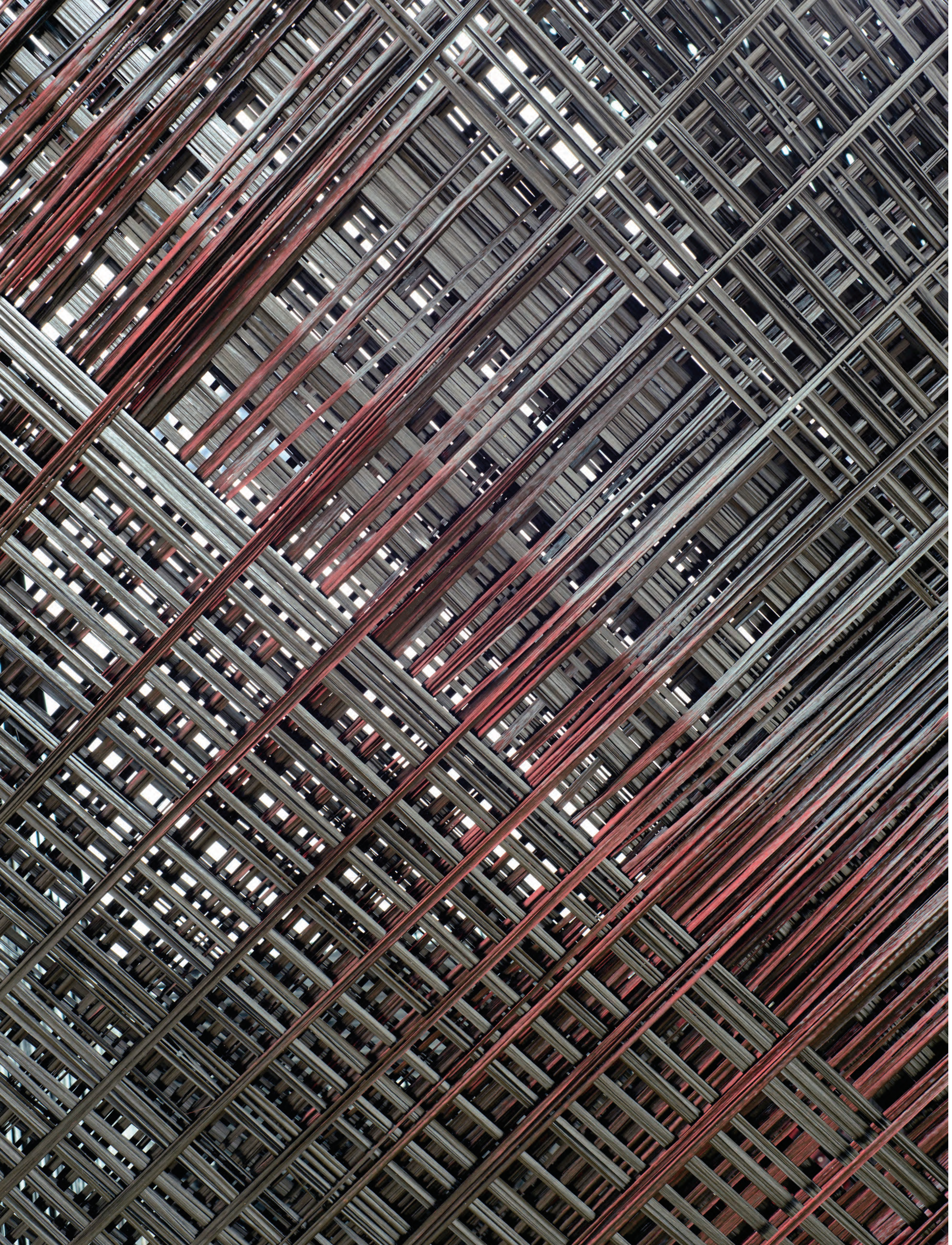


Craft-Based CFRP Systems for Rapidly Deployable Architectures

Andrew John Wit
Assistant Professor, Division of Architecture and Environmental Design, Tyler School of Art, Temple University
Cofounder, WITO* Laboratory for Intelligent Environments

Mariana Ibañez
Assistant Professor, Massachusetts Institute of Technology School of Architecture and Planning
Principal, Ibañez Kim

Simon Kim
Associate Professor, University of Pennsylvania School of Design
Principal, Ibañez Kim

INTRODUCTION

Carbon fiber reinforced polymer (CFRP) is revolutionizing the ways in which automotive, aviation, marine, and product designers think about the design and production processes. CFRP's high strength-to-weight ratio, its material/structural efficiencies in design and fabrication, and its ease and accuracy of application through robotic fiber placement or hand winding/layering, as well as its ability to be fashioned into complex yet repeatable geometries, have opened up new possibilities for solving previously complex design and engineering problems. Although these traits make CFRP a more than interesting choice for utilization within the discipline of architectural design, current industrial processes for the placement of CFRP put emphasis not on the finished artifacts' visual, tactile, and sensory-based possibilities that could be exploited through the utilization of this new material, but rather, solely on the production of optimized shells and easily repeatable forms. Unlike fields such as aviation, automotive, and marine design, where products are mass-produced to have identical dimensions, structural properties, and appearance, architecture requires the freedom and flexibility to seamlessly alter individual building elements or the design as a whole on a project-by-project basis. For this reason, this paper questions current methodologies of building construction and proposes a system for rapidly deployable architectures constructed by hand and/or robotic craft-based CFRP tow placement methodologies.

Through the lens of the recently completed project *rolyPOLY* (figs. 1 and 2), this paper examines the benefits native to CFRP in the context of architecture while being applied and evaluated through the artifact's optical, structural, functional, sensorial, and tactile merits.

CONTEXT

The craft of building is a complex process. Even small detached buildings such as single family homes similar to the Sekisui Heim prefabricated home system can require tens of thousands of individualized elements from a parts lists of over several hundred thousand (±30,000 individual elements of 300,000 possible in the Sekisui Heim system).[1] This level of complexity in fabrication and assembly not only requires vast amounts of time, precision, and infrastructure, but also limits the

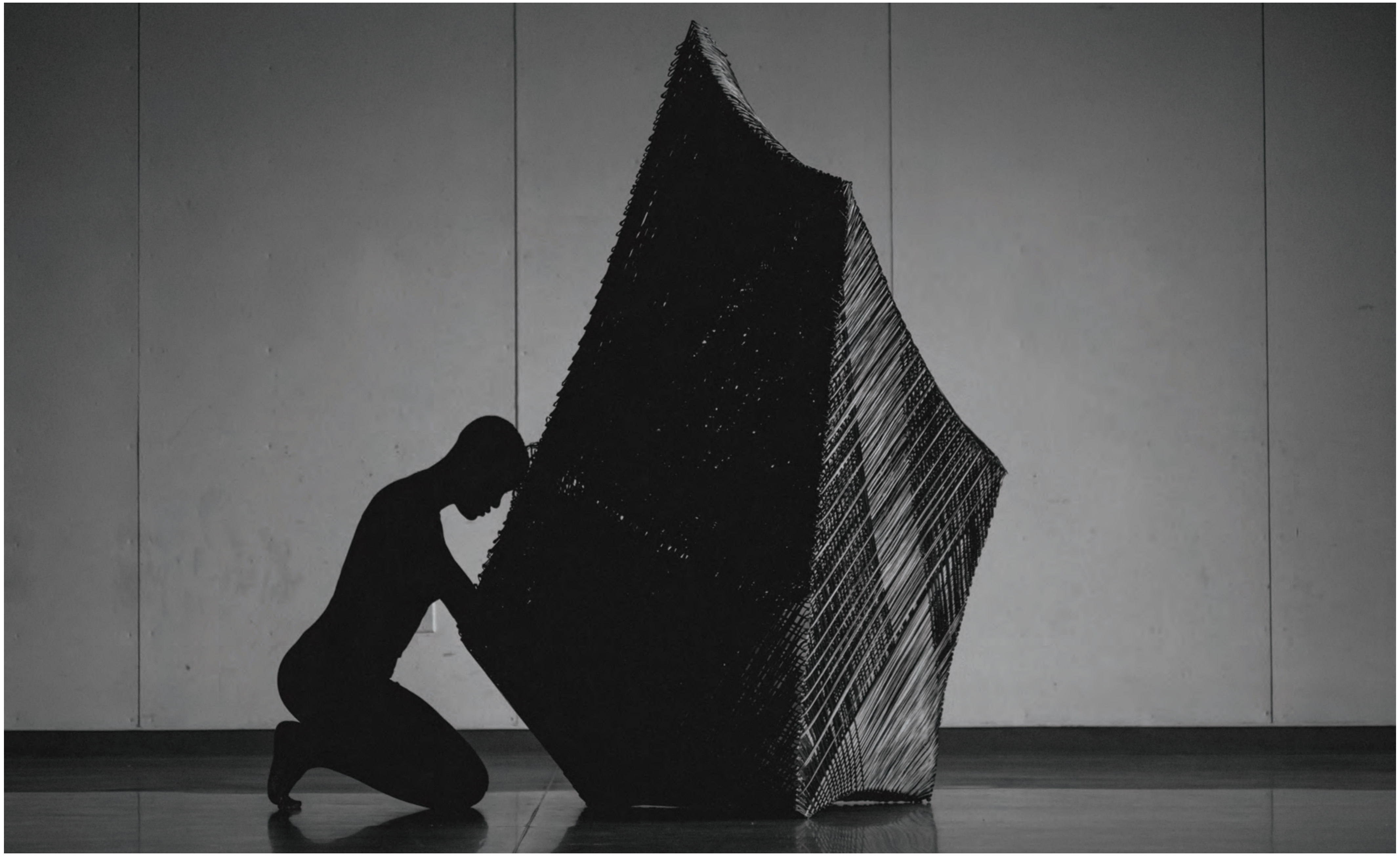


Figure 1: rolyPOLY Confessional

formal, spatial, sensorial, and craft-based possibilities within the system, as most design variations have been envisioned from the onset of the systems creation. In addition to limitations within the design process, vast amounts of construction waste (roughly ±8,000 lbs. per 2,000 sq. ft. house in the U.S. as of 2014)[2] are created through the use of non-reusable formworks, inefficient construction methodologies, and standardized materials that must be reshaped to fit the desired building composition. Rather than optimizing current outdated fabrication and material systems, this research proposes the creation of novel design and fabrication systems built upon a pallet of flexible and integrated material systems, which not only increases material efficiency and design possibilities, but also reduces complexities associated with complex fabrication through the minimization of infrastructure and parts. Additionally, this research aims to seamlessly introduce the potential for embedded, "active" building systems which create sensate environments, adapting both geometrically and digitally to the inhabitants and their surrounding environment.

CFRP

Recently, CFRP has been becoming increasingly relevant within the discourse of architectural design research and fabrication, as seen in recent projects such as the "RV" Prototype (Greg Lynn, 2012), the 2012, 2013–14, and 2014–2015 research pavilions by the ICD + ITKE Institutes at the University of Stuttgart (Knippers, Menges), C-Lith, created at the University of Michigan in 2014 (Trandafirescu + Wilcox), and the 2014 Fiberwave pavilion completed at the IIT (Peluso). This growing number of projects has been aided in part by the emergence of more novel tools for the rapid simulation of, and computing for, the robotic placement of CFRP tow systems. Additionally, CFRP's increasing global availability and sinking cost has also allowed for a wider examination of its use within the architectural and surrounding discourses. But to better appreciate how CFRP and similar materials can fit into the design discourse, we must first put aside our current preconceptions of how buildings "should" look and go together, and reevaluate these systems in the context of this novel, formless building material. To initiate this process, we must first gain a more robust understanding of the material itself, as well as its innate strengths and weaknesses (fig. 3).

CFRP can be constructed from a variety of different polymer matrices (epoxy, vinylester, polyester thermosetting plastic, as well as several others) that are reinforced by strands of carbon fiber.[3] Variables within the system, such as resin type and/or content (ratio of resin to carbon), strand count, and fiber orientation, as well as winding, weaving, and layering patterns, can all be utilized as a means to customize the material's structural and formal characteristics to make it more project-specific.

Additionally, resin systems can be applied as wet (i.e. directly applying to the carbon fiber at the time of fabrication) or pre-impregnated (resin applied before fabrication). Although wet applications can be desirable because of their potential to be cured without the use of a kiln if hardeners are added, maintaining a consistent resin content, clean/safe working environments, and the minimization of material waste (as the resin will have a short working timeline) can be difficult. On the other hand, custom ordered, industrially manufactured pre-impregnated (i.e. pre-preg) CFRP can ensure a high level of resin and fiber consistency and stability. Additionally, they can be extremely easy to work and handle, while also potentially having working times of days or weeks and shelf lives of months or years, but in exchange require "baking" in a constant temperature for a specified duration of time. The following research examined both hand and robotic craft-based coreless winding through the utilization of low-temperature curing (four hours at 260°F), epoxy pre-impregnated, 12K (i.e. 12,000 strand), 24K, and 50K CFRP tow.

rolyPOLY

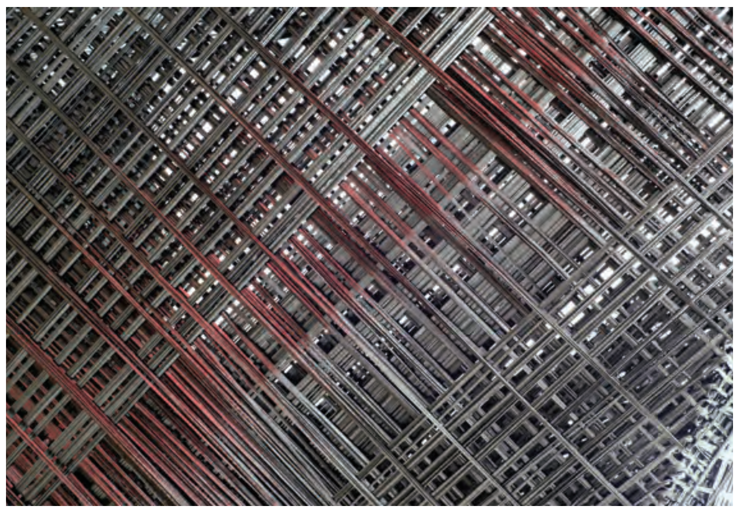
rolyPOLY followed a lineage of small-scale hand and robotically wound prototypes focused around the implementation of pre-impregnated CFRP tow into the larger architectural workflow introduced for the "One Day House" initiative completed at Ball State University in the Spring of 2015 (Wit et al. 2016). Developed as the initiative's first occupiable, large-scale prototype (fig. 4), this project was also designed as a traveling exhibition currently on display at the Tyler School of Art and slated for display in the *Beyond the Horizon* exhibition at the

Figure 2: Conceptual Diagram of rolyPOLY's Tumbling

Philadelphia Museum of Art in 2017. Designed for a single occupant, the artifact can be occupied in all orientations while remaining structural. As an aggregating system, additional modules can also be linked to create larger, more complex volumetric, occupiable spaces. Additionally, the project acts as an active site for personal and communal interaction through the integration of a system of embedded sensors and actuators that offer unique, interactive singular or collective experiences.

Whereas initial studies were focused around the programming and simulation of robotic winding, composite-based form-finding, and obtaining high levels of structural/material efficiency achievable through utilization of CFRP in conjunction with coreless winding, the goal of *rolyPOLY* was to move beyond form and structure. The greater purpose was to explore the potential for the creation of new repertoires and typologies of visual, tactile, and sensorial complexity possible with CFRP tow that would be difficult, if not impossible, to replicate through the use of typical off-the-shelf building materials (fig. 5). To accomplish this, emphasis was not given to the artifact's initial formal potentials. Rather, the complex formal and tactile attributes were allowed to emerge through the material's inherent properties and tendencies during the winding process.

Figure 3: rolyPOLY CFRP Winding Detail



Formally based on an 11-sided sphenoid hendecahedron primitive, *rolyPOLY* has an occupiable interior volume of 7' x 4.5' x 4.5' (at the time limited by resin type and the institute's largest kiln), weights a minimal 20 pounds, is constructed of over 100,000 linear feet of 12K pre-impregnated CFRP with a resin content of ±27.51%, and required roughly 24 hours of hand winding to complete. The design and fabrication process were straightforward and consisted of nine interconnected stages:

1. Initial form finding
2. Form relaxation
3. Edge extraction
4. Reusable/reconfigurable frame/gripper design
5. Digital fabrication and assembly of removable/reusable steel frame
6. Winding pattern design and of CFRP around frame
7. Baking
8. Frame extracting
9. Integrating interactive systems

As overall form was not central to this study, a base primitive was chosen as the projects starting point. The sphenoid hendecahedron was chosen because it allows for a high level of formal variation along all faces. As each face is unique, it allowed for a variety of occupiable orientations to emerge, and for the potential for high levels of structural and tactile adaptability.

When working with CFRP tow, it was essential to create high levels of internal layer compression in order to minimize delamination during the winding process. To combat this problem, traditional methods of CFRP placement rely on systems such as a ridged core in which tow is wound over, or by placing the part in a compressive mold or vacuum bags, which helps facilitate layer compression during the curing process. As coreless winding utilizes neither, it was necessary to produce the appropriate compressive forces by another means. Rather than introducing an external force or secondary material, rolyPOLY and subsequent prototypes utilized the natural tendency for CFRP tow to act similar to a fabric membrane when in tension when wound. To facilitate this process, it was necessary for all flat surfaces to be transformed into doubly curved surfaces. All straight perimeter edges of the artifact were relaxed as tensile cables under a gravitational loading in the MPanel software. This edge relaxation allowed for the formation of tensioned doubly curved surfaces with high levels of internal compression as the CFRP tow was wound across each panel face.

Upon the completion of edge relaxation, the new edge curves were extracted, converted into individual tensile panels and relaxed as a tensile membrane under tension. Two of the eleven sides were left open to allow for accessibility and for the addition of interactive systems. To compensate for unexpected deviations during the winding process, each new tensile panel was also slightly inflated by 10%.

Following the completion of the new relaxed form, the edges were extracted to create a rapidly deployable frame. The frame consisted of three parts (fig. 6):

1. A welded 1/4" round bar steel frame
2. Bent-in-place 1/8" plywood CFRP grippers
3. Standard conduit hangers

The frame consisted of eight individual panels. Each panel was individually bent, trimmed, and finally welded together. Following this, each panel was joined together through the use of standard conduit hangers. Each edge required a minimum of three conduit hangers and additional round bar blanks, which minimized rotation in the frame during winding. The CFRP grippers were designed with 1/8" "teeth" which matched the width of the 12K CFRP, then laser cut in 4' strips from 1/8" plywood. Following the assembly of the eight panels, the CFRP grippers were bent in place and attached to the frame via conduit hangers. Each CFRP gripper was oriented perpendicular to its two intersecting panels.

Following the fabrication of the frame, the winding of CFRP commenced. Winding was the most important aspect of the research and occupied the longest portion of the design and fabrication process. Aspiring to create new typologies of tactile/structural surfaces, winding studies looked at geometrically generated, as well as randomly generated, winding methodologies (fig. 7). From pattern and density to thickness and moiré, these studies explored not only the skin's design, but also how light, sound, and robotic systems could interact and be embedded. Through the craft of hand winding, each potential pattern was tested, edited, and combined to create rolyPOLY's final affect. Just as each of the eight wound panels are geometrically unique, so are their winding patterns and their visual, tactile, and sensorial affects. Following pattern design and testing, the final winding process was initiated and consisted of three distinct winding typologies:[4]

1. Peak winding
2. Valley winding
3. Spiral winding

The utilization of these three techniques ensured the robust winding of the artifact, and they are further discussed in the below listed paper. Following the completion of the winding process, *rolyPOLY* was placed in a

Figure 4: rolyPOLY on Display at the Tyler School of Art

large kiln and fired at 260°F for four hours. In addition, the artifact was left in the kiln during the ramp-up and ramp-down times, allowing for a consistent raising and lowering of internal temperatures. After re-acclimating to room temperature, *rolyPOLY* was removed from the kiln, and the internal frame was effortlessly removed by unbolting the frame and sliding the individual element out through the two open panels. Because the system is completely collapsible, demounting created no waste, and the frame could be easily reconfigured for the fabrication of the next module.

Figure 5: rolyPOLY Visual, Tactile, and Sensorial

THE CONFESSIONAL

Upon completion of the monocoque shell, the artifact was ready for occupation. To further enhance the unique atmosphere created by the craft-based winding, a responsive system was designed and integrated into the project's skin. Run by Arduino controllers, sensors, accelerometers, and microphones were embedded to collect data and interact with the occupant in real time through sound and light. Titled the *Confessional*, the final system consisted of the installation of soft, stretched tensile skins clasped to the two open panels in *rolyPOLY* and directly linked to the integrated sensor-based system.

Stitched into the nylon are sensors to allow for the interaction with the human occupant. The *Confessional* responds to sound, through the integration of a microphone that transmits sound, and to touch, through embedded accelerometers. Recorded by a microprocessor, the signal is processed and can be sent to any output device. In this case, LEDs were utilized, translating sound into light (fig. 8).

The purpose of the interaction is a critical one: with the ubiquity of sensor technologies and the interest in architecture as a sensate environment, this new media must turn toward meaningful personal and communal interaction. Much of architecture—as a dynamic

Figure 6: rolyPOLY Frame/CFRP Winding Detail

space—is given over to a certain "building technologies" mentality that focuses on human comfort while losing human culture. The goal of the interactive skin is to locate a response behavior based on cybernetic theories of the postwar. Rather than placing human-machine relationships as a human-centric hierarchy, Gordon Pask and Nicholas Negroponte created a more fluid interchange in which human and nonhuman agents were working in a collective endeavor.

In this capacity, the stretched membrane may hold any number of sensors and actuators that offer a singular or a collective experience. For future development, flex sensors may be woven in the tensile surface to measure push/pull on the membrane. Motion sensors, accelerometers, and microphones would create a live environment for the occupant of lights and sound. Conversely, the modules may also be networked with each other so that messages or communiques may be transferred from one module to another.

With *rolyPOLY*, what was quickly discovered is the need for personal and sociable aspects in a human space. The visual patterning that comes from unique winding patterns of CFRP becomes a personal choice of the inhabitant. The amount of responsivity and exposure to the collective interface is also a choice. As individual needs change, the *rolyPOLY* can be flipped into a different orientation from horizontal to vertical, or picked up and moved farther and closer as desired by the occupant.

CONCLUSION

Although this research is in its infancy, it shows some of the unique formal, structural, visual, tactile, and sensorial possibilities wound CFRP can offer the discipline of architecture through both hand and robotic winding. To further this research, a series of large-scale projects (*Dinner for Six*, *cloudMAGNET*, and the "One Day House" initiative) have been initiated, investigating different aspects of CFRP (i.e. structure, skin, sensorial elements, etc.) and embedded interactive systems in relationship to the discipline of architecture. By means of a collaborative think tank between WITO,* the Immersive Kinematics Group (*Project lightHOUSE*, fig. 9), Ibañez Kim, and Temple University, this research hopes to redefine how we build, think about, and interact with buildings through the creation of interactive, craft-based CFRP architectures.

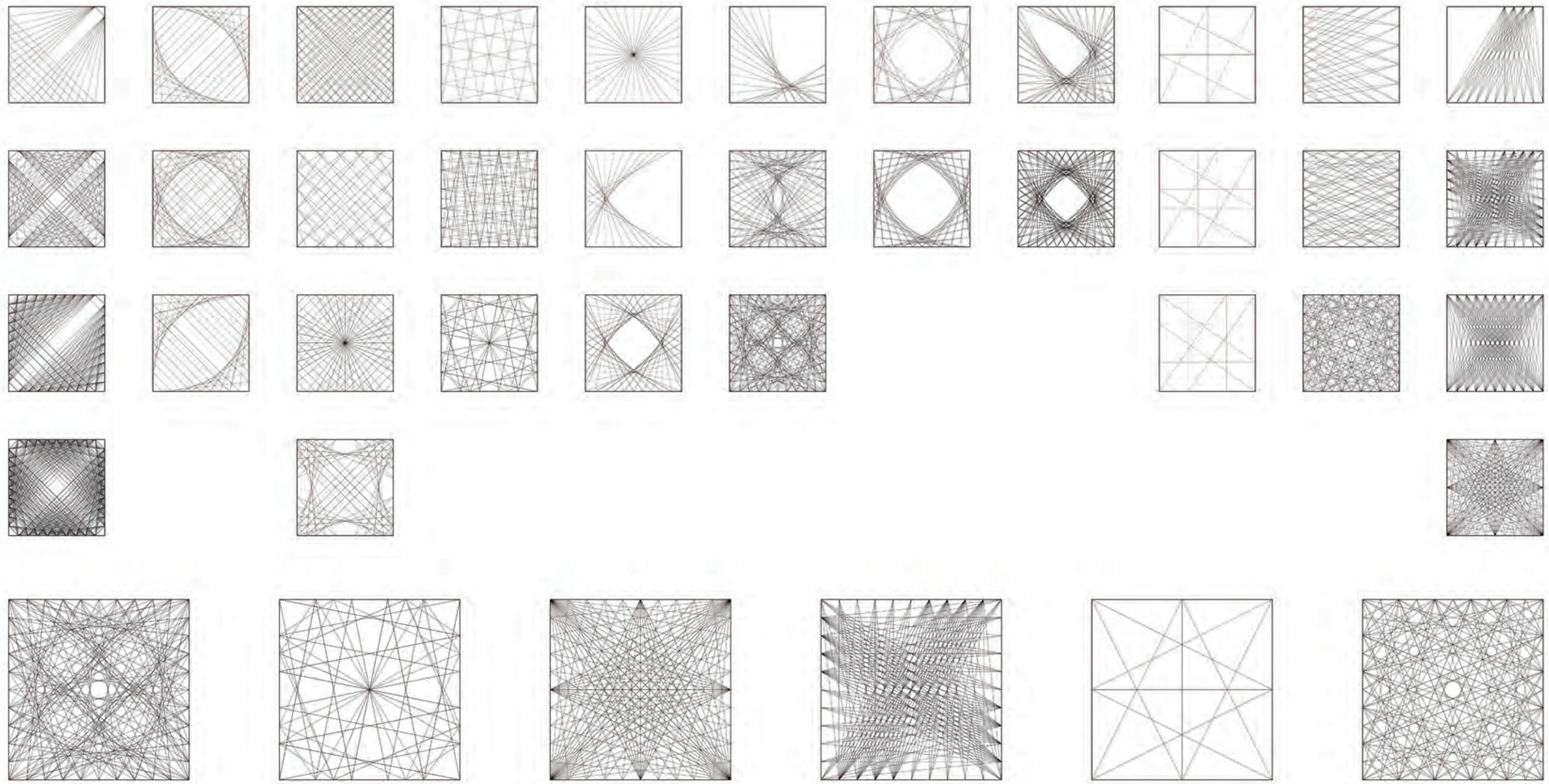


Figure 7: rolyPOLY Initial Winding Studies

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Figure 8: Interacting with the Confessional

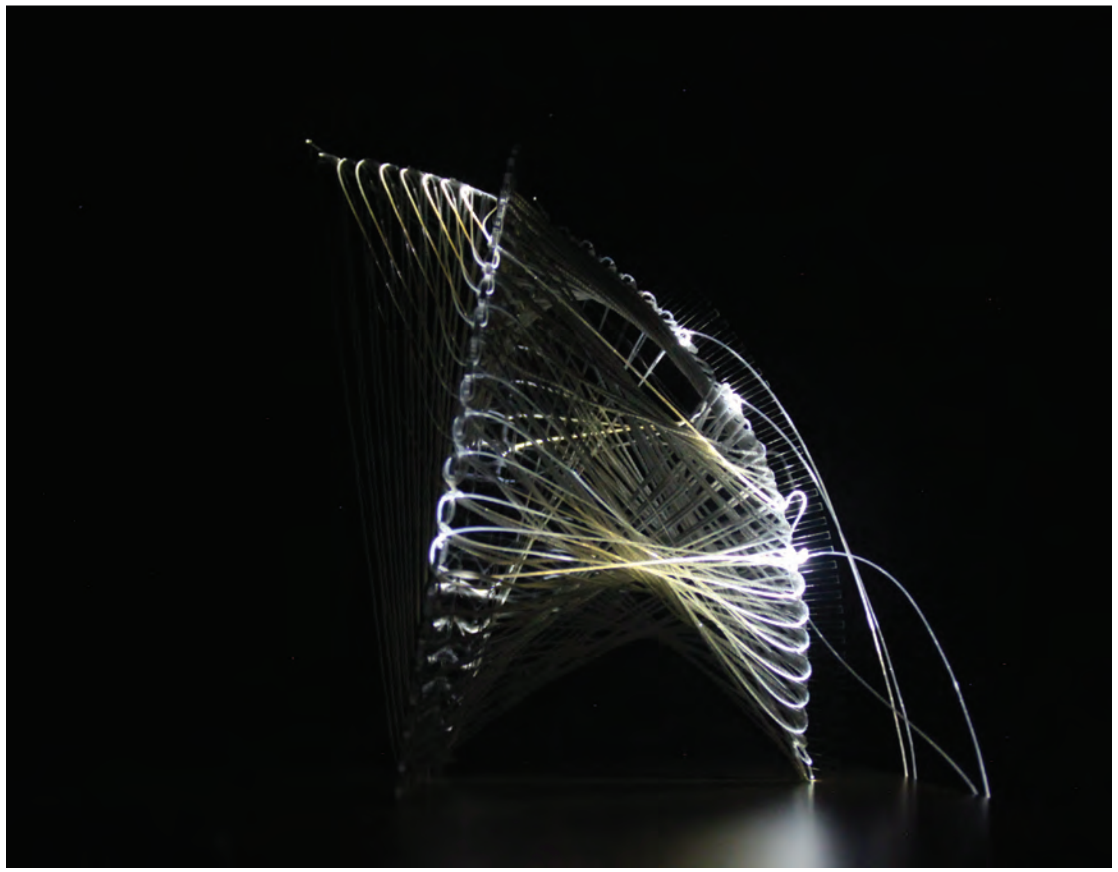

Figure 9: Project lightHOUSE Interactive CFRP Prototype

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Figure 10: rolyPOLY, Craft-Based CFRP Systems for Rapidly Deployable Architectures