CLOUDMAGNET, A CFRP FRAMEWORK FOR FLEXIBLE ARCHITECTURES

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Abstract. To examine CFRP’s viability within architectural practice, this paper explores new possibilities and methodologies for the materials integration into the design and production processes. Through the lens of the /One Day House/ initiative and its recent subproject /cloudMAGNET/, this paper explores and evaluates new typologies of formwork and winding techniques for CFRP based structures derived from tensile modeling and CFD analysis. Through examinations in cored and sacrificial coreless winding, this paper outlines new formal, structural, adaptive and production possibilities afforded by the integration of CFRP into the architectural workflow.

Keywords. Additive manufacturing; composites; carbon fiber; form finding; analog / digital fabrication.

1. Introduction

Recently, we have witnessed the rapid development and integration of computational design tools and digital/robotic production platforms into architecture and surrounding disciplines. These tools have not only allowed for the creation of more complex/efficient forms, fabrication methods and assembly processes, but have also allowed for the use of new, non-standard material systems such as carbon fiber reinforced polymers (CFRP). By removing the formal and structural constraints of traditional materials, CFRP and other composites in conjunction with computational modeling have given designers the ability to not only reimagine form, but also the disciplines existing construction processes.

Although these tools and materials have given architects the ability to simplify existing fabrication systems, we have continued to see the embodied complexity within buildings and their assemblies explode, making the construction of even the simplest of forms overly cumbersome. While architects have leaned towards the complexification of enclosures, materials and assembly systems, we have observed an opposing shift in industries such as automotive, aviation, aerospace and recreation, where complex multi-part assemblies have been replaced by sophisticated yet simplistic composite materials such as CFRP. In a world where mechanical complexity is being quickly replaced by computational and material complexity, CFRP’s initial formless/malleable nature allows for the creation of complex, multi-layered parts with specifically programmed characteristics.
allowing for smarter materials, the minimization of parts, and the simplification of fabrication/assembly systems.

Although CFRP has gained traction within industries centered around mass production, we have yet to see its acceptance into the norms of architectural construction. There are several reasons architecture lags behind: the material currently remains expensive; there is a lack of knowledge around CFRP within design, architectural engineering and construction fields; the necessity for expensive/material intensive formwork’s traditionally associated with CFRP go against architectures one-off, low-cost building culture; and it remains difficult to accurately model and analyze composite structures in currently available design software’s. To further examine CFRP’s viability within architecture, this paper examines contemporary uses of CFRP within architecture, while simultaneously exploring new possibilities for CFRP’s integration into the design and production processes through the lens of the One Day House initiative and its recent subproject, cloudMAGNET. Through the investigation and evaluation of new typologies of formwork for wound CFRP both cored and coreless, this paper outlines new formal, structural, adaptive and production possibilities afforded by the integration of CFRP into the architectural workflow.

1.1. CFRP IN ARCHITECTURE

Over the past decade, there have been growing numbers of projects testing the merits of composites, specifically CFRP within architectural research and practice. In practice, we see projects like Atelier Bow-Wow’s portable BMW Guggenheim Lab completed in 2011, the first noted fully CFRP structure at an architectural scale (Frearson 2007). Recent works of Foster + Partners also push CFRP, with projects ranging from their large shading screens on the Dubai Apple Store, their roof on the Chicago Apple Store, as well as the CFRP roof on the new Steve Jobs Theater. Spanning 155 feet, the structure currently stands as the world’s largest CFRP roof. These projects, although novel in their material and structural capabilities do not fully exploit CFRP’s potential as they focus solely on structure and efficiency, applying CFRP similarly to traditional architectural materials.

Atelier Bow-Wow’s project for example, creates a light-weight, modular structure through the remaking of conventional material sections from CFRP and applying them to conventional architectural/structural forms. Although creating a minimal structure that maximizes openness and transportability, the visual and tactile qualities of the building remain similar as those created with a steel structure. Similarly, Foster + Partners Dubai Apple Store façade, utilizes layered, cylindrical CFRP tubes creating the appearance of a woven louver system, rather than utilizing the materials malleable characteristics to weave an actual structure. Although Foster + Partners CFRP roof structures take a different approach utilizing custom designed and fabricated elements, the composites remain enclosed accentuating the thinness of the roof, but limiting the materials potential strictly to efficiency.

On the other hand, Kengo Kuma’s Komatsu Seiren project takes the use of CFRP in a new direction. Rather than reinforcing the buildings existing structure through the addition of CFRP sleeves as typically done, Kuma wraps the entire building in a vail of CABKOMA (CFRP) Strand Rods, moving the project beyond
material efficiency by developing a new building aesthetic.

1.2. CFRP IN CURRENT ARCHITECTURAL RESEARCH

Where in practice, CFRP tends to be utilized for conventional solutions, in architectural research, we have seen the emergence of novel CFRP applications beyond efficiency, redefining the design process, aesthetics, simulation and production. Recent projects completed at the University of Michigan, the University of Stuttgart and Temple University begin to exemplify new potentials of composites in architecture.

Over the past five years, the ICD/ITKE Institutes within the University of Stuttgart have continually pushed the boundaries of what a composite architecture could look and feel like. Through the development of novel methods for robotic coreless CFRP winding, their projects have shown CFRP’s potential at various scales. Coreless winding, implemented in their 2012, 2013-14 and Elytra Filament pavilions have demonstrated that CFRP can be applied through various winding methods, producing non-monocoque structures, while at the same time introducing a new, lightweight, fibrous aesthetic to architecture (La Magna, et.al 2016; Prado, et.al 2017; Reichert, et.al 2014; Menges, Knippers 2018). In their more recent 2014-15 research pavilion, they push the materials efficiency and visual properties even further, through the placement of CFRP rovings onto the interior of an inflated ETFE bubble creating the potential for a construction process nearly void of waste and completely unique in aesthetics. Building upon this research and the previously completed CFRP projects produced by the authors, cloudMAGNET aims to find new methods and uses for CFRP within the discourse of architectural design and production.

2. The One Day House and background research in CFRP

Recently at the Tyler School of Art, a series of CFRP projects (rolyPOLY, roboWINDER, Dinner4Six, etc.) have been designed, fabricated and tested under the larger research umbrella of the One Day House initiative. Examining novel systems for adaptive/robotic housing, the initiative aims to not only reinvent the relationship between environment, building and occupant, but also aims to simplify the process of making, while simultaneously allowing for high levels of formal, aesthetic and environmental adaptability. Through the integration of wound CFRP tow as a flexible structural framework and a lightweight microPCM (micro-encapsulated phase change material) fabric enclosure system, the project looks at buildings not as a complex assemblage of thousands of unique parts and materials, but rather as a simplistic system, that through the integration of embodied computational/material intelligence, can adapt to and self-mediate ever-changing environmental conditions.

To realize the vast aspirations of the initiative, a series of short term projects were initiated. Each project examines in depth a single aspect of the newly proposed building process (Wit, Kim, et.al 2016; Wit, Ng, et.al 2016). Initial research was completed in roboWINDER. Focused around the relationship of both cored and coreless robotic CFRP tow winding in relationship to building form and
resin application method (i.e. wet wound vs. pre-impregnated tow), this project
defined a robust framework for CFRP modeling and application being utilized
in subsequent projects. Following the *roboWINDER*, research, a specific CFRP
tow and resin system was chosen. A durable, pre-impregnated resin system was
chosen specifically for its material consistency (±27.5% resin content), pre/post
 cure stability, low-temperature curing properties, structural attributes, low toxicity
and long shelf life and has been implemented in all subsequent projects with strand
counts of either 12k (12,000), 24k or 50k.

The project *rolyPOLY*, a tumbling enclosure for a single occupant completed
with Simon Kim, began a deeper investigation into corelessly wound, modular,
self-supporting monocoque structures with a specific emphasis in the visual
and tactile qualities possible through CFRP. Pushing this research further in
the ongoing project also with Kim, *Dinner4Six*, a room-scaled enclosure for
six individuals adds a new dimension to the research through the rethinking
traditional metal coreless formwork as an integrated, internal, tensile sacrificial
CFRP structure. This integrated formwork allows for the minimization of waste
through the utilization of CFRP tow as the formwork/form generator, overall
building structure as well as the enclosure system.

3. cloudMAGNET

In a world where climate change has become increasingly unpredictable and
growing populations will continue to foster increased material shortages, it has
become necessary to reimagine our current design processes, material pallets and
assembly methodologies. *cloudMAGNET* examines the co-dependencies between
material, form, energy and the environment. Through the design, prototyping and
production of a series of environmentally performative, (i.e. cloud generating
enclosure systems) for the cloud forests of Monteverde, Costa Rica, this project
aims to not only bring attention to the shrinking of the cloud forests through the
visual condensing of air into clouds, but also aims to develop a viable, material
active enclosure system for architectural applications. Through the utilization of
flexible, wound CFRP structures, reinforced by an integral microPCM embedded
Dyneema fabric skin and formally sculpted through tensile fabric modeling,
and CFD analysis, *cloudMAGNET* aims to simplify large-scale construction
methods while actively controlling internal spacial conditions such as temperature,
humidity and lighting. The following focuses on the design, production, testing
and results of the CFRP aspect of the project.

4. EARLY PROTOTYPES. MATERIAL FOLLOWS FORM

Between 2016-17 a series of nearly twenty CFRP prototypes were designed, built
and tested during the development process of the *cloudMAGNET* prototype. Initial
prototypes focused purely on the formal flexibility of CFRP and how the material
could create purely performative forms, rather than how material, application and
computation could be utilized to create forms the material desired. Based on
Bernoulli’s principle of pressure, where reduced pressure is correlated to increased
speeds of fluids such as air, two prototypical forms were derived in 3D modeling
software’s maximizing the effects pressure and temperature change on the PCM impregnated skin. Derived from the aggregating of Venturi tubes, these initial forms created optimal conditions where air was forced from larger cross-sections to smaller. The forms were then simulated in CFD software to verify flows, pressures and the aerodynamics of the enclosure system. Data from CFD analysis was utilized to create a back and forth dialog between the design and simulation process.

As the wind forces being applied to the prototypes in Monteverde were similar those being applied to a building in severe weather conditions, a series of typical structural typologies were applied the forms, i.e. randomly wound monocoque shells, diagrids, as well as a variably wound grid shell structure (Fig. 1). As the final formal characteristics of the initial prototypes was quite complex, a removable cored system was created from laser cut cardboard to be utilized in ¼ and ½ scale prototyping. Cardboard was chosen for its recyclability as well as for its abilities to withstand kiln firing while still being easily separated from the CFRP by submerging the artifact in water post curing.

![Figure 1. Initial Winding prototypes at 1/8 scale.](image)

Utilizing a unique slicing algorithm, each prototypical form was sliced into a series of fifteen unique sections, each with eight triangularly shaped CFRP grippers added to its perimeter during slicing. Each gripper was uniquely labeled with a corresponding letter and number allowing for its easy location during the winding process. Depending on the structural typology, CFRP was wound around the cores in different ways. Some creating consistently wound structures, others asymmetrical structures or structures with varied material densities. For example, in the grid based systems, winding began at S1G1 (section 1 gripper 1) and rotating clockwise, moved one gripper at a time until it met its corresponding gripper at S15 before reversing direction and returning to S1G1. This type of systematic winding allowed for the easy buildup of necessary structural depth while also allowing for easy variations in winding. The process was continued until the predetermined structural density was achieved.

Although successful at small-scale, allowing for extremely strong structures
and low-cost rapid prototyping, when brought up to full-scale of 15’ in length, the cored system introduced a series of problems ranging from material waste in the production of the core, form resolution in relation to the CFD model, complex module connections, undesirably high structural weight, an unyielding in the navigating the core in the winding process and finally the rigid form made global shipping to the site nearly impossible. For these reasons, a new approach was taken, centered around a corelessly wound structure with high levels of structural flexibility and compressibility.

5. CORELESS WINDING. FORM FOLLOWS MATERIAL

In 2016, a series of coreless prototypes were initiated built off the framework developed in rolyPOLY, culminating in the summer of 2017 with the testing of a series of four, uniquely wound and clad, 1/4th scale (approximately 5’ by 4’ by 4’) CFRP prototypes in the cloud forests of Monteverde, Costa Rica. The prototypes were tested under the rubric of CFRP frame flexibility and durability; transportability; the compatibility of the CFRP frame to the PCM impregnated Dyneema fabric; the levels of change and control of internal pressures, temperatures and humidity in relationship to form, structure and PCM content and distribution; stability of the CFRP structure in severe, unpredictable weather conditions; as well as for the accuracy of the imbedded electronics monitoring systems. The following focuses solely on the aspects of the development of the prototypes related specifically to the CFRP framework. Other aspects will be discussed in future papers.

Unlike the initial prototypes where the complex forms were predetermined through Bernoulli’s principal and CFD analysis and necessitated the use of a core, similar to conventional systems previously discussed, these prototypes investigated the use of CFRP tow or cables treated as a series of intersecting cable networks in pure tension. As a network of cables acts similarly to a membrane in tension, tensile modeling and simulation was used to generate the forms of the new structure. Although this method of form finding can potentially minimize the types of formal outcomes, it also maximizes the efficiency of the material, fabrication and assembly processes by utilizing the CFRP tow as its own formwork. A back and forth dialog between 3D modeling and CFD analysis allowed for the tuning of the formal outcomes.

5.1. FORM FINDING THROUGH TENSILE MODELING

Form finding for the second stage of prototypes was completed using the Kangaroo and Meliar MPanel plug-ins for Rhino 3D. Kangaroo was utilized for initial form finding where forms could be quickly developed, modified, extracted and tested in the CFD software, while MPanel was used for the generation of a more precise final form; estimating intersecting cable network deformation through the winding process by means of simulated surface deflation; and finally through FEA analysis on tensile membranes as a guide for the CFRP network.

Initial form finding began by the simple parameterizing of five elements (A, B, C, D, E): A: Large circle representing where air enters the structure; B: Small
rectangular section where air leaves the structure; C: The Z-distance between A & B; D: rotation angle between A & B and finally, E: A square inside A. Upon the locating of these four elements in space, A & B are bridged by a tensile membrane, and E is extruded intersecting with the conical membrane. The areas of membrane outside of E are then removed prior to physics simulation, changing the top section of the conic from a circle, to a square with four edges (A1, A2, A3, A4) arched towards B in the Z-direction.

After extracting the geometry of all edges, four joined edge membranes are created between edges A1, A2, A3, A4 and B1, B2, B3, B4 creating a revised base form. Next, the material parameters are entered into the MPanel software allowing for the membranes to find their relaxed form through simulation. At this point, parameter C can be altered creating a rotation between the top and bottom edges until the desired internal air movements are derived. The rotated membrane is then re-simulated and the final form is derived (Fig. 2 left). As the system is parameterized, the process can be repeated and simulated rapidly until a desired resultant is found in CFD analysis. Following the selection of the final form, FEA analysis can be run in the MPanel plug-in to determine CFRP placement locations during the winding process.

5.2. CORELESS WINDING

Many CFRP prototypes were tested throughout the design process, but final winding was completed through the fabrication of a modular, plug & play steel framework consisting of the same A, B, C parameters used in the form generation process (Fig. 2 left). The frame was built of 1.5” welded square tube sections with a series of ¼” holes spaced 1” O.C. on the members Z-axis surfaces. Each of the holes represented a potential winding point where either a steel eyelet or vertical spacer with eyelet could be placed. The Z-axis members were also constructed as a bolt-on system allowing for the creation of the vertically arched A elements as well as allowing for various Z-heights to be achieved with the same formwork.

For winding, the simulated tensile membrane was broken down into a series of 16 (A1-A8 & B1-B8) rotated points in space, from which the CFRP network would be wound. Odd numbers all represented edges whereas even numbers referred to the center of the arched member. As the winding of the main form only touched the frame at 16 points, the arched edges of A and the rectangular edges of B, necessary for the attachment of the Dyneema skin were fabricated separately. Edges A & B were fabricated by braiding ten strands of 24k tow into a single CFRP cable. Arched edge A was fabricated in four pieces by measuring the lengths of each computed arch, and firing them in the kiln as an unweighted catenary cable hung from their calculated end points. Rectangular edge B simply required the wrapping of a continuous CFRP cable around the eight eyelets on the B-frame.

Winding took place in a series of alternating stages, each being applied with roughly 10 lbs. of force. CFRP tow was first wound a CW (clockwise) direction moving from point B1>A2>B2>A3>B3>A4 and so on until the winding reached back to the origin point B1. At this point the winding would reverse, follow the same logic in a CCW (counter-clockwise) direction until again reaching B1. Upon completing a full rotation, winding would restart in the CW direction now
moving from B1>A3>B2>A4>B3 etc., again repeating in the CCW direction upon reaching B1. The shifting of each subsequent layer increases pressure within the tensile network moving the systems from a series of independent cables into a membrane like system. This process was continued, skipping one number farther each pass for a total of eight passes (Fig. 2 right).

Initial prototypes were created purely though the winding of CFRP tow in pure tension. Although successful, it was found in early prototypes that this methodology used more material then desired and had higher levels of inherent error. As each layer of tensioned CFRP was added to the system, an uncontrollable level of loosening would appear in the initially wound layers, creating a condition where the initial 2-3 layers had little to no structural integrity. To avoid this loosening, and simultaneously reduce structural weight, a reusable, pretension system was developed using small gauge steel cable and/or non-stretch string.

Rather than winding eight layers of CFRP to get the desired formal/structural properties, the first four layers were wound using a removable tensile substrate (Fig. 3 left & center). Following the previous winding scenario, the first four layers were wound using 1/16” steel cable secured to the frame through turnbuckles. Following the cable winding, the turnbuckles were tightened minimizing the chance of cable slippage during the CFRP winding process. Additionally, by winding cables first, the desired form of the structure was predefined in a material that would not slide out of shape as tension was added to the system. Following the completing of the temporary cable network, the final four layers of CFRP were wound moving from B1>A4>B2>A5>B3 etc. while repeating the same process as previously described.

Following winding, each structure was fired in a large kiln at a temperature of 260°F for four hours with two hours of temperature ramp up/down times. Post curing, the members of the steel framework are simply unbolted and the CFRP frame can be easily removed from the eyelets and reset for the next prototype. The four prototypes, with their high levels of programmed flexibility at the wide ends, were nested inside each other and bent inward into a single 18” diameter
box for shipping. Upon arriving in Costa Rica, the prototypes were taken out of the box where they immediately assumed their pre-bent shape. For the initial 1/4th scale testing in Costa Rica, the CFRP structure, the A & B edges and the Dyneema frame are simply attached via zip ties and industrial strength Dyneema fabric welding tape.

Figure 3. Left: early prototype with sacrificial formwork. Center: Wound prototype in kiln. Right: Complete structure 2 of 4.

5.3. RESULTS AND CONCLUSIONS

Unlike the initial cored prototypes, the coreless prototypes showed potential in several areas: Although less structurally ridged than their cored counterparts, they created no construction waste, were far more materially efficient, were extremely easy to fabricate consisting of only four elements (i.e. the coreless frame, the arched “A” edges, the rectangular “B” edges, and the Dyneema fabric skin), while also showing the ability to program flexibility in certain areas of the structure that could be simply reinforced by the attached skin system (Fig. 4). Upon testing in the cloud forest, the structure showed good potential in dealing with the high wind loads being applied, as the CFRP could flex and adapt based on the amount of flow passing through the structure (Fig. 3 left). A slight delamination of layers was noticed in several areas after the week of intense testing and will need to be reevaluated and tested in during the winding process. Inconsistencies in the process could also be eliminated through the automation of the winding process. Additionally, more research is needed in the scaling up of the project to full-scale and in the translating the knowledge learned in cloudMAGNET into the architectural scale project Dinner4Six.

Although more research is necessary in moving flexible coreless winding before it is feasible at the scale of architecture, the CFRP frames in conjunction with the PCM impregnated Dyneema frames in cloudMAGNET showed good potential in how architectural forms, fabrication and assembly processes can be reimagined and simplified.
Figure 4. Sampling of coreless wound prototypes.

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References


