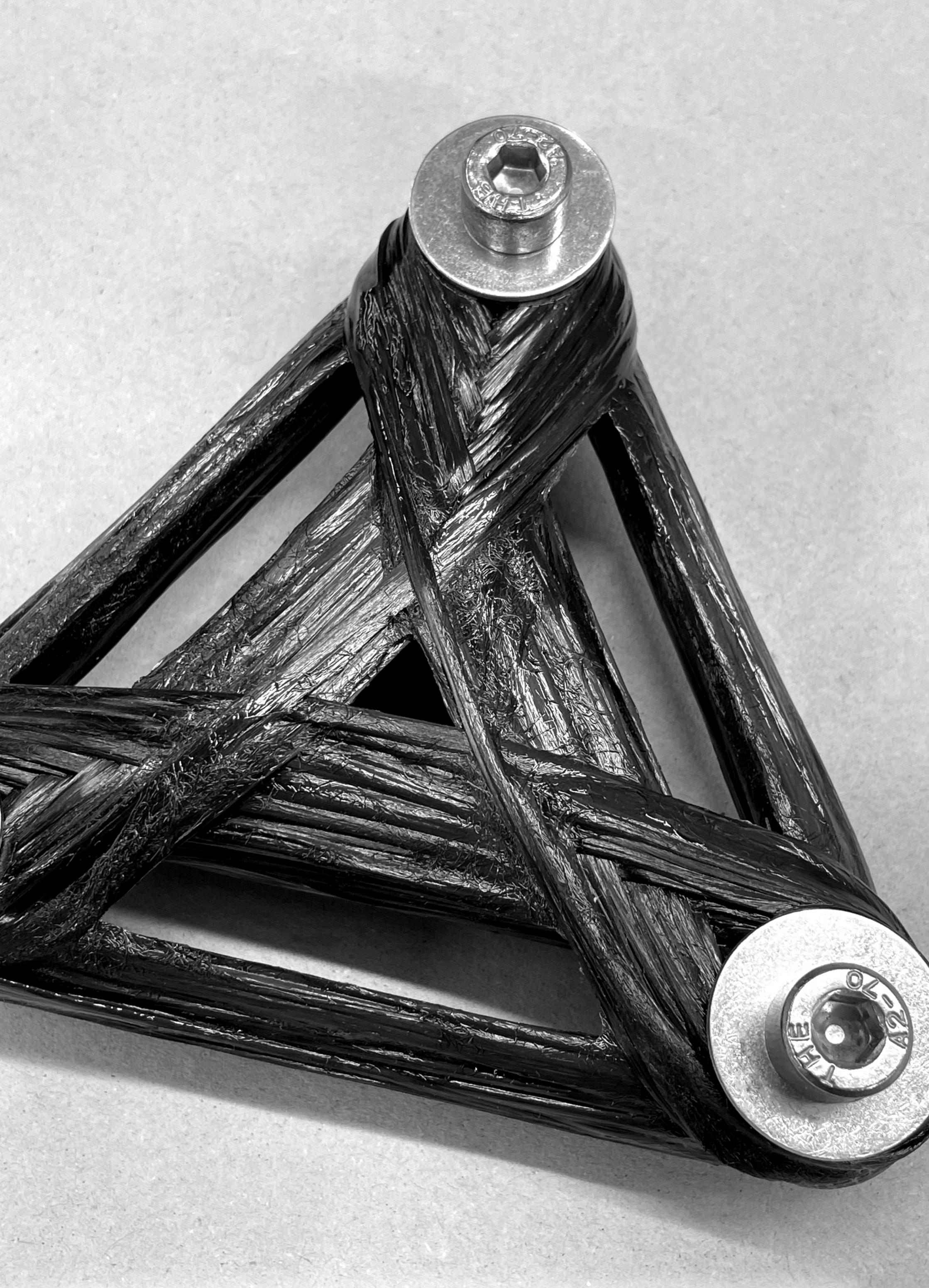
This paper covers the mechanical performance investigation of different load induction concepts for CFW. The concepts were created by altering the fiber arrangement around the anchor element and introducing additional elements. Generic samples with and without a subsequent consolidation were fabricated, quasi-statically tested in tension and compression, and their failure mechanisms and locations were analyzed.

Fourteen concepts were derived from the state-of-the-art fiber configuration, each with a specific intention. The aim was to improve the mechanical performance of the load induction area, reduce its variations, and compare it to the theoretical structural capacity of the middle segment of the sample. The number of fibers at this position was kept constant to allow a direct comparison. Several concepts introduced additional metallic pins, or 3D-printed fiber guiding elements, apart from hooking configuration variations. Others introduced an additional subsequent wrapping of the fiber bundles. Some concepts were consolidated by bilaterally pressing the sample together with metallic plates. The sample mass was determined as a measure of build volume consumption. The mechanical performance and its scatter were evaluated on spring stiffness and failure load for tension and compression. The theoretical structural capacity of the samples was calculated based on the material properties. Finally, the predominant failure mechanisms and locations were discussed, and the feasibility of transferring the concepts into an automated production was evaluated.

As its main contribution to the thesis's primary objective, this paper evaluates the impact of the consolidation and fiber arrangements on the uncertainties.

Author's Contribution

The author contributed significantly to generating the load induction concepts and designing the study on a conceptual level. In addition, he supported the data curation and performed the data analysis of the mechanical investigations.



Triangular sample demonstrating complex fiber–fiber interactions resulting from simple syntaxes, compare Figure 2.1.

4.8 Adaptive Winding Pin and Hooking Capacity Model for Coreless Filament Winding

Pascal Mindermann, Götz T. Gresser

Sage – Journal of Reinforced Plastics and Composites, ahead of print
submitted: 2021-12-03 – accepted: 2022-03-30 – published: 2022-05-13
https://doi.org/10.1177/07316844221094777

This paper explains the calculation procedure for predicting the hooking capacity for anchor elements in CFW. Moreover, a novel winding pin made by additive manufacturing was designed to decouple the fiber net from the winding pin's main axis. A method is presented to convert more complex geometries of anchor elements into the basic hollow cylinder configuration.

The novel winding pin entails single or multiple arms attached to a pole. The surfaces of such elements are used to anchor the fibers, making the fiber net more similar to the ideal model and increasing design freedom. The pin can be mounted using an internal bolt connection or clamped to a modular fixture system. A disk prevents fibers from slipping off at the end of each arm and limits the volume for absorbing fibers. For the adaptation of the winding pin to the fiber net, a parameterized CAD model was generated. An early design stage and the final configuration of the winding pin design are presented. Based on geometrical pin parameters, the local fiber net configuration, material properties, and process parameters, the developed model stepwise calculates the occupation of the pin capacity for a given hooking syntax. The fiber volume of each step is iteratively calculated as a helix accumulating from the inside out at the pin. For this, a mathematical description of the hooking syntax was found. After calculating the individual hooking volumes, they are assigned to their angular positions around the pin and added up to identify which half of the pin absorbed more fibers. Once one side of the pin is filled, the pin capacity is exhausted. Depending on the hooking syntax, this state can occur before the entire pin volume is occupied. This approximative calculation model was validated in experimental tests on conventional winding pins consisting of a sleeve-washer combination and the novel winding pin.

The algorithm for the occupancy prediction and the individualizable pin design are the main contributions to the primary objective of the thesis.

Author's Contribution

The author contributed substantially to all aspects of this paper.

Star-shaped sample with an integrated fiber-optical sensor and additional wrapping modifying the bundles' cross-sectional shape.

4.9 Implementation of Fiber-Optical Sensors into Coreless Filament-Wound Composite Structures

Pascal Mindermann, Marta Gil Pérez, Naoki Kamimura, Jan Knippers,
Götz T. Gresser

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submitted: 2021-12-01 – accepted: 2022-04-04 – published: 2022-04-08
https://doi.org/10.1016/j.compstruct.2022.115558

This paper describes the implementation of fiber-optical sensors into the CFW process. Strain-field data were collected with high spatial resolution and compared to finite element simulations to study the structural behavior. The developed methods were validated on different generic samples.

Multiple sensor implementation techniques were developed to protect the sensor against breaking damage and improve the sensors' bonding to reinforcement fibers. Different protective measures using additional elements, placement guidelines based on the winding and hooking syntax, and adjustments techniques were elaborated. Furthermore, a custom sensor placement tool assists in embedding the sensor in a fiber-rich area of the bundle cross-section. The fiber-optical sensor data sets were visualized in 2D and 3D plots. Qualitative tension, compression, and torsion analyses were performed by mapping the sensor locations to the component geometry. The sensor data patterns for different load scenarios, including thermic loads, were monitored. The FOS data were statistically summarized for different load intensities and then compared to the ideal load distribution from a FEM. Then, the actual load induction distribution was calculated for each attachment point based on the sample's FOS data and geometric parameters. The next step led to a segment-wise comparison between FOS and FEM in the same unit. Another technique developed in this study allows calibration of the load induction distribution in the FEM iteratively by reselecting arrays of strain-field data along the fiber segment with minimum bending load influence.

The main contributions to the thesis's primary objective are the sensor integration and analysis methods for the load induction and structural behavior.

Author's Contribution

The author's contributions include the development of all aspects of sensor integration. He participated in the sample design process and performed the sample manufacturing. Moreover, he gathered the data during testing and wrote the software tools for sensor data handling, visualization, and analysis. Finally, he was involved in the data analysis on a conceptual level.

Mesoscopic fiber architecture of the demonstrator component's middle region.

4.10 Design of Fiber-Composite/Metal–Hybrid Structures Made by Multi-Stage Coreless Filament Winding

Pascal Mindermann, Ralf Müllner, Erik Dieringer, Christof Ocker, René Klink, Markus Merkel, Götz T. Gresser

MDPI – Applied Sciences, 12(5), 2296
submitted: 2022-02-05 – accepted: 2022-02-20 – published: 2022-02-22
https://doi.org/10.3390/app12052296

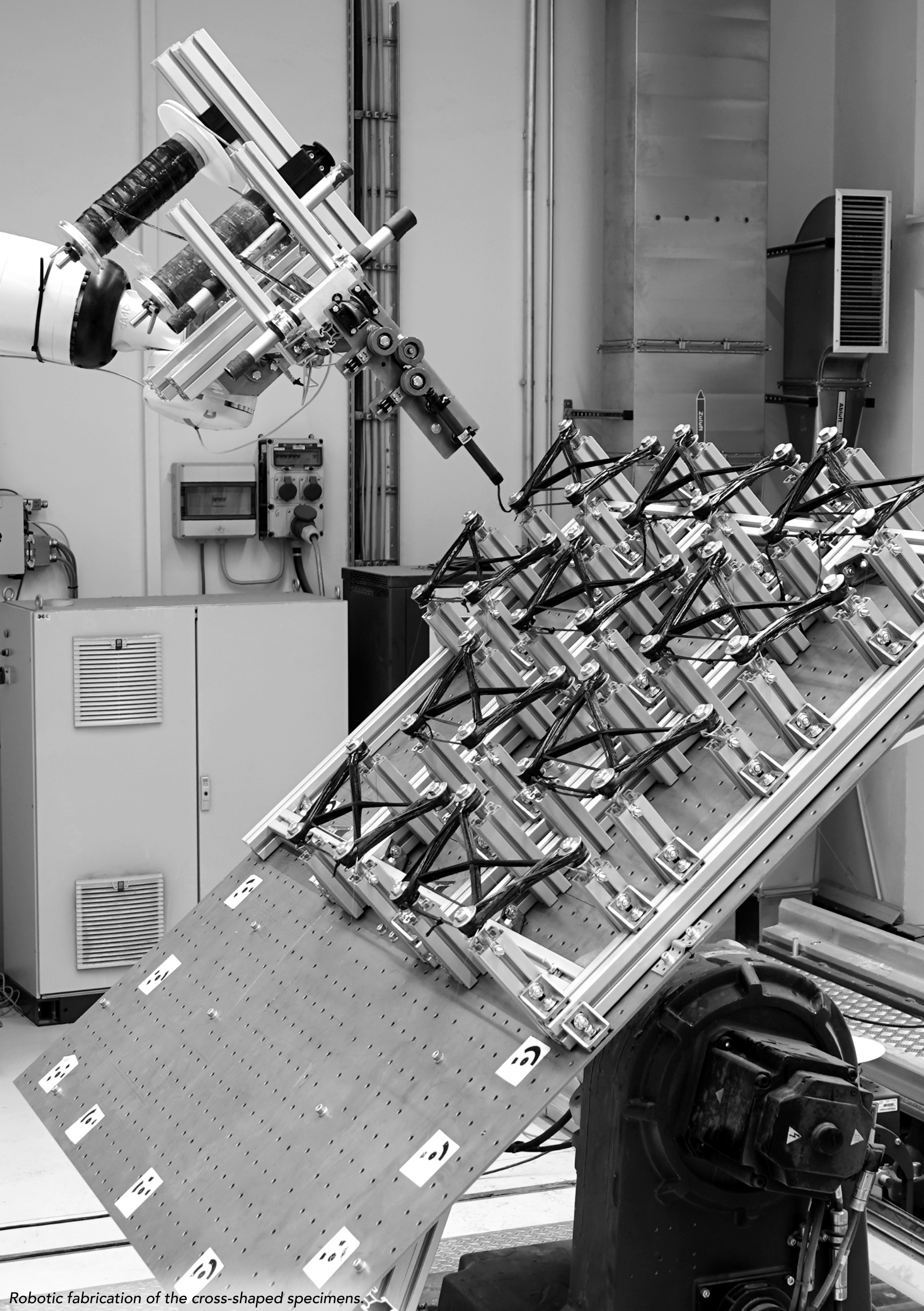
This paper precis several advancements of CFW, which were demonstrated in the context of a case study in an engineering application. The hybridization of several processes which rely on different material systems is demonstrated together with the deployment of an additively manufactured winding pin and the introduction of multi-stage winding. Developing an object-oriented digital design and management tool tailored toward CFW accompanied this study.

The hybrid approach was utilized to increase the mass-specific stiffness of the case study object by beneficially combining CFW with laser powder bed fusion and conventional manufacturing methods. Along with this, additively manufactured winding pins expand the design freedom of the fiber net. As the pins are used as connectors, their dimensional accuracy was investigated, and their surface roughness was quantified before and after applying smoothing techniques. In addition, introducing multi-stage winding into CFW reduced fiber–fiber interaction and simplified fabrication. Within the case study, it could also minimize the winding fixture's complexity. The custom-coded digital design tool assists in design, analysis, and visualization tasks during all project phases. As a curated and object-oriented database, it operates non-destructively on several levels of detail based on a fundamental graph-theoretical model. The parameters assigned to object attributes can be tracked by their origin.

This paper contributes the object model for design, the multi-stage and hybrid material concept to the main objective of this thesis.

Author's Contribution

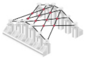
The author provided all study aspects related to fiber composites, and developed and coded the digital design tool. He also supported the stiffness evaluations and assisted with the surface roughness evaluation of the winding pins. Finally, he contributed to the remaining aspects on a conceptual level and delivered the design of the winding pins.



Robotic fabrication of the cross-shaped specimens.

4.11 Computational Co-Design Framework for Coreless Wound Fibre–Polymer Composite Structures

Marta Gil Pérez*, Christoph Zechmeister*, Fabian Kannenberg°, Pascal Mindermann°, Laura Balangé, Yanan Guo, Sebastian Hügle, Andreas Gienger, David Forster, Manfred Bischoff, Christina Tarín, Peter Middendorf, Volker Schwieger, Götz T. Gresser, Achim Menges, Jan Knippers
* equal first author contribution, ° equal second author contribution



Oxford – Journal of Computational Design and Engineering, 9(2), 310–329
submitted: 2021-09-14 – accepted: 2021-12-12 – published: 2022-02-25
https://doi.org/10.1093/jcde/qwab081

This paper summarizes the development of a computational co-design framework that allows the concurrent and integrative development of CFW structures. Furthermore, data exchange between different domains is facilitated by introducing a centralized object model, allowing comparative analysis of the process domain's interrelations and interactions. The approach was demonstrated within a case study on the laboratory scale.

By considering multiple design criteria, the fiber net simulation provides an initial syntax whose mechanical performance is accessed by numerical structural simulations. The fabrication domain interacts with the object model via the setup parameters, particularly the winding head, anchors, winding trajectory, and pre-tow fiber material. Production parameters were recorded during the entire sample fabrication. Destructive mechanical testing evaluated the structural capacity and failure modes, while structural monitoring using fiber-optical sensors allowed measuring the strain field and computing the load distribution. For this, the geometries of all samples were laser-scanned to obtain an accurate description of the cross-sectional shape. The objective of the integration domain was to map the initially incompatible data of the other domains, which are provided on several levels of abstraction and in separate coordinate systems. The fully equipped object model then allows identifying and quantifying causal relationships. The conducted case study on three sample types showcases the framework's potential by revealing interrelations between the fabrication, simulation, and evaluation domains. The object model for inter-domain interrelation finding is the main contribution of this paper to the thesis' primary objective.

Author's Contribution

The author contributed significantly to the investigations through his involvement in manufacturing, preparing, and testing the samples. He provided all aspects related to implementing fiber-optical sensors and the strain-field measurements. Moreover, he committed to handling and analyzing fiber-optical sensor data and made further contributions in supporting the creation of the co-design framework on a methodological level.

5. Overarching Discussion

The aim of this thesis was to improve CFW through a consistent digital characterization covering all process facets. To achieve this and confirm the equivalent hypothesis, two objectives must be accomplished, structured into a total of five sub-objectives. Adjustments in the physical (A) and digital (B) domains are accompanied by quality (C) and efficiency (D) enhancements and process extension (E). The findings related to the advancements are presented according to the research objectives. Figure 5.1 illustrates how the individual advancements relate to the sub-objectives, the papers, and research approaches.

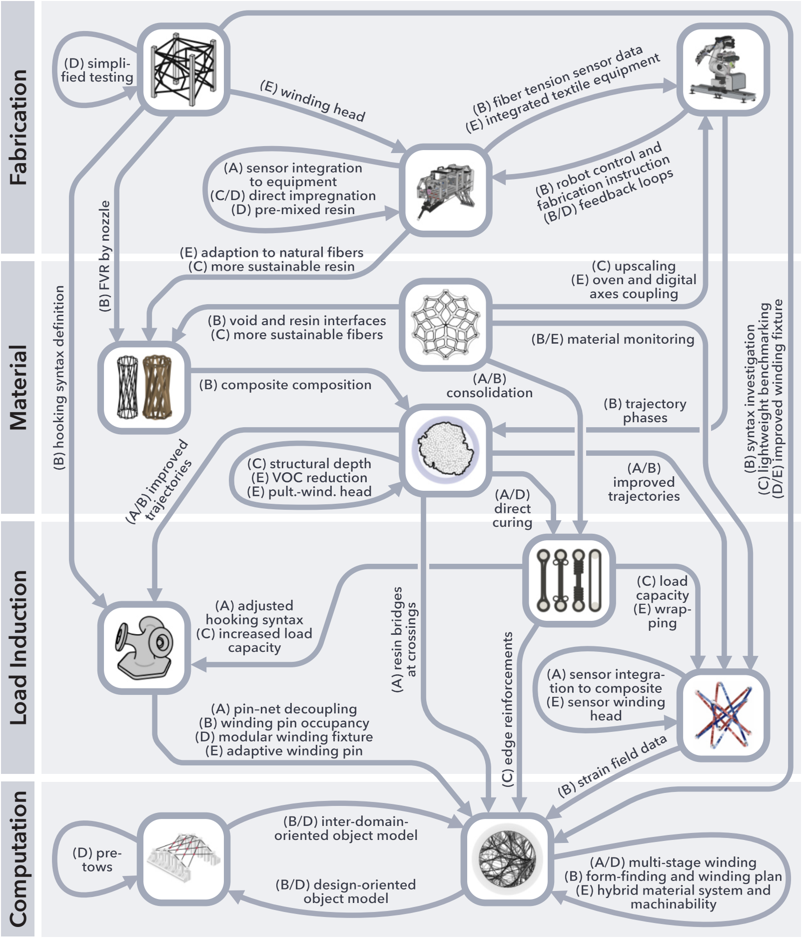


Figure 5.1 Overview of the interrelation between the advancements (arrows), the papers (icons), and the sub-objectives (capital letters) along with the research approaches (gray areas).

5.1 Implementation of Adjustments in the Physical Domain

Sub-objective (A) aims to align actual fabrication and the digital model to a greater extent by implementing adjustments in the physical domain. The sequential development of CFW, according to sub-objective (A), started with integrating sensors, first into the equipment and then into the material. This measure highlighted the importance of the fiber bundles' cross-sectional shape, which pultrusion-winding addresses. Subsequently, this innovation led to the investigation of the consolidation's impact on the load induction areas. Originating from these findings, the introduction of the adaptive winding pin increases control of the fiber net nodes. Finally, this novel pin was combined with the concept of multi-stage winding in a case study to validate the alongside developed digital tools, which transition to the next sub-objective.

The **sensor integration** into the winding head enabled monitoring and controlling of the most critical two process parameters in CFW, which are fiber tension and FVR. This technique could be further developed by integrating a force and torque sensor on the robot flange. This additional information would extend the TCP velocity control by incorporating automated shape adjustments to the predefined trajectory.

A sensor system in the winding head only indirectly reflects the situation in the material and is limited to the winding session. So, in the next step, sensors were directly integrated into the composite material. For this purpose, **fiber-optical sensors** were selected to keep disturbances in the winding process and composite material low. The sensors' high spatial resolution allows capturing the entire strain field from which manufacturing deviations, the structural behavior, and the load induction distribution were derived. Nonetheless, the fiber-optical sensors increase the component price and complicate the winding as they are susceptible to damage while unprotected.

In order to keep the cross-sectional shape of the beam more constant and define its shape arbitrarily, direct curing of UV-triggered resins was introduced by **pultrusion-winding**. This innovation enhances structural capacity by increasing structural depth and also reduces geometric and material parameter variations. Unnecessary resin bridges at crossing points can be prevented as they are challenging to model digitally. Further research needs to address the low processing speed and the limitation to translucent fiber materials.

As the increase in **consolidation** is beneficial for the fiber net segments, its impact on the load induction area also was investigated. A consolidation negatively affects the fiber path in this area and thus diminishes structural performance. Moreover, consolidation molds increase investment costs, complicate the winding process, add process steps, and pose challenges in design, as the topology of the mold must be precisely tuned to the CFW structure.

The introduction of auxiliary elements and adjusted hooking syntaxes improves anchors' structural performance while reducing fluctuations by a more material-appropriate **fiber arrangement**. However, complicated automation is the resulting disadvantage.

A redesign of the **anchor element** complemented the investigations on the fiber arrangements. The adaptive winding pin decouples the pin from the fiber net orientation, expanding design freedom. In addition, it eliminates fiber kinks and makes the regions at nodes more similar to a primitive digital representation of the fiber net. While the pin is customizable to the local fiber net configuration through additive manufacturing, it exhibits a high surface roughness. Surface smoothing techniques and the developed winding trajectories for pultrusion-winding mitigated this disadvantage. Nevertheless, the need for additive manufacturing currently limits the adaptive pin to small-scale engineering applications.

The adaptive winding pin's potential can only be exploited through the developed digital design tools. Their beneficial combination was validated in a case study in which the number of anchor points and the winding fixture were reduced to a minimum. As a result, the fiber–fiber interaction was dominant and **multi-stage winding** was introduced to reduce the deviations between the digital model and its physical counterpart to improve the validity of structural calculations.

All these measures significantly reduce the scatter of process and object parameters so that a digital model can be created with sufficient accuracy without excessively increasing the level of detail.

5.2 Implementation of Adjustments in the Digital Domain

Accomplishing sub-objective (B) enhances the accuracy of the digital description of the physical counterparts by extending digital models and improving computational methods. The need for the digital infrastructure was mainly motivated by structuring diverse and extensive data sets coming from fabrication and testing protocols. In order to exploit the full potential of those developed software tools, fiber net design and inter-domain correlation functionalities were developed. The design tools require a mathematical description of the hooking syntax, whose development was strongly interlinked with finding an improved trajectory creation method. Together with advancements in automation and fabrication, it reduces variations in the process parameters. This reduction will make inter-domain correlations clearer when using the object model.

Triggered by material parameter variations, **data-related methods** were created to acquire the composite material holistically. First, the significance of the void content and resin interfaces between rovings was revealed for CFW, as both phenomena result from a lack of consolidation. The fiber–fiber interaction, nozzle geometry, and the fiber depositions angle influence the variation in CFW along the fiber. The concept of consolidation by curvature is ineffective for many applications. Also, gravity impacts the resin distribution during thermal curing. In order to account for the consequences of these effects, calculation methods utilizing analytical geometry and a holistic consideration of the composite composition (FVR, RVR, VVR, FMR, and RMR) were developed and likewise applied to natural fibers, which show substantially more variations than synthetic ones. Methods based on the cross-sectional area or the mass are preferable to volume-based methods. The comprehensive digital material description allows accurate mass budgeting of components needed for various assessments. Moreover, data on the material aging was collected and digitally integrated, indicating that the resistance needs enhancement for long-term outdoor applications.

The above-mentioned comprehensive examination of the material, fabrication instructions, production protocols, test-related measurements, and design-related geometrical information constitute extensive and diverse data sets. The developed digital tools collect and structure these data sets while tracing their origin. By uniting the various data sets in an **object model**, analysis and visualization support all phases of the CFW project. Intuitive visualizations are essential for the accessibility of the gathered data. However, improvements are needed as analysis and visualization methods are currently computationally intensive. Two interoperable object models were created, one facilitates the design process, and the other explores inter-domain correlations. The object-oriented database follows the single source of truth principle and is the prerequisite for describing, analyzing, and manipulating the digital representation. The object model can be further developed into a fully-equipped digital twin of the process and its structures. Essential for CFW is the feature of the digital infrastructure to transform between levels of detail non-destructively while maintaining the graph-theoretical basis. In CFW, some data can only be destructively obtained or unavailable in early project phases. In such cases, the significance of the model's predictions depends on the quality of the estimation of missing parameters. For example, the algorithm for estimating the winding pin occupancy was developed to relay only a few parameters known at an early project stage. Complementing this, the advancements in the first sub-objective simplify the digital methods needed to describe the structure sufficiently.

After the form-finding is complete, the design-oriented object model outputs the winding syntax. Since minor modifications in the fiber, net lead to extreme divergences in mechanical performance, and the hooking syntax impacts the fiber net configuration, the fabrication plan also requires a clear description of the hooking syntax. The influence of hooking syntax is particularly prevalent, with large winding pin diameters and short adjacent segments. First, a specification of the **hooking syntax** was defined from the local perspective along the fiber path, which is more suitable for manual winding. Then, the hooking syntax was described using analytical geometry. This specification is independent of the fiber path direction, can be used in algorithms, and allows the individual consideration of a single pin without information beyond the local fiber net.

Based on this mathematical description, an algorithm was developed to determine the **occupancy of a winding pin** after each winding step. The algorithm requires only a few simple input parameters and is computationally cheap to execute. In this way, the occupancy estimation can be included in the object model already in early design phases, even for large anchor clusters.

Originating from the description of the hooking syntax, a new method for generating winding **trajectories** was created. This improved winding technique reduces fiber damage and variations in fiber tension during production. Initially motivated by the requirements of pultrusion winding in the form of a bend-free deposition of already cured segments, this winding technique allows the damage-free winding of fiber optical sensors under more constant pre-stress and prevents the adaptive pin's surface roughness from damaging fibers.

As part of the thesis, adjustments were made to the robot code and control system, such as distinguishing between traveling phases and hooking motions. Besides, a transition phase was implemented between these sections of the winding trajectory, in which winding head reorientations are preferentially performed while refraining TCP translation motions. Together with the checked **fabrication instructions** in the form of a winding plan or robot code, these before-mentioned improvements to the trajectory increase the fiber deposition quality. The digital tools' clear and error-free instructions reduce the human influence and lead to higher reproducibility.

In addition to the trajectory adjustments, **feedback loops** were integrated into the robot controller to adjust the TCP velocity regulating the fiber tension in real-time based on sensor readings from the winding head. Similarly, the resin volume flow was dynamically adjusted to control the impregnation quality depending on the TCP velocity. Currently, this second feedback loop is solely based on a volume conservation law and neglects resin leakages. However, future research on integrating an eddy-current sensor in the winding head could allow contact-free measuring of impregnation quality to predict the FVR during winding. An estimation of the fiber sag could be developed based on the fiber tension sensor data.

The second developed object model focuses on finding **correlations** between different process domains to enable future co-design. Finding correlations becomes easier with comprehensive data sets entailing reduced scatter. The progress in accomplishing the thesis' primary objective contributes to this more accurate data collection. In the next step, finding correlations leads to the targeted elimination of the identified sources of interference. This process insides enable early intervention in the event of occurring errors during production, similar to sensor monitoring of process parameters. Conversely, it can also prevent errors during production and even earlier in the design phase. The inter-domain correlations have the potential to improve the digital process characterization even further. The disadvantage of this method is that correlations in parameters do not have to result from causality.

Furthermore, a crucial contribution to the object models is the material-integrated **fiber-optical sensors**, which allow spatially-resolved inspections of the composite material's state. From this, digital methods for various use cases are derived. Local defects are detected so that causative factors can be identified. Changes over the component's entire lifespan can be monitored. For the first time, insights into the structural behavior and the actual load distribution were obtained by analyzing the sensor-measured strain field of the component using both object models.

In summary, all these measures improve the level of detail of digital object-oriented models and provide methods for improved data acquisition and analysis. Adjustments in the digital domain also reduce the scatter in the process parameters due to their impact on the manufacturing process. Thus, it can be emphasized that advancements in this sub-objective are the most efficient way to achieve the desired process characterization since they positively affect both domains. However, some data-related methods are only possible by advancements in the physical domain, such as sensor integration.

In the following paragraphs, the sub-objectives of the secondary objective of this thesis are addressed.

5.3 Quality Enhancement of Fabricated Structures

Fulfilling sub-objective (C) enhances the quality of the fabricated structures and is synonymous with an effectivity increase in the CFW process. The developments aligned towards this sub-objective can be classified into three groups: increasing the mass-specific and total mechanical performance and enhancing the efficiency of the structures. All three indicators must be present for a structure to be considered high quality.

CFW structures were compared to metal-based structures for two applications to benchmark the **mass-specific mechanical performance**. The methods described under sub-objective (B) are helpful for composite mass budgeting. The first comparison was performed in the context of an application with strict design specifications. In this case, the performance advantage of the CFW structure benefited from the material properties of carbon fibers and the direct connection of load induction points within the design space. The CFW design language is predestined for lattice structures, allowing substantial mass reduction. As a truss structure, the design aligns fiber orientation with force flow. The other showcased application achieves the mass-specific advantage by an innovative combination of CFW with other manufacturing technologies. The hybrid concept utilized metallic elements to absorb compressive loads and the fiber composite in component areas where tension loads predominate. The challenge of this combination is the increased influence of interfaces, which was solved by additively manufactured winding pins in the present case. While a significant increase in the mass-specific performance is desirable, the total load capacity must first fit the application. Therefore, several following adjustments were made to both morphological fiber net primitives to increase the total mechanical performance.

The **fiber arrangement** was optimized at the nodes, as was the anchor itself. Coupon tests were performed with different fiber arrangements to reduce variation while increasing spring stiffness and maximum load capacity for tension and compression at a constant sample cross-section. Although increasing the pin radius and material usage primarily impacts mechanical performance, it is often not modifiable due to build-volume constraints. The concepts that reach higher force levels complicate automation by requiring auxiliary elements. Despite the advances in performance, there is still a large discrepancy between the sample's actual and theoretical load capacity. As in an integral design concept of CFW, variations in the amount of deposited material are not possible along the fiber path; installing edge reinforcements will still be necessary to solve this problem on a sub-syntax level.

The other measure, carried out at the nodes of the fiber network, complements the fiber arrangement development by redesigning the anchor element. Although the **adaptive pin**'s mechanical potential was only indirectly tested within a case study, the following indicators strongly suggest an increase in total mechanical performance caused by the extended topology of the pin. First, the pin reduces fiber kinks as the arm orientation corresponds to the fiber net configuration. Second, the topology of the pin allows more complicated hooking syntaxes, which result in a larger wrapping radius. These extended fiber attachment possibilities are especially relevant for compressive loads as the results of the fiber arrangement investigations are transferable to the adaptive winding pins. Finally, the pins reduce punctual load induction in the composite over several points due to the multiplicity of its arms.

The other morphological fiber net primitive considered is the segments, which would often be oversized in tension and compression if the edge reinforcements were insufficiently pronounced. Regarding the segments, the more relevant aspect is the flattening of the fiber bundle when placing the roving at a crossing point. Usually, the orientation of this self-initiated shape alteration is counterproductive as it leads to a low **structural depth** concerning the later application. Pultrusion-winding allows through direct curing to define the cross-sectional shape of the segment, counteracts this flattening, and thus maximizes the structural depth. Therefore, the developed trajectory method requires control over the rotational orientation of the fiber bundle. Pultrusion-winding can be combined beneficially with the improved fiber arrangements at anchors and the adaptive winding pin.

When mass-specific and total mechanical performances are sufficient, the **efficiency** of the structures needs to be addressed to optimize the structure's quality further. This indicator was examined in this thesis by deploying sustainable fiber and resin materials, reducing waste, and upscaling structures.

Flax fibers have proven to be a **sustainable alternative** to carbon and glass fibers due to their balance between stiffness, strength, embodied energy, and global warming potential. Other alternatives investigated, such as hemp and jute, would also be competitive but suffer from the dominating negative impact of the epoxy on the sustainability metric due to their low FVR. Therefore, especially in such material systems, the use of bio-based resins helps lower the overall footprint. Moreover, partial consolidation of these structures' segments could increase FVR, improving their ecological quality further. Some natural fibers' deformable cross-section could be beneficial for achieving this. Nevertheless, carbon fibers remain the only viable selection for high-performance, lightweight applications.

If the resin mass ratio deviates from the optimum, structural performance and ecological quality are compromised. Compared to resin baths, the **cartridge impregnation** allows accurate control of the resin consumption. In addition, the resin is applied just before the fiber deposition so that less resin is lost during production from free-spanning dripping fibers. As a result, the production becomes cleaner, and the peristaltic pump supplying the impregnation unit also allows retrieving the unused resin after production. This resin could be reused and more easily accounted for in the FVR calculation.

The last efficiency improvement targets large-scale applications. Here, the **upscaling** of the building system reduces the number of components and connectors. As a result, the upscaled system requires less material per square meter of building floor space. The disadvantage is that upscaling entails challenges in fabrication. These primarily concern high process forces, material throughput, production time, geometric tolerances, and transport cost.

The findings demonstrate that for CFW, all three quality indicators increased while fulfilling the thesis' primary objective. Many mentioned advancements relied on the advancements accomplished for the primary objective.

5.4 Improvements in Process Efficiency

By achieving sub-objective (D), the winding and auxiliary processes become more efficient. The findings regarding this sub-objective are grouped along the process workflow, starting from digital planning over preparation and winding execution to testing.

In the **design phase**, the developed digital tools provide functionalities tailored to CFW and thus simplify the engineer's work. So, predefined and user-coded functions allow representing CFW objects in a way that resembles their design language and is human-readable. Further developments aim at natively integrating prismatic designs into the object model to ease the transition between CAD and CFW design tools. The first step toward this link was made by the fiber net configuration translating to the arm arrangement of the adaptive winding pin. In addition to more convenient handling, these specialized digital tools increase determinism as modifications are automated and less dependent on human intuition or are continuously logged. This stepwise listing of tasks makes the design process more transparent. Digital process planning allows for checked and clear production instructions, which increases the process efficiency in manual winding since operators need shorter training or less focus for an error-free execution. Multi-stage winding amplifies these benefits by shortening winding sessions and limiting errors to a single stage. Moreover, it makes fixtures more available as an already load-bearing structure no longer requires support.

Pre- and post-processing should be reduced to a minimum, as they do not represent value-adding process steps. Since post-processing comprises cleaning and demolding, improvements were made mainly due to a cleaner process. The following advancements in winding fixtures and material systems reduce the preparation time. By deploying a modular winding fixture in conjunction with the clamped adaptive winding pin, considerable time savings were achieved, particularly when component geometries frequently change. While the system prevents tolerances from deteriorating, it adversely restricts the winding pin positions to a predetermined grid, which affects the component design. Avoiding mixing resin also shortens the preparation, which was done by using an inert resin system allowing larger quantities at once or by repeated and damage-free freezing and thawing of premixed resin amounts.

During the **winding session**, various adjustments make the execution more convenient for the operators. Deploying pre-tows is another strategy to avoid mixing resin before each winding session. Here, an adequate resin content, application-oriented spool capacity, and sufficient pot-life need consideration. Pre-tows can also reduce resin runoff, whereas the direct UV curing of the resin in the winding head removes this influence. A direct impregnation on the winding head prevents impregnated fibers from spanning freely through the setup. The last three aspects ensure the efficient use of resin and make the process cleaner and safer. Free-spanning fiber should similarly be avoided if dry, as otherwise, fly lint occurs. Another advancement to reduce workload during the winding session is the sensor-informed feedback loops interrupting the process to fix issues early. An immediate intervention requires less effort than fixing an intensified problem later. It also prevents degradation of the component quality.

All advancements mentioned regarding this sub-objective aim primarily to reduce the **workload** for engineers and operators, leading to a safer winding execution. As a result, the winding becomes cleaner, the process steps simplify, and the winding session shorten. Furthermore, this improved situation makes the operators' work more convenient which helps to reduce mistakes as the average focus is elevated.

Finally, findings regarding the **testing** implemented simplifications to lower cost and speed up the sample fabrication process. An essential advancement was the transfer of results from small-scale to full-scale and from simple to expensive testing methods. This strategy drastically reduced the required material and effort for sample production, increasing the number of samples and decreasing statistical deviations. Although the principle was successfully demonstrated, further research is needed to generalize it to all CFW applications.

The advancements made towards this sub-objective have made the CFW more efficient. Several aspects were only realized through accomplishing the thesis's primary objective.

5.5 Installment of Process Extensions

Sub-objective (E) is dedicated to installing novel features into CFW and expanding it to new applications. The advancements made here can be assigned to the following items: winding head, peripheral equipment, material system, fixture, and anchors.

Different versions of CFW **winding heads** offer a range of functionalities, while additional peripherals were expanded and implemented into the setup. Winding heads with dual-resin and dual-fiber capability were realized. The dual-resin feature creates gradient structures, for example, incorporating additives. Dual-fiber systems allow the processing of continuous hybrid reinforcing materials or integrating additional fibrous elements, such as sensors.

Spools for dry and pre-impregnated **fibers** with a passive internal tension regulation were integrated into the winding head. Despite the reduced fiber capacity or increased winding head volume, this configuration benefits the fabrication of smaller components as fiber feeds do not restrict trajectories, and robot motions do not cause fiber tension fluctuations. However, tension control systems must be designed with a larger capacity to compensate for ample robot motions for external fiber feeds.

If an integrated **impregnation** is required, an internal resin reservoir is sufficient for a small scale, whereas an external resin feed is more appropriate for a large scale. With an external resin feed, the flow rate can be controlled, while a metering pump allows the dosing of absolute resin quantities. Logging the pump settings includes the resin consumption in the fabrication protocol. The solved challenge of designing a head-mounted impregnation unit was to achieve a sufficient impregnation quality without significant leakage or applying restrictions on the winding head orientation even though the fibers are constantly under tension and remain in the impregnation unit for a short time only. Especially in the case of natural fibers, increased fiber deflections to improve impregnation quality require additional fiber guiding elements in the impregnation unit. All fiber guiding elements have to prevent fiber damage. On the inside rounded nozzles must prevent fiber damage when the developed trajectories cannot be applied.

The found winding head design configurations extend the robotic CFW process by including natural fibers, sensors, and additives. In addition, they also cover a wide range of material consumption rates and component sizes. **Further developments** concern the integration of additional sensors, such as consumption counters, optical positioning, force/torque sensors, eddy current sensors, and resin chamber monitoring. On the other hand, integrating actuators could also extend the capabilities, such as active tension control, nozzles with adaptive stiffness or orientation, and automated hooking motions performed by the nozzle.

The design of the **peripheral textile equipment** depends on the setup and winding head configurations. Solutions were found for various aspects: fiber and resin storage, connection to the winding head (material supply and data retrieval), fiber tension regulation, and resin feed control. A compact manufacturing system was realized by integrating the equipment onto the robot base, allowing winding by mobile robots and autarkical on-site manufacturing. This advancement eliminates transport-related costs and size limits. Natural fibers require drying before impregnation, for which continuous dryers should be utilized, but they currently exceed the volume limitation of such a mobile robotic system.

In the area of **winding materials**, progress on this sub-objective aims to reduce the impact of adverse properties to facilitate the adoption of CFW. For example, regarding pultrusion-winding, compiling a new resin system removed VOCs. So, the process can be extended to applications where safety regulations previously prohibited its use.

In addition, the aging behavior of the composite material was **monitored**, possibly facilitating the establishment of building regulations applicable to such non-standard building systems. Ultimately, their establishment would disseminate CFW in the industry. In the future, the developed fiber-optical sensor integration methods could realize long-term structural health monitoring as an intrinsic feature of CFW structures. For this purpose, the temperature influence has to be compensated effectively.

Furthermore, a **bio-based resin** system that theoretically has an theoretically unlimited pot life was utilized. It maintains the fiber–fiber interaction between winding sessions and extends the length of individual winding sessions. A disadvantage of this particular resin was the required hot curing, which led to the development of a custom-built oven inside the winding setup. Such temporary ovens provide a way to cure large structures without considerable investment costs.

The last items in this sub-objective are the **winding fixtures and anchors**. Here, additive manufacturing was deployed to extend their functionalities. 3D-printed fixtures made of water-soluble thermoplastic material extended the rapid adaptability of the fixtures to diverse geometries. Applying additive manufacturing to the anchor system resulted in the design of the adaptive winding pin, which embodies several enhancements already mentioned, such as increased fiber net design freedom and expanded hooking syntaxes.

Moreover, other measures were introduced to expand the range of CFW applications. These include the digital coupling of **robotic auxiliary axes** extending the application spectrum of CFW to large-scale structures. This aspect could be further developed into collaboratively winding robots increasing design freedom or reducing fabrication time.

Such systems could also automate the subsequent **additional wrapping** of fiber bundles, which is currently performed manually. This technique subsequently modifies the mesoscopic fiber net geometry while increasing fiber bundle consolidation. On a small scale, it also allows correcting fiber deposition inconsistencies or fiber tension deviations. Initially, the wrapping technique was developed to improve the integration quality of fiber optical sensors.

Finally, the introduced hybrid material concept permitted post-processing of the finished structures. This **machinability** feature extends the application of CFW to engineering applications requiring precise geometrical tolerances.

The findings in this sub-objective have extended the CFW process and made it worthwhile for new applications. Furthermore, the various proven designs are transferable to future projects.

5.6 Consolidation of the Achieved Advancements

As discussed above, all sub-objectives were sufficiently accomplished. Therefore, the consolidation of all realized advancements constitutes the digital process characterization of CFW as the central result of this thesis. With this, the **hypothesis** can be confirmed, claiming that such a consistent digital characterization considerably enhances the CFW manufacturing process.

The result's significance is highlighted by the transformation of CFW from a premature into a highly-performing manufacturing process with uniformly improved **target metrics**. Each sub-objective (A–E, Figure 3.1) is dedicated to specific target metrics: the primary objective addresses controllability (A/B), determinism (A/B), documentation (B), and the robustness (A/B) of the process, while the secondary objective targets effectivity (C), efficiency (D), flexibility (E), and side/after-effect absence (D). The target metric of atomicity is not relevant for CFW. In contrast, a constant improvability is still given and was even increased by the extension of CFW to new applications by sub-objective (E). The significance of the thesis's result encounters limitations, such as the actual impact of the advancements on safety factors and numerical simulations utilized for design.

The advancements cover all facets of CFW (equipment/processing, product/data handling), manual and robotic winding, both relevant application contexts (engineering and architecture), and a wide range of structural scales from 3×3×3 cm^3 to ∅23×7 m^3. The advancements in the research approach regarding the **fabrication system** were mainly driven by engineering design and software developments. Thus, CFW was transformed from a static to a dynamic fabrication process by including sensor-informed feedback loops and procedurally generated and verified winding trajectories combined with digital coupling between robotic axes in an upscaled fabrication setup. Furthermore, the setup configuration was diversified by exploring different technical application-orientated options for robotic-system integrated textile equipment, starting from a stationary and external resin bath impregnation and a rudimentary fiber guiding head.

The applied methods regarding the **material system** research approach included mainly investigation techniques such as structural testing, microscopy, visual inspection, thermogravimetry, DSC, and evaluating mass and dimensions on the component level. Initially, the material section in the form of a cold-curing epoxy-based carbon and glass fiber material system was revised. Moreover, UV-triggered and bio-based resins were introduced in terms of matrix systems. The fiber system's alternatives, including natural fibers, were technically implemented and then ecologically evaluated. Also, different fiber appearances were included, such as rovings, tapes, yarns, and pre-tows. Finally, detailed descriptions of the composite composition, the fiber bundles' cross-section, and the material aging were generated.

The research approach focusing on **load induction** was improved by applying additive manufacturing, analytical geometry, the development of algorithms, experimental design, and structural testing. The development originated from winding pins formed by standardized elements connected by elaborate adapters limiting the fiber attachment directions and assuming a uniform load induction distribution. The load capacity and its scatter were improved by adjusting the fiber arrangement at the pin and including auxiliary elements. Besides, the developed adaptive winding decouples the pin orientation from the fiber net configuration leading to improved hooking. Apart from that, the actual load induction was determined by fiber-optical sensor measurements. The initially rather rudimentary description of the hooking syntax and the estimation of the pin capacity by physical prototyping was replaced by a mathematical definition for an algorithm stepwise predicting the pin occupancy.

The last research approach addressed the **computational infrastructure** and thus deployed mainly digital methods such as algorithm creation, coding, and structural simulation combined with structural testing. Beginning with a fabrication protocol and proprietary software tools fragmented over different tasks, an object-oriented software solution was tailored towards CFW, centralizing data sets in a structured manner. This object-model permits semi-automated data analysis and visualization, allowing form-finding and correlating data sets between process domains.

Considering all those process facets, as structured in research approaches, is essential for the **digital process characterization**, as they all interact with each other intensely. As the definitive result of this thesis, the digital process characterization matters as it satisfies the demand for efficient and highly performative structural components for engineering and architecture.

6. Conclusion and Outlook

Coreless filament winding was comprehensively characterized by applying digital tools and made more accessible to describe due to physical adjustments. So, the digital and physical advancements work in mutual conjunction. With accompanying advancements, all relevant target metrics of the coreless filament winding manufacturing process could be improved. The target metrics relevant for coreless filament winding are controllability, determinism, documentation, robustness, effectivity, efficiency, flexibility, side/after-effect absence, and improvability. While not every advancement addresses all target metrics simultaneously, the totality of the advancements achieved a significant improvement in coreless filament winding. Many of the discussed findings were only possible because of the consistent digital description, partly reliant on advancements from the physical adjustments. The fulfillment of the objectives forms a digital characterization of the coreless filament winding, which presents itself as the central result of this thesis. An essential attribute of the thesis is the holistic view of coreless filament winding as reflected by the research approaches structuring the comprised papers into fabrication, material, load induction, and computation.

Already alone by general technical advances, any arbitrary manufacturing process will ever have the potential for further improvements or new applications. However, all sub-objectives of this thesis can be classified as sufficiently satisfied to evaluate the hypothesis. The primary objective targets to answer the hypothesis directly and includes physical and digital process adjustments. These simplified the physical object and made the digital description more accurate. To ensure that the achievement of the primary objective does not degenerate the other target metrics, the secondary objective must be achieved simultaneously. It structures into three sub-objectives. The sub-objective targeting quality enhanced the mechanical and ecological performance of the produced structures. Efficiency improvements simplified and accelerated the coreless filament winding workflow. Finally, process extensions have eliminated limitations and opened up new applications.

The hypothesis states that *a consistent digital characterization covering all process facets is required to establish coreless filament winding as a manufacturing process with improved target metrics*. This claim can be confirmed due to the simultaneous achievement of the primary and secondary objectives. The thesis' process characterization was only feasible because all facets of coreless filament winding were considered holistically as possible when generating a digital object and process representation.

Although not all details of the coreless filament winding process or its structures were definitively reproduced digitally, the entirety of the advancements realized in this thesis and the matching research findings have improved the characterization of coreless filament winding. As a result, the peculiarities of coreless filament winding and their interactions are now better understood, covering all process facets. This outcome allows for better managing the specific requirements in future projects by simplifying decisions about the fabrication setup configuration or which specific technological advancements are needed for each process facet. The motivation is that implementing only a reasonable selection of measures is more economical than consistently deploying all. This consideration does not apply to the computational infrastructure as it is efficient in improving process target metrics in any project and increases the overall predictive validity of simulations.

The next step in the digital characterization of coreless filament winding is quantifying each advancement's impact on safety factors and material savings using finite element analysis. Then, a reasonable combination of different advancements into a single process could be investigated. Here, the selection depends on the targeted application. Hereafter, further steps that need more research are proving a considerable amount of application-independent inter-domain causations, which have the potential to improve the digital process characterization even further. It would also prevent errors during the design and production phase. Finally, the digital characterization development could guide towards realizing a fully-equipped digital twin of the process and its fabricated structures. Moreover, continuing developments could aim toward co-design.

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