Hybrid Bivouac
High-Modulus Composite Membranes for Packable Shelters

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

This thesis explores an iterative modelling and fabrication process for fibre-based composites through the design of a lightweight, portable shelter for backpacking and mountaineering. Existing tent typologies compromise either lightness or strength, leaving users to choose between lightweight and minimal enclosures that require flat, dry land upon which to be pitched or bulky and robust shelter systems that can be suspended when a ground pitch is not an option. Designers' ability to address these trade-offs with more complex solutions has been limited by the amount of time required to manufacture one-off prototypes and the cost of high-performance materials. This project demonstrates how a design process that combines computational modelling tools and low-fidelity physical prototypes can be used to optimize the flexible composite membrane of an ultralight tensile structure and increase the functional performance of subsequent high-fidelity physical prototypes. Modelling and fabrication methods from racing sail design – which rely on finite element analysis models to inform the placement of high modulus filaments – are adapted to simulate and fabricate an uncompromising and adaptive tent system. Through a fibre-based composite architecture, the application of this integrative fabrication approach can significantly improve the portability and mechanical strength of a wide range of lightweight shelters.

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisors, David Correa and Maya Przybylski, for your support in pursuing a multi-disciplinary topic. Your constructive and critical feedback in linking prototyping and material investigations to the broader field of architecture was a crucial part of this work.

Thank you to the additional faculty and staff who were a part of this journey and my committee member, Rick Andrighetti, who, despite joining the discussion later in the project, jumped in with thoughtful questions that strengthened the overall thesis.

To my friends and colleagues, thank you for sharing your process and passion for modelling, making and research. Your helpful suggestions, criticisms and edits were valuable contributions to the project.

I would like to acknowledge and thank Matthew Bruhns, who photographed the prototyping and testing process. This project would not have been the same without the addition of your compelling visuals.

And finally, thank you to my supportive family and partner, Dylan, who endured snow, wind and mosquitos while helping me rig and test prototypes. Your boundless enthusiasm for adventure outdoors is a constant source of inspiration.

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Photograph by Wolfgang Hasselmann, *Untitled*. April 16, 2020. https://unsplash.com/photos/MDzPCAcWopk.

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Image by Bruce Hamilton, *The Visual Appeal of the Tent Provided an Ideal Backdrop for One of Bucky's Many Interviews*. 1976. Personal Collection of Bruce Hamilton. https://www.outinunder.com/content/north-face-and-r-buckminster-fuller-special-connection-part-2.

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Image courtesy of the Artstor Digital Library, Otto, Frei. *German Pavilion Expo 67’*. 1967. University of Michigan Library. https://library-artstor-org.proxy.lib.uwaterloo.ca/asset/AWSS35953_35953_34203189.

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Photograph by Ingvartsen, Anders. *ISOROPIA Installation*. 2018. Photograph. https://www.archdaily.com/901729/isoropia-center-for-information-technology-and-architecture/5b95a9daf197cc72ee0002ed-isoropia-center-for-information-technology-and-architecture-photo.

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Data Source: Sendgeance. “Best Portaledge For Big Wall Climbing: Top 5 Picks in 2021,” October 29, 2020. https://sendgeance.com/best-portaledge/; Elizabeth Paashaus. “Best Hammock.” Outdoor Gear Lab (blog), April 17, 2020. https://www.outdoorgearlab.com/topics/camping-and-hiking/best-hammock; Chris Greer, Amber King, Matt Bento, and Andy Wellman. “Best Ultralight Tent of 2021.” Outdoor GearLab (blog), May 3, 2021. https://www.outdoorgearlab.com/topics/camping-and-hiking/best-ultralight-tent.

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Image by ICD/ITKE University of Stuttgart. ICD/ITKE Research Pavilion 2014-15: On-Site Robotic Fiber Placement of Reinforcement Fibers with Parallel Distribution. 2015. ArchDaily. https://www.archdaily.com/770516/icd-itke-research-pavilion-2014-15-icd-itke-university-of-stuttgart/55acefb4e58ece12db000250-icd-itke-research-pavilion-2014-15-icd-itke-university-of-stuttgart-on-site-robotic-fiber-placement-of-reinforcement-fibers-with-parallel-distribution.

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Photograph by Matthew Bruhns

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Photograph by Matthew Bruhns

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Photograph by Matthew Bruhns

Part 1
Introduction

AIM

The pursuit of lightness is present in all things that move, whether living or manufactured. The design of movable shelters is no exception. Maintaining lightness must be kept central to any portable architecture, along with the provision of a protective and durable enclosure[1]. However, these requirements are often at odds in a world where structural redundancy and an overall lack of material efficiency are commonly practiced. The most prolific typology for portable buildings, the tent structure, has been continually employed throughout history, but very little has changed over the last several decades in how these widely-used shelters have been designed and manufactured. This thesis attempts to evolve this typology by adapting progressive design and material practices from adjacent industries (mainly flexible composites technology) and applying them to the design of a small portable architecture. In parallel to the central technological exploration, this thesis explores the role of complex modelling methodologies in the conceptual development of dynamic membrane structures.

RELEVANCE

Portable shelters have played a key role in the global evolution of architecture. The first human-conceived shelters were the products of a need to migrate rather than the static occupation of a site.[2] These proto-architectures were produced to address changing

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[1] Zuk and Clark, *Kinetic Architecture*, 27.

[2] Kronenburg, *Architecture in Motion*, 15.

FIG 1.01 *Previous page:* Rendering of an early iteration of the Hybrid Bivouac tent design.

conditions like food availability and climate. Only later in societal evolution did human-built shelters become permanent.[3] Despite the eventual shift to the immovable architectures that now make up most of our modern environment, we still depend on portable enclosures in times of transition, crisis, celebration, and exploration to create rapidly available housing, hospitals, event spaces and work facilities.

From the woven canopies of Bedouin black tents to the retractable membrane roofs of modern sports stadiums, movable architecture relies on lightweight textile enclosures[4]. The characteristic of lightness is crucial to portability in that it reduces the amount of work required to erect and move the shelter and the resources required to construct it. Equally important is the inherent pliability of a textile membrane, enabling it to be folded, rolled, or compressed when it is not deployed. This quality allows assembled enclosures to be packed and transported in their entirety, creating an instantly continuous environmental barrier upon erection. However, in the current paradigm of lightweight textile enclosures, this layer's pliability and lightness have a negative relationship with durability, strength, and modulus, leading to the general strategy of offloading the tensile capacity of the enclosure to the supporting structure or a secondary cable network system. This paradigm has led to the stagnation of textile enclosure technology, with designs resigned to the assumption that the membrane performs the sole function of a homogeneous environmental barrier, despite the potential for greater structural efficiency.

In nature, "shape is cheaper than material" [5], meaning that the logic of an organism's evolution is predisposed to assign geometric complexity before allocating more energy-intensive material to achieve a biological function. A stunning example of this can be seen in a spider's web. These wispy structures are biologically designed for a high level of tensile efficiency while maintaining the pliability

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[3] Hinte and Beukers, *Lightness*, 12.

[4] Yousufi, "Fabric Structures," 11–12.

[5] Vincent, "Smart by Nature," 44.

FIG 1.02 A temporary tent hospital was erected in Central Park during the Covid-19 pandemic in 2020.

FIG 1.03 The portable black goat hair tents of Bedouin nomads provide shade from the harsh sun of the desert and protection from cold winds in cooler seasons.

needed to adapt to the movement of objects and environments to which they are tethered. In a silkworm cocoon, the matrix of silk strands acts as an integrated tensile structure and enclosure.[6] To build redundancy into these systems would require the expenditure of precious energy of which these organisms have none to spare. Unlike the building methods of humans, wastefulness is not a part of the natural world's building vocabulary. However, we can learn from this practice of material efficiency and apply it to new design methods and the fabrication of lightweight, portable structures.

FIG 1.04 Spiders spin webs that are both strong and resiliant.

SCOPE

Like the late 20th century architects Frei Otto and Buckminster Fuller, pioneers in lightweight construction have periodically engaged in the development of small portable structures as a means of focusing and expanding their architectural ideas. In the 1970s, for example, Fuller became popular in the mountaineering community for his participation in developing the iconic expedition dome tent manufactured by outdoor brand The North Face.[7] A few years later, Otto also collaborated on the development of an adaptable frame tent structure to be used on steep mountainsides in Saudi Arabia during pilgrimages to the Valley of Muna.[8] Following this tradition of cross-disciplinary engagement, the typological focus of this thesis is the design of a single-occupant enclosure for multi-day endurance sports like backpacking and mountaineering. This scope provides a narrow view on the requirement for lightness, focusing on the issues of portability and adaptability with respect to site.

FIG 1.05 A silkworm lays out its silk to reinforce the fiberous scaffold of the Silk Pavilion installation by the Meditated Matter Group.

Building on the principles of lightness and portability, this project's framework is defined by the following three areas: material investigation, functional testing, and complex modelling. These three topics are not independent of each other but, instead, represent different ambitions in this work.

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[6] Oxman et al., "Silk Pavilion."

[7] Bruce Hamilton, "The North Face and R. Buckminster Fuller."

[8] Meissner and Möller, *Frei Otto*, 41.

FIG 1.06 Frei Otto and Rashid Engineering designed a tent for the steep mountainsides of the Muna Valley.

FIG 1.07 Buckminster Fuller and the dome tent inspired by his architectural ideas at the UN Conference for Human Settlement, Vancouver, 1976.

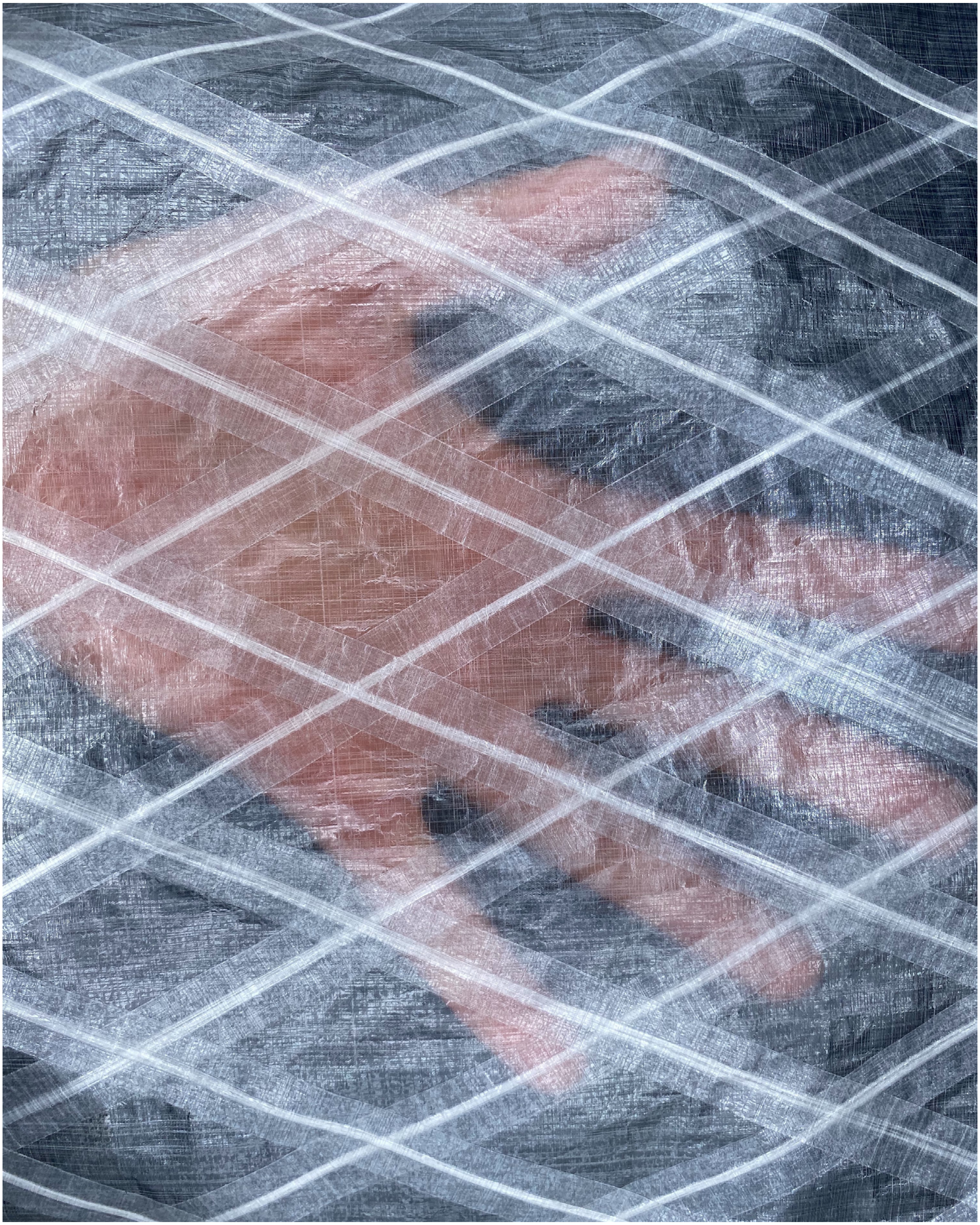

FIG 1.08 Investigation of high-modulus composite materials through prototyping.

The first area, material investigation, is a technology-focused exploration of flexible material composites that enable an optimized membrane system. By leveraging the increasing accessibility of lightweight *high-modulus materials* (high resistance to elastic deformation[9]), this thesis seeks to generate a material syntax that reflects the complex efficiency of natural structures, allowing the membrane to play a greater role in the structure of fabric architecture. The second lens through which to view this work is the functional testing and application of the material technology to a user's need, in this case, adaptable and lightweight shelters for backpacking and mountaineering. This application shares many of the same goals as larger portable architectures, like lightness, portability, and ease of construction, but enables prototyping and testing at a more accessible scale. Finally, material investigation and functional testing are connected through modelling practices that aim to incorporate the performance of materials and functional requirements into a set of physical and digital modelling workflows. As this proposed system is *form-active*, meaning that it derives its formal tectonics from the forces that are being imposed on it, experimentation and simulation are crucial to the design development process.

The ongoing movement in open-source information and technology has equipped designers and architects with increasing access to tools and material resources previously associated with the technical expertise of engineers and manufacturing specialists. Through the cycles of exploration described in this thesis, a scalable and multi-disciplinary methodology for the design of functional and dynamic products and buildings was used.

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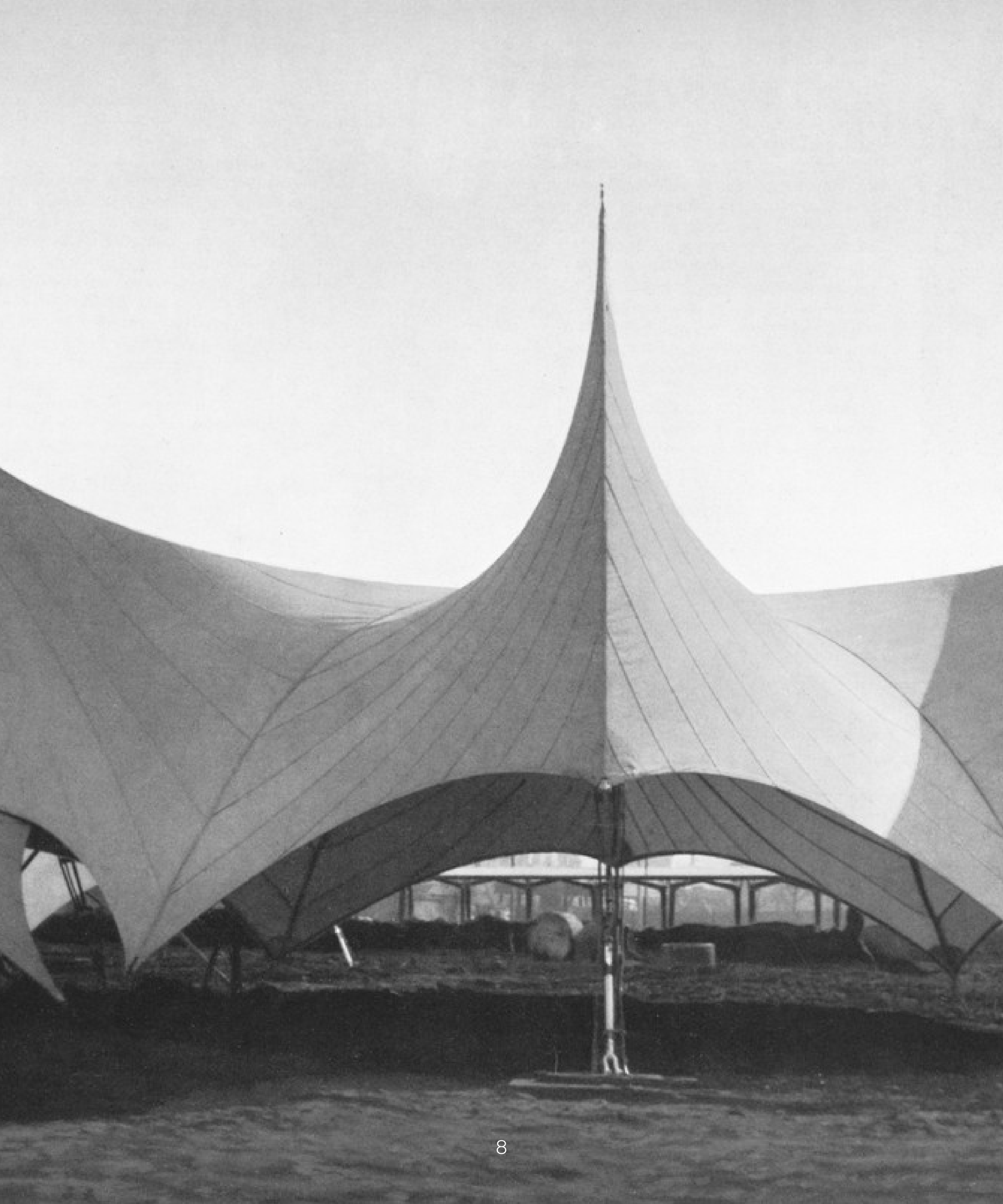
[9] Tortora and Merkel, “Modulus,” 364.



Part 2

Context and Precedent

THE TENT ARCHITECT

It would be near impossible to discuss the merits of membrane structures without referencing the works and accomplishments of the architect and structural engineer Frei Otto. Early in his career, Otto became known for his significant contributions to lightweight and innovative architectural structures. Prior to his architectural education, Frei Otto's fascination with efficient tent structures was set in motion at a prisoner of war camp in France, where the former foot soldier preoccupied himself with the task of creating shelters, with a limited supply of materials, acting as the camp's architect.[1] Following the war, Otto continued to focus on lightweight and economical structures, completing a formal education in architecture and, later, civil engineering.

One of the many legacies of Frei Otto's work was his commitment to physical modelling experiments. He used this practice of model making to better understand the structures he pioneered, many of which were based on forms found in nature like bubbles, cellular structures, and spider webs.[2] Otto's models used tensioned cables, meshes, and soap films to generate flowing geometries, which served as the structural proof of concept for his built architecture.[3] This methodology was unique in that it built on physics phenomena to maintain the efficiency of a design through a *form-active* system,

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[1] "Biography: Frei Otto."

[2] Meissner and Möller, *Frei Otto*, 101.

[3] Otto, *Frei Otto*.

in which there is a reciprocal relationship between structure and form.

FIG 2.01 *Previous page:* The complex curves of Frei Otto's tent architecture.

COMPUTATIONAL DESIGN TOOLS

In the last few decades, computational models have replaced physical models in approximating the physical behaviour and unique topological conditions of complex tensile structures. Although physical models still play an important role in form-finding, the speed at which computational models allow for rapid iteration has made experimentation with tensile membrane structures far more accessible than in the early days of Frei Otto's practice. In conjunction with the value of rapid iteration, digital models can be developed with associative relationships between design parameters. This inter-relation allows for individual parameters of the design or simulation (like base geometry or material performance properties) to be edited without rebuilding the entire model. Within the parametric modelling pipeline, parts of the creative process can be assisted through the use of *generative design* tools, which employ constraint-based algorithms, called *solvers*, to iterate geometries based on the procedural inputs.[4]

Complex modelling pipelines are being tested and documented within academic institutions like the Centre for Information Technology (CITA) at the Royal Danish Academy through exploratory projects and installations. One example of this work is *Isoropia,* a form-active installation for the Danish Pavilion at the 2011 Venice Biennale. This project combined physical modelling practices with a variety of parametric design tools to generate, simulate, and refine a dynamic canopy structure comprised of a tensioned knit membrane, steel cables, and flexible fibreglass poles. In this hybridized structure, the form was dependant on the reciprocal interaction between both membrane, poles and their respective material properties. As a result, the project's modelling pipeline echoed the dynamic nature of the work by using both precise and freeform manipulation tools.[5]

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[4] Stasiuk, "Design Modeling Terminology," 5.

[5] La Magna et al., "Isoropia."

FIG 2.02 To validate and test the structural design for the German Pavilion at Expo '67, a full-scale prototype was constructed at the University of Stuttgart.

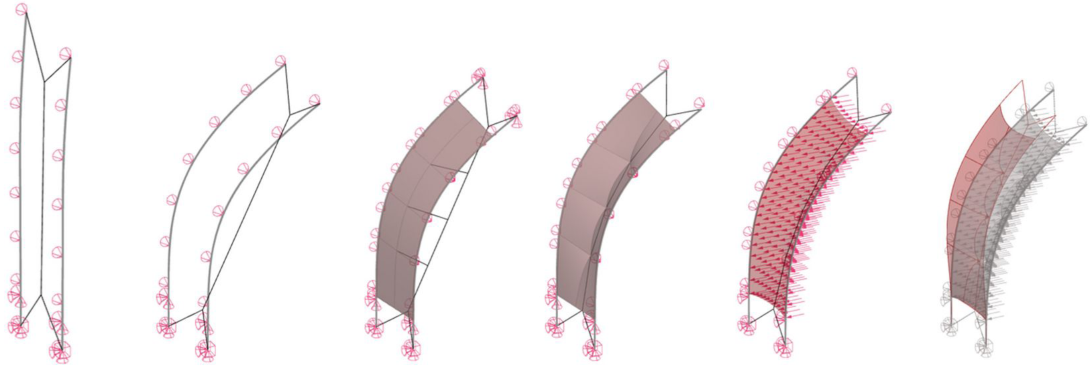


FIG 2.03 Simulation steps in the form development of *Isoropia* using parametric modelling tools.

EMBEDDED FIBRE ARCHITECTURE

Unlike the *Isoropia* installation, the architecture of Frei Otto relied on the assumption that the membrane was *isotropic* (homogenous in its tensile performance), thus offloading the true tensile work to a secondary cable system. The work by CITA takes the tensile membrane structure one step further by engineering the membrane by adding strength and material to the knit structure where stress occurs within the fabric, leading to a reduction in cable elements and structural redundancy.

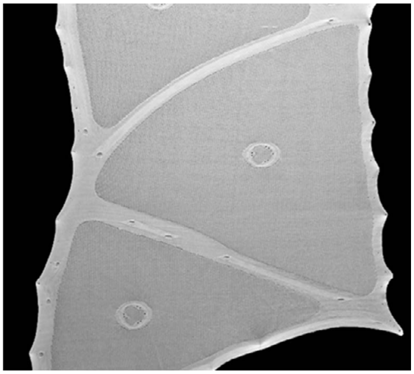


FIG 2.04 CNC knit panels from the *Isoropia* installation showing a reinforced knit structure in regions that will experience greater stress.

This hybridization of cables and membrane gives way to advances in lightweight construction that other commercial industries have benefited from for decades. The competitive world of America's Cup racing yachts has proven to be a particularly fertile ground for innovations in lightness.[6] Aerodynamics aside, lighter ships require less work to move forward. With this fact widely understood, no expense has been spared in finding new ways to tune the strength to weight ratio of the vessel, especially when it comes to the sails. Like membrane roof systems, sails are pliable and need to withstand changing loading. The weight of high-performance sails is reduced by arranging strands of high modulus materials within the sail composite. This fibre architecture efficiently directs stress within the sail to the mast and boom connection points without adding bulk to the entire membrane surface.[7] Computational models that predict and graphically map forces and stresses within the membrane are required to inform the specific placement of these filaments. This modelling process is called *Finite Element Analysis* (FEA). Wind speed and direction and membrane material properties are inputted into these FEA models, and the deformed sail (and various mappings of membrane behaviours like stress and strain) are provided as outputs. The insights gained in this process serve as a guide for where additional reinforcing is required, reducing the need for extensive empirical testing and expensive prototypes.

[6] Marsh, "America's Cup — Pushing Materials to Their Limits."

[7] Pearson, "Textiles to Composites: 3D Moulding and Automated Fibre Placement for Flexible Membranes," 313.

FIG 2.05 Otto's architecture relied on steel cables to carry most of the tensile loads.

FIG 2.06 The Venice Bienale installation *Isoropia* by the Centre for Information Technology and Architecture at The Royal Danish Academy of Fine Arts.

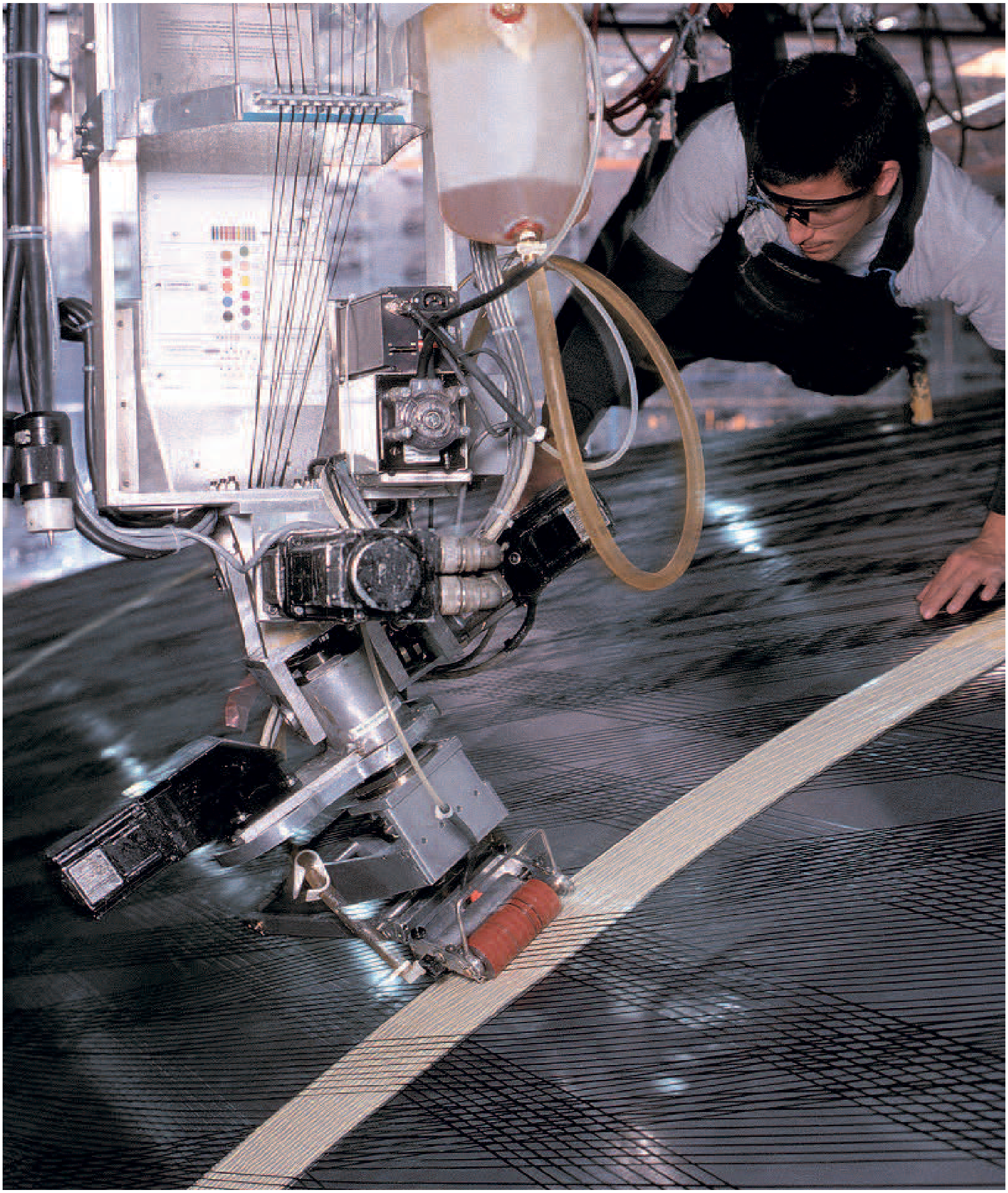
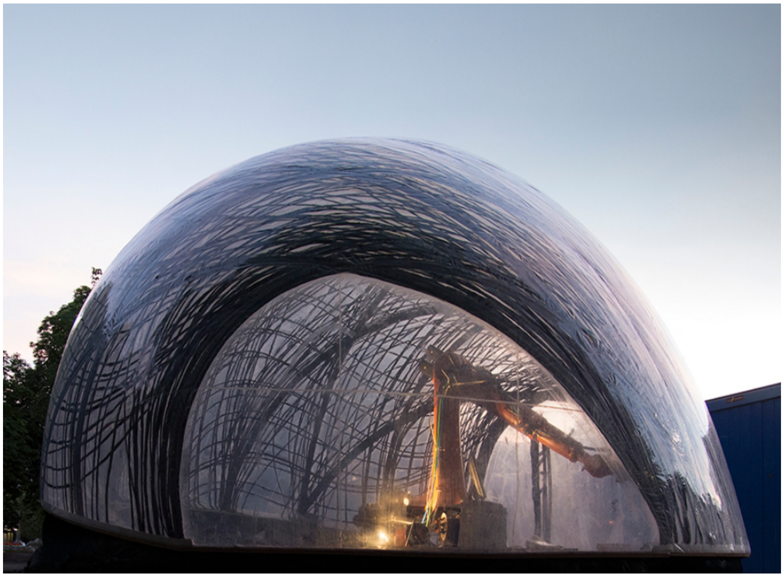


FIG 2.07 Filaments are laid on a 3D mould at a North Sails manufacturing facility.

FIG 2.08 ICD/ITKE Pavilion 2015.



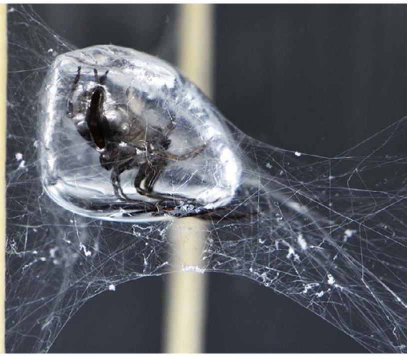


FIG 2.09 Argyroneta Aquatica building a web to support an underwater air pocket.

This mapping of filaments based on FEA data has also made its way into experimental architectural installations, such as the 2014-2015 Research Pavilion by the Institute of Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart. This installation was constructed by depositing carbon fibre filaments on the inside surface of an inflated ETFE membrane enclosure to create a self-supporting and weatherproof shell. Adapting strategies from the web building behaviours of *Argyroneta Aquatica* (diving bell water spider), a reinforcing structure with regional variation in filament density was generated through a robotic deposition system.[8] The resulting structure bears many aesthetic similarities to the filament reinforced racing sails, where the structural system is expressed through the distribution and orientation of the embedded fibre matrix. Ultimately, these intricate membranes have the material efficiency of natural structures, making them valuable precedents for the evolution of light and portable shelter.

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[8] Doerstelmann et al., “ICD/ITKE Research Pavilion 2014–15.”

Part 3

The Movable Shelter

The narrowest human territory is one's own private sphere. Like the entity it belongs to, it is mobile.

Frei Otto, Occupying and Connecting[1]

The word *bivouac* means "to take shelter temporarily." [2] In contemporary outdoor culture, this word has also come to represent the products and practices associated with temporary and minimal forms of encampment. A bivouac or "*bivvy*" can refer to the emergency enclosure used to survive an unexpected overnight in the backcountry or a ledge on a multi-day rock climbing route, temporarily co-opted for cooking and sleeping between days of climbing. When compared to a standard tent, the defining characteristic of a bivvy is the implication of transience and its temporary use within a journey of sorts.

BIVOUAC TYPOLOGIES

Current ultralight tent models vary in form and structure depending on how they engage with their site, leading to different preferred typologies depending on the type of terrain being travelled. Most ultralight shelters are designed as tent structures for use on flat ground, simplifying the anchoring and structural requirements and ultimately leading to lighter enclosures. To avoid the challenge of locating a flat site, some backpackers prefer a hammock-style shelter that is tensioned between trees. Although these shelters

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[1] Otto, *Occupying and Connecting*, 3.

[2] Merriam-Webster, "Bivouac."

FIG 3.01 *Previous page:* A portaledge camp on the vertical rock walls of Baffin Island.

can be quite minimal, the need for load-bearing fabrics and webbing can increase the system's weight. For more extreme mountaineering and climbing trips, a robust hanging tent, called a *portaledge*, must be used to allow for bivouacking on vertical rock or ice walls during long and sustained climbs. Specific examples of these three typologies (ground tent, hammock, and portaledge) can be understood through the state-of-the-art products described below:

Hyperlite Gear, Echo 2 Shelter System: This minimal shelter consists of a composite fabric canopy pitched up by two hiking poles held in tension by ground anchors along the edge of the canopy. The use of hiking poles is crucial to the functionality of ultralight shelters because it reduces the number of rigid elements that need to be stowed and carried during travel by adding multifunctionality to essential items. Under the canopy and supported between the hiking poles, a human-sized mesh enclosure with a waterproof composite base creates a ventilated and protected environment for sleeping. The weight of the system, not including hiking poles, is 823 grams (roughly the weight of a full sports water bottle).[3]

Tentsile, Una: This suspended platform uses three tensioned straps to span between trees, suspending the shelter above potentially wet or uneven ground. A single flexible pole and coated nylon enclosure create a shelter above the platform, just large enough for one person to sit or lie down. The system's total weight, including anchors, is 3200 grams (roughly the weight of a cast-iron pan), significantly heavier than a similarly sized ground shelter.[4]

Black Diamond, Single Portaledge: A well-known shelter among big-wall climbers, this piece of equipment is often suspended thousands of feet above flat ground. The extreme nature of its use is reflected in its robust design and materials. Like most portaledges, the Black Diamond variant is a two-part system consisting of a rectangular platform, used as a sleeping surface and belay ledge,

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[3] Hyperlite Mountain Gear, *Echo 2 Ultralight Shelter System*.

[4] Tentsile, *UNA 1-Person Hammock Tent (3.0)*.

FIG 3.02 An ultralight tarp tent by Hyperlite Gear.

FIG 3.03 A three-point hammock tent by Tentsile.

FIG 3.04 Hanging Portaledges by Black Diamond.

and a pyramidal *fly*, a weather-sealed enclosure that drapes from anchor to platform to provide protection from precipitation, wind, and falling debris. The platform maintains rigidity with a four-sided aluminum frame suspended by a load-bearing connection at the peak of the fly to a *station* on the rock face (an anchor with multiple connection points to the rock for redundancy). The resulting system weighs more than most single-occupant shelters, with a total weight of 9900 grams (about the weight of a large sledgehammer).[5]

Currently, there is no single ultralight shelter system that responds to the range of siting conditions addressed by the typologies above. Suspended shelters are especially heavy and limited in how they engage with their environment. This site-specificity can be particularly problematic on backpacking and mountaineering trips that traverse varied terrain types, and where ideal camp locations are not known ahead of time or camp locations are decided based solely on distance and not the terrain conditions that will best suit the shelter being used. Through these precedents, an opportunity is presented to develop a shelter that is responsive to its siting conditions and allows for multiple modes of site engagement. This challenge is explored through the design of the *Hybrid Bivouac* explored in this thesis.

HIGH-PERFORMANCE MATERIALS

Among these shelter variants, there are a handful of different materials that are typically used. The standard material for most performance shelters is a woven nylon fabric with a silicone or polyurethane coating. Specific weights and weaves of the fabric can range from a lightweight ripstop structure to a durable ballistics weave, which is mechanically tested for high abrasion resistance and breaking strength.[6] The lightest weight shelters, those used for trips where the limits speed and distance on foot are being pushed, often rely on *Dyneema® Composite Fabric* (DCF). This material is made of several bonded plies of parallel

FIG 3.05 Close up of Dyneema® Composite Fabric Face.

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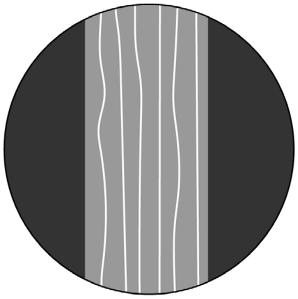
[5] Black Diamond Equipment, "Single Portaledge"; Black Diamond Equipment, "Deluxe Single Fly."

[6] Tortora and Merkel, "Modulus," 37–38.



UHMWPE
(Ultra High Molecular Weight Polyethylene)

Regular PE
(Polyethylene)

FIG 3.06 Diagram comparing the polymer structure of UHMWPE and standard PE.

strands of ultra-high-molecular-weight polyethylene (UHMWPE) filament laid perpendicular to the layers below and sandwiched between a polyethylene terephthalate (PET) film. The merits of this material come from the material properties of the UHMWPE, which is known for having a specific strength similar to carbon fibre with the added benefit of pliability, making it ideal for ultralight and packable applications.[7] These properties are achieved using a manufacturing process of *gel-spinning*. This spinning method involves the dissolving of polyethylene (PE) in solvents to create a gel which is then drawn out to align the structure of the polymer as the filaments are drawn out. The parallel orientation of the polymer structure can be thought of as long continuous ropes rather than the loose structure of the unaligned PE. This material is also used in performance sails as both a membrane fabric and reinforcing filament within a composite tape.[8]

The use of UHMWPE composites in portable shelter systems is still rudimentary when compared to how the material is being used in other performance applications, like the racing yacht sails, where the fibre is used for regional reinforcement within a non-homogeneous composite. Dyneema® composite fabric has not been used in load-bearing shelter systems, likely due to its susceptibility to creep and seam failures.[9] However, with precise reinforcement and bonding, this material has the potential to provide the strength and durability required to support high loads at a fraction of the weight of current enclosures. By mapping the materials according to regional strength and durability requirements within the design, this thesis proposes a weatherproof enclosure that is light and compressible for ease of packing and transportation.

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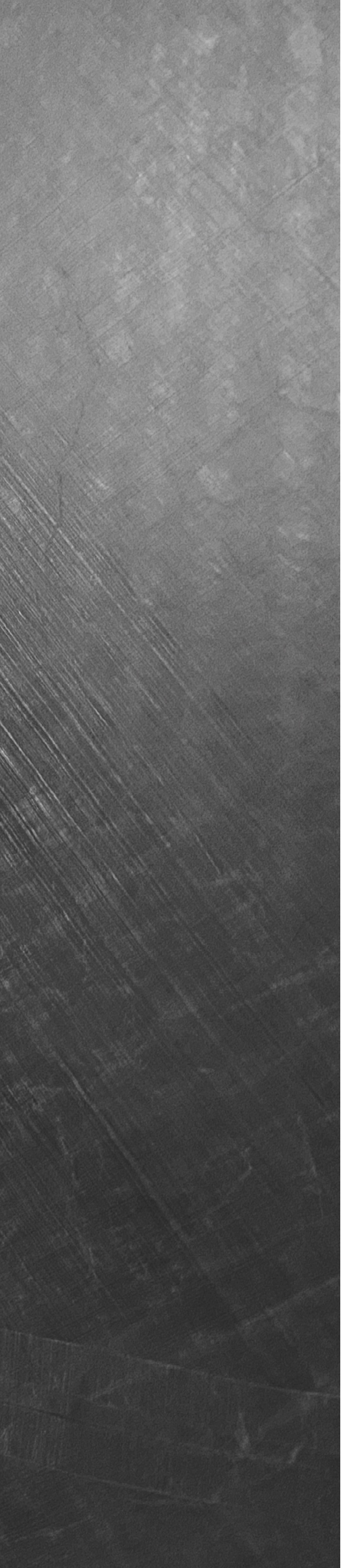
[7] Marissen, “Design with Ultra Strong Polyethylene Fibers.”

[8] Pearson, “Textiles to Composites: 3D Moulding and Automated Fibre Placement for Flexible Membranes.”

[9] Marissen, “Design with Ultra Strong Polyethylene Fibers,” 322.



Part 4
Making the Bivouac

In the development of the novel shelter system, the Hybrid Bivouac prototyping activities fluctuated between material investigation, functional application testing, and complex modelling (FIG 4.01).

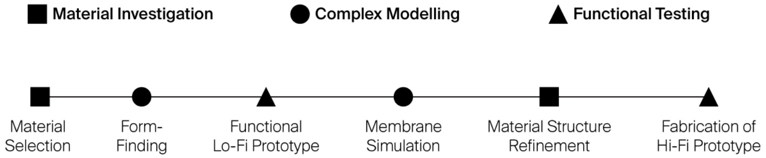


FIG 4.01 Design process sequencing.

MATERIAL SELECTION

A structure's performance is defined by the combined characteristics of the materials that it is made of and how these materials are structurally arranged. Material investigation and development are critical parts of this thesis, relying on the selection of advanced raw materials and composite structures to resolve the conflicting characteristics of a light, strong, and packable system. The first step in this process was to select materials through the qualitative evaluation of swatches, small sections of membrane composites.

The Dyneema® composite material family was chosen as a starting point for this investigation due to the high strength-to-weight ratio of UHMWPE. However, this strength refers to the material's behaviour in tension. When examining the material performance in compression, there are limitations. The high modulus filament is ultimately quite slippery and does not readily stick together within typical resin-based composites. In some other applications, this is seen as a benefit. In ballistic composites, for example, the slippage of the material helps to absorb the forces of an impact.[1] Fortunately, within the membrane of a tent structure, UHMWPE would be allowed to act fully in tension, while its softness and flexibility would allow the membrane to remain compressible for packing.

Several different variants of DCFs are commercially available, varying in strength depending on the number of UHMWPE plies embedded within the textile. In general, the increase in layers also adds bulk and buckling resistance to the material, reducing its ability to compress into a small volume. Three weights of DCF were selected so that the placement of thicker materials within the structure could be optimized later in the design process, mitigating the trade-off between strength and compressibility. Several *pressure-sensitive adhesives* (PSAs) were also evaluated with the varying weights of DCFs to ensure a lasting bond and water tightness of seams.

In the fabrication of some composite racing sails, flexible tapes embedded with high modulus filaments are mapped onto the membrane to increase the strength and prevent deformation within the sail. Based on this technique, a novel tape was developed for the Hybrid Bivouac to transfer loads efficiently within the textile enclosure and direct forces to the anchoring points. In order to create this tape, a spool of UHMWPE filament was acquired from a mill, and various adhesive and backer materials were prototyped. Two PSA products, 3M 9485 PC and an adhesive formulated by DSM, the manufacturer of Dyneema® materials, were explored, and their qualitative performance in peel strength, flexibility and conformability was observed. While the 3M glue added considerable tensile strength and better peel strength, it was also stiff and required application in a straight line, while the DSM adhesive tape created a lighter and more flexible composite with the possibility of curved reinforcing patterns. Swatches were then created by arranging the

FIG 4.02 *Previous page:* Detail of seams on Hybrid Bivouac protoype.

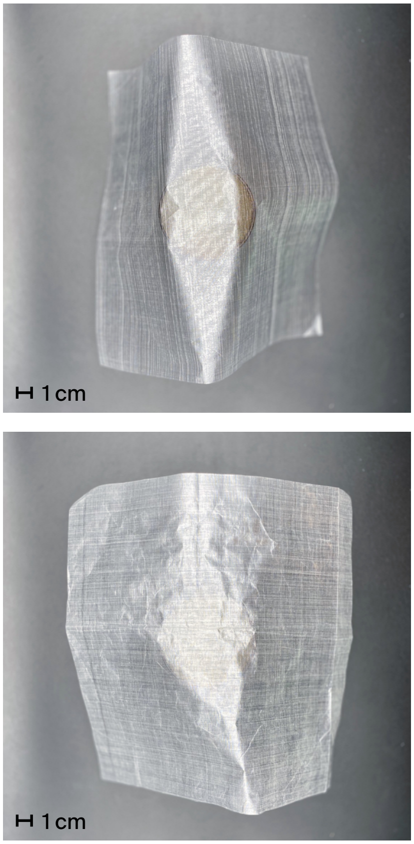


FIG 4.03 Comparison of buckling resistance in two different weights of Dyneema® composite fabric. The lighter material *(top)* has less buckling resistance but the heavier material *(bottom)* has a greater tensile strength.

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[1] Marissen, “Design with Ultra Strong Polyethylene Fibers,” 322.

FIG 4.04 Close up of UHMWPE filament spool.

FIG 4.05 Filament tape made with double-sided PSA and DCF backing.

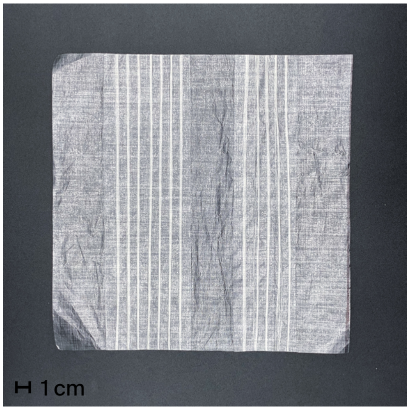


FIG 4.06 Multi-filament tape prototype.

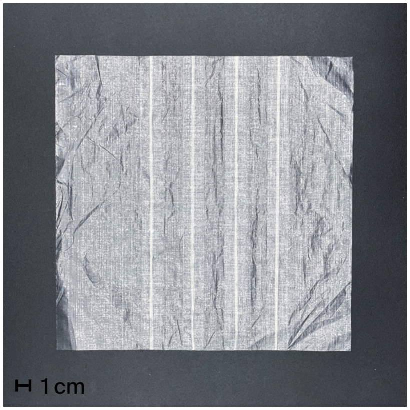


FIG 4.07 Single filament tape prototype.

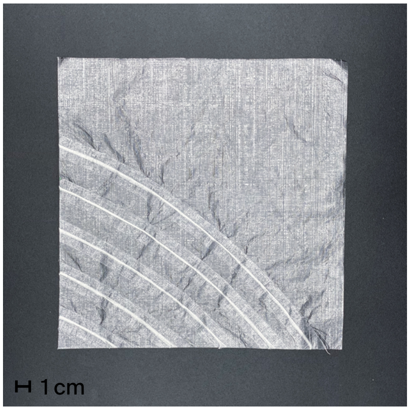


FIG 4.08 Curved filament tape prototype.

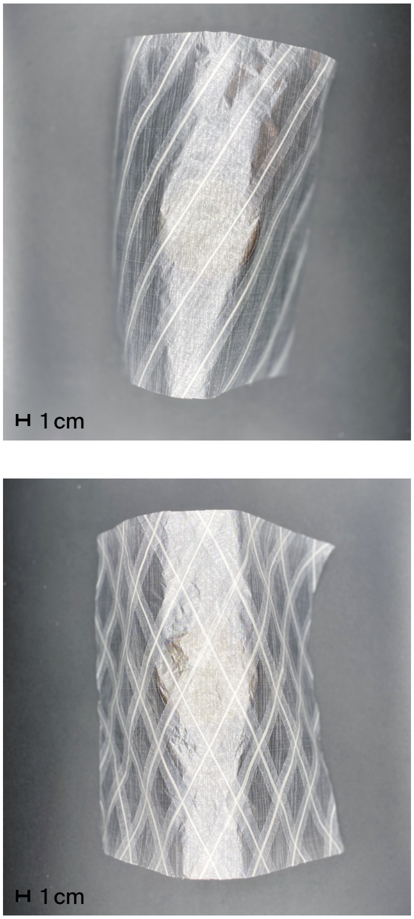
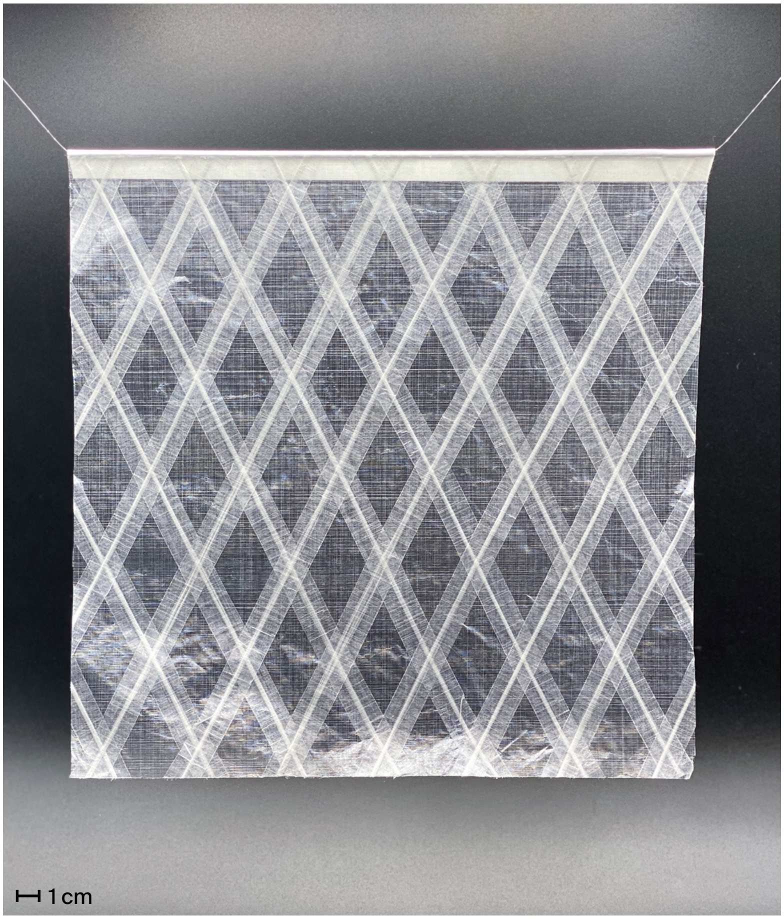


FIG 4.09 Comparison of buckling resistance in parallel tape reinforcing and intersecting tape reinforcing.



filament tape in various orientations on pieces of DCF membrane to explore the compressibility of the resulting composite structures.

In addition to the selection of materials for the final design, suitable materials for prototyping were also selected to mitigate the high cost of DCF fabrics when ordered in low volumes. Hard-structure, or paper-like Tyvek®, was chosen for scale models due to its ability to be bonded with the same PSAs as were chosen to use with the Dyneema® composite fabrics and soft-structure, or fabric-like, Tyvek® was selected for low fidelity functional prototypes due to its water resistance, comparable weight to DCF and sewability.

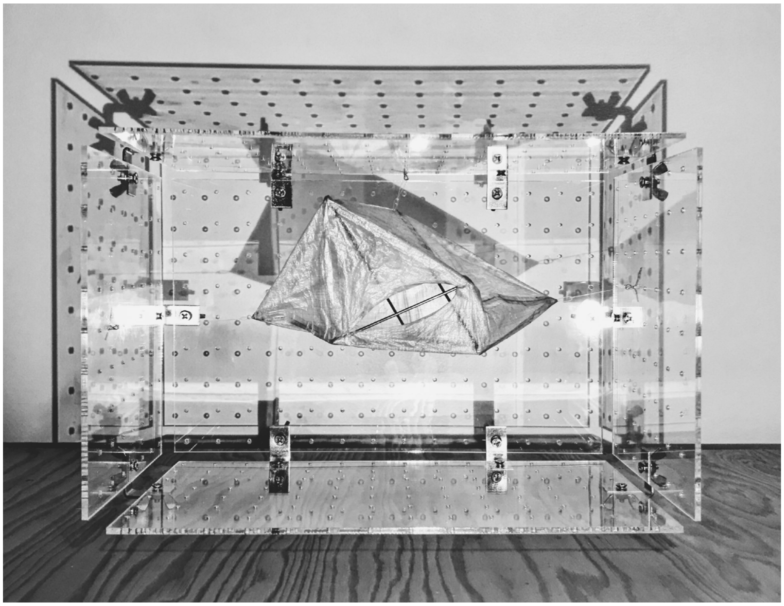
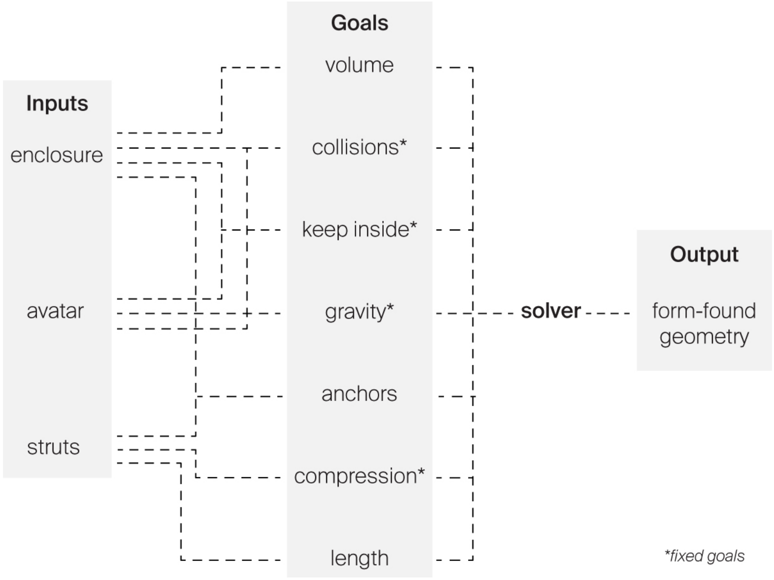


FIG 4.10 Configurable physical model.

FORM-FINDING

A form-finding workflow was engaged as materials were being selected. The preliminary modelling was performed using a configurable physical model to explore the validity of a three-strut tensegrity structure for maintaining volume within a suspended tent enclosure. This model is based on an early hypothesis that using three independent poles within a tensioned enclosure would provide the most efficient system, requiring the least amount of rigid elements and anchoring while maintaining the shape of the enclosure. A model was then constructed using five pieces of acrylic that were laser-cut to size with a grid of small holes. These pieces were then assembled into a box with the front face left open. The acrylic enclosure could then be used to anchor cables made of fishing line, which, in turn, tensioned a 1:20 model tensegrity tent with different anchoring conditions. The initial tent model was constructed with three lengths of thin metal rod and an enclosure made from a lightweight DCF. The model was suspended from the top and tensioned on either side. This configurable system helped establish physical goals for the structure, which were later translated into the digital model.

FIG 4.11 Parameters for digital model.



With the preliminary hypothesis of the tensegrity system validated by the physical modelling exercise, an equally configurable digital model was created using the 3D modelling software Rhinoceros 3D and the parametric design plugin Grasshopper 3D.[2] Within this software suite, an additional plugin was employed to simulate the physics of the system, called Kangaroo Physics.[3] Kangaroo is a physics-based solver, meaning it simulates the physics of the structure based on real-world goals, such as gravity, loads or spring modulus, that are assembled within the parametric environment of Grasshopper 3D. Numeric sliders were added to the grasshopper definition to adjust goal values, thus informing the solved geometry. As a form-finding tool, this method is extremely effective. It allows a designer to incrementally see the geometry change as constraints in the model are shifted, enabling rapid iteration and highlighting physical problems that may result from specific configurations.

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[2] Robert McNeel & Associates, *Rhinoceros 3D*; Davidson, *Grasshopper 3D*.

[3] Daniel Piker, *Kangaroo Physics*.

In the first round of digital form-finding, a model was set up to manipulate the following geometry inputs: *avatar* (the placeholder for a human occupant), *strut* (the tent poles), and *enclosure* (the tent membrane defining the internal volume). These elements were then assigned both fixed and configurable goals to generate and assess a range of geometric possibilities. It is essential to differentiate between fixed and configurable goals. Fixed goals are parameters that remain unchanged in the real-world environment, regardless of the form, like gravity, the weight of the occupant and the structural logic of the tensegrity system (which depends on certain elements acting in tension while others remain in compression). On the other hand, configurable goals are intentionally changed to generate new forms, for example, the independent length of each strut, the quantified volume of the resulting enclosure, and the position of anchors. Ultimately, the changing of goals did not always result in a geometry that would be deemed acceptable for its use case, but a promising structural concept was eventually achieved.

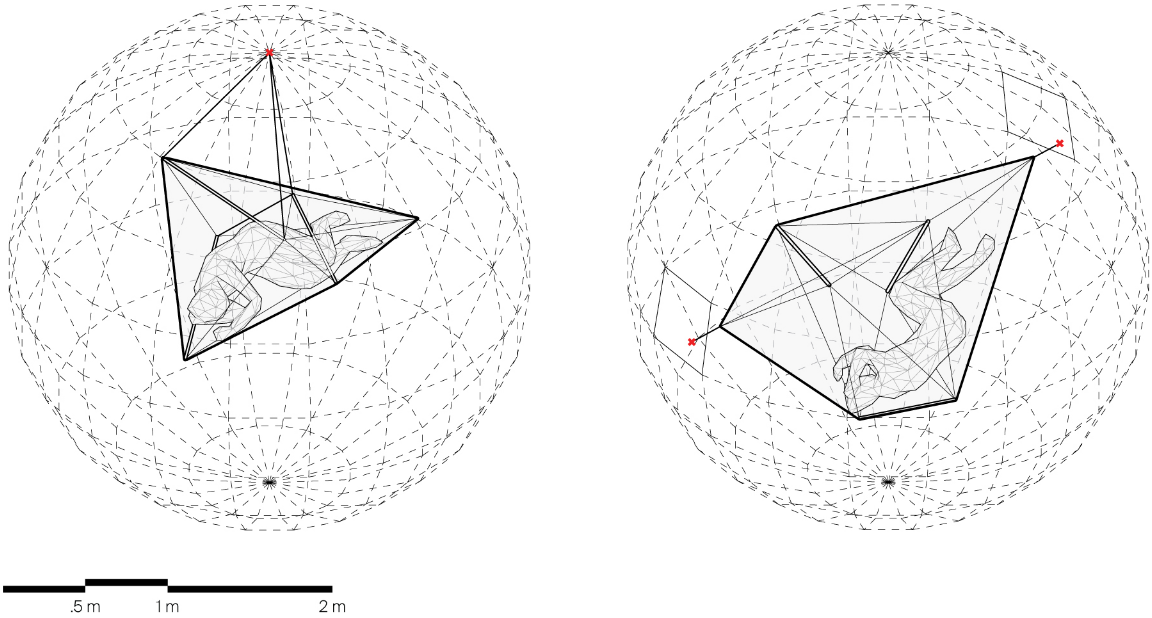


FIG 4.12 The parametric Kangaroo 3D model employed a spherical ‘scaffold’ to configure different anchoring conditions like the hanging condition (left) and hammock condition (right).

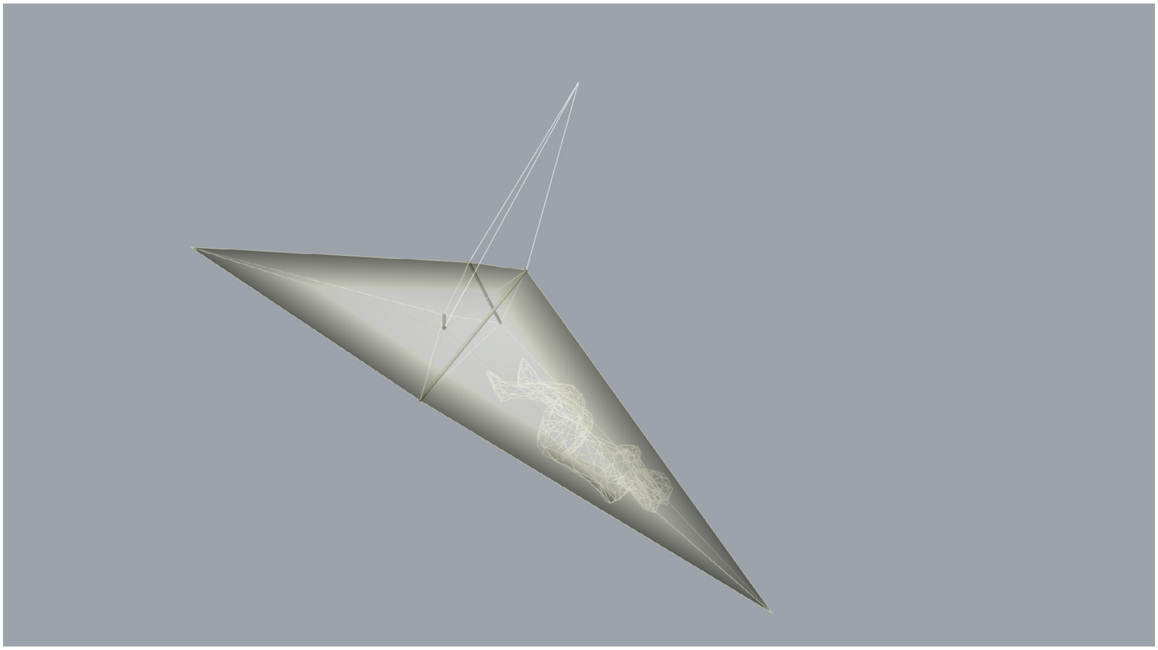


FIG 4.13 Example of unsuccessful form-found Kangaroo 3D output.

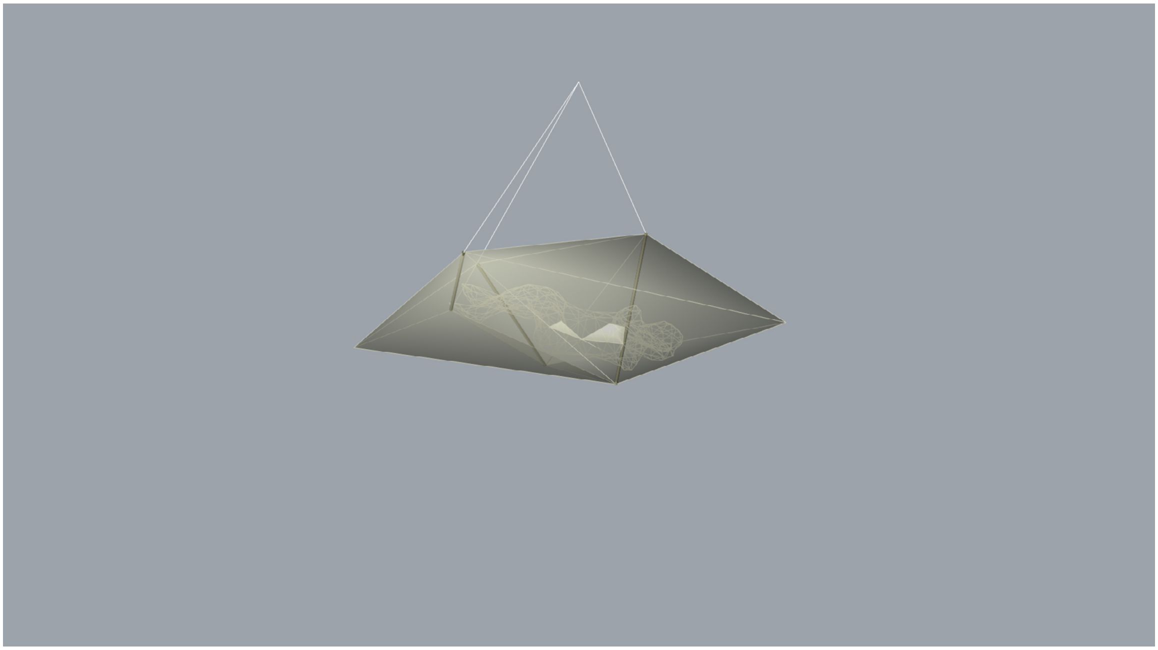


FIG 4.14 Example of productive form-found Kangaroo 3D output.

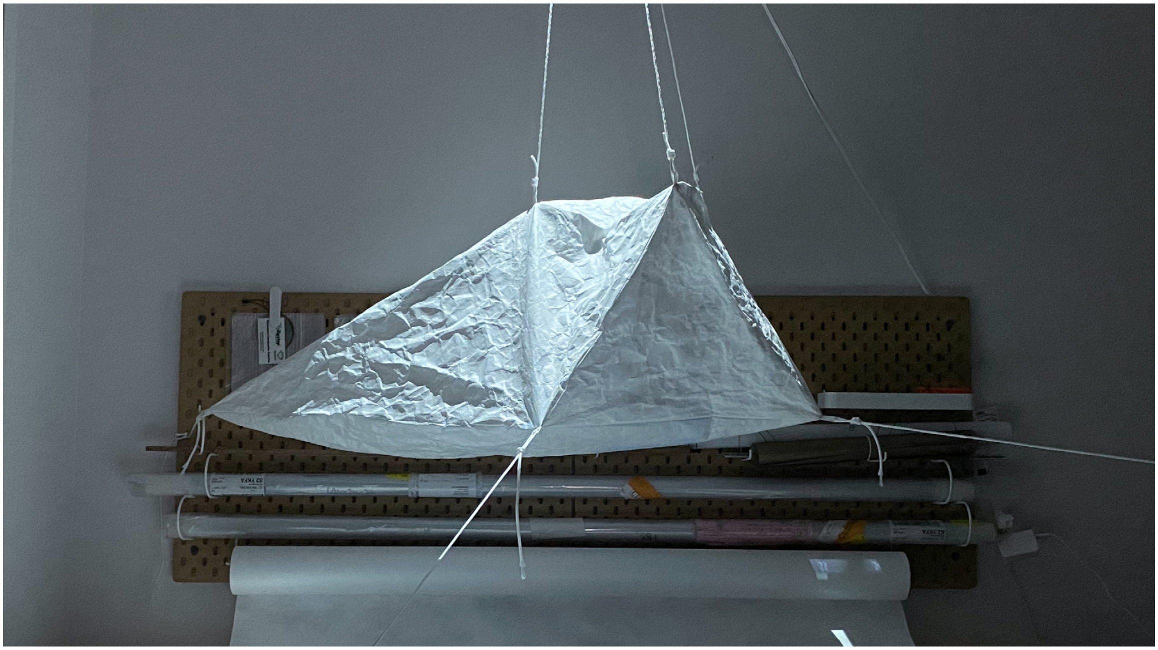


FIG 4.15 Physical 1:2 model based on Kangaroo 3D outputs, unweighted.

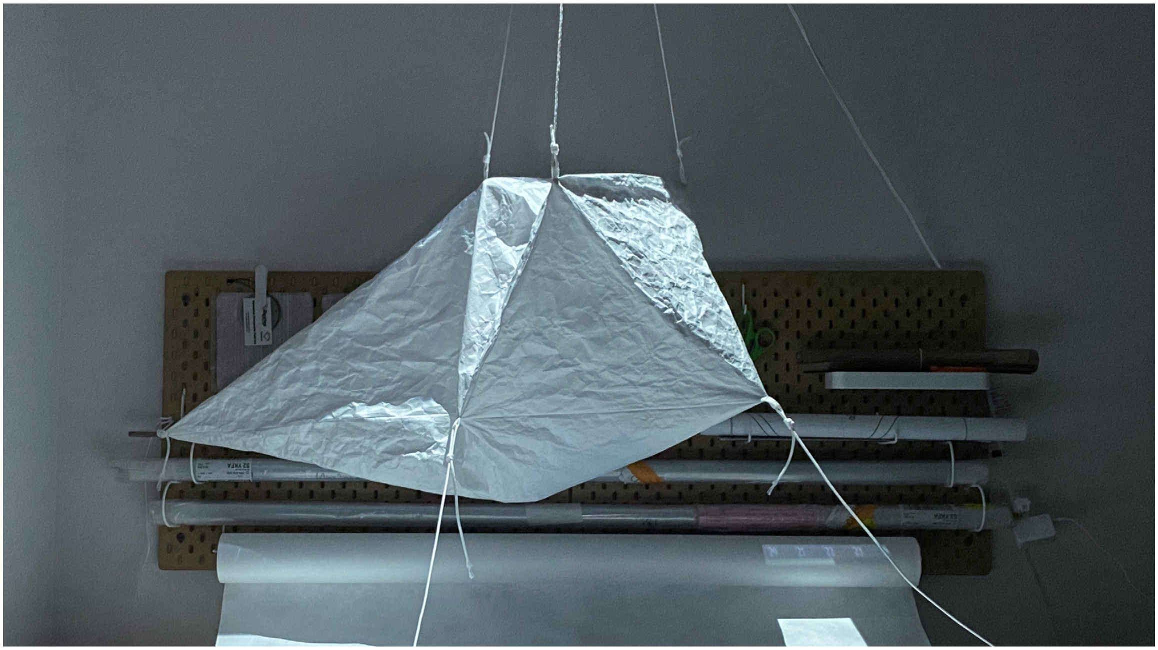
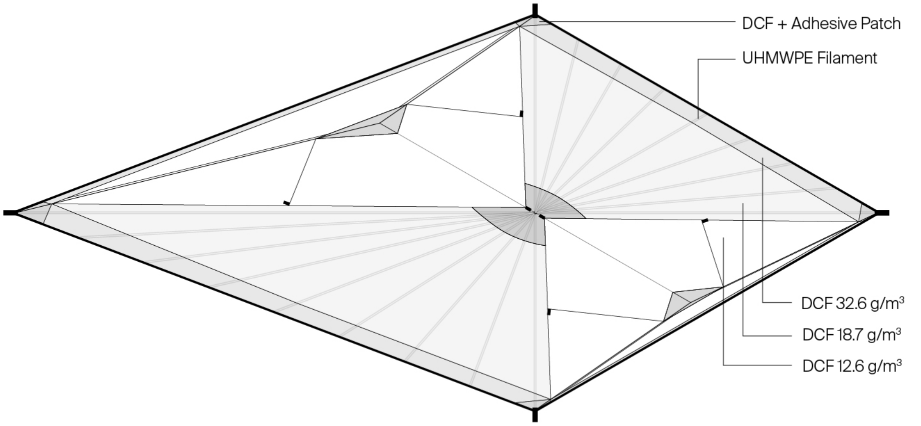


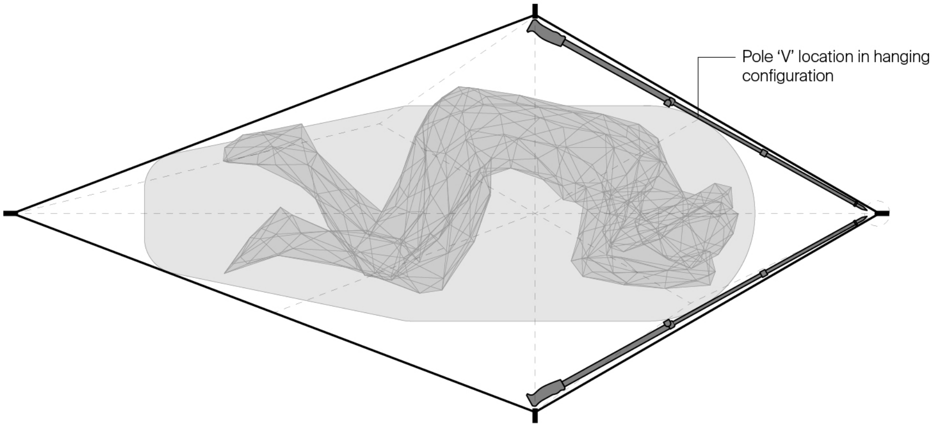
FIG 4.16 Physical 1:2 model based on Kangaroo 3D outputs, weighted.

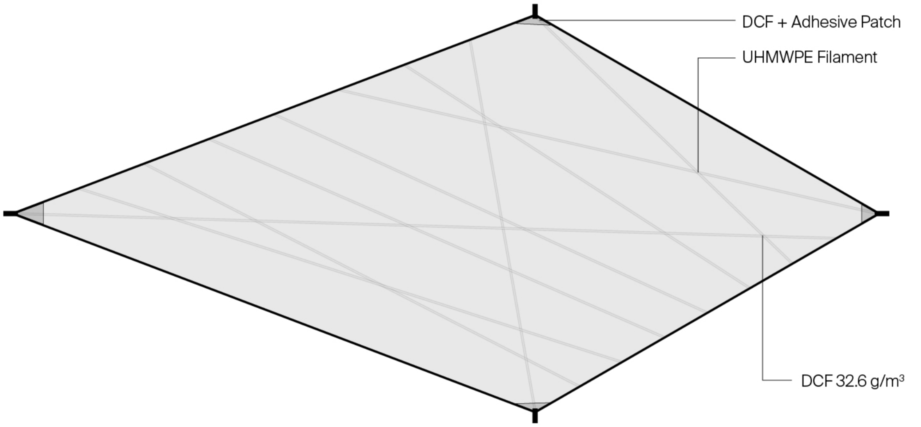
FIG 4.17 Physical 1:2 model with 'V' connection.

To validate the geometry with real-world physics, a half-scale model was constructed out of Tyvek®. It was quickly observed that the tensegrity scheme required anchoring at each corner to maintain its shape while unloaded and that it collapsed in on itself with the addition of an internal load if substantial tension was not maintained at each anchor. From a functional perspective, it was assumed that the flat triangular roof formed a dip that may be prone to pooling water, which may lead to further collapse in the enclosure's structural integrity. This failure led to the hypothesis that a rigid connection between pole elements supporting the bottom of the structure would be required to maintain the volume and stability of the structure when suspended and supporting the weight of an occupant. A new scheme that included a rigid connector between two of the three struts to create a structural "V" was proposed. This new scheme allowed for multiple site configurations through the rotation of the "V" within the enclosure. Orienting the "V" upside down allowed for the peak of the enclosure to be held up, while orienting the "V" parallel to the ground mitigated the collapse of the

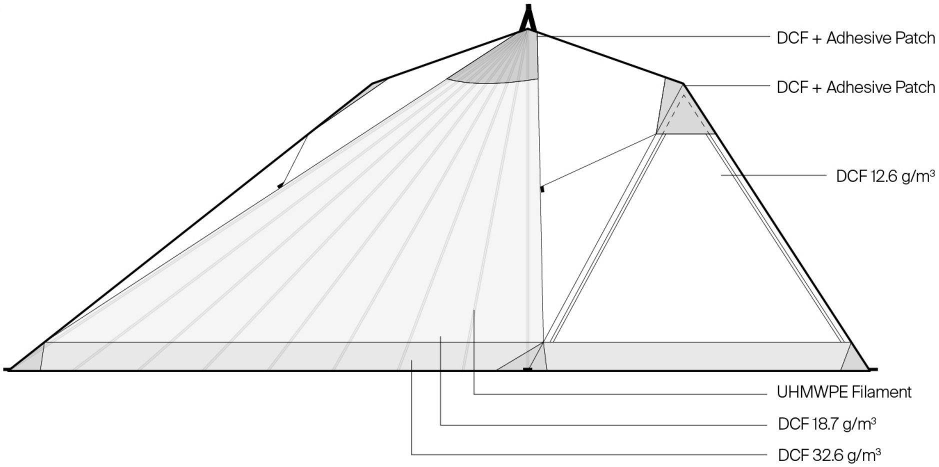
Orthographic Drawings:
Plans

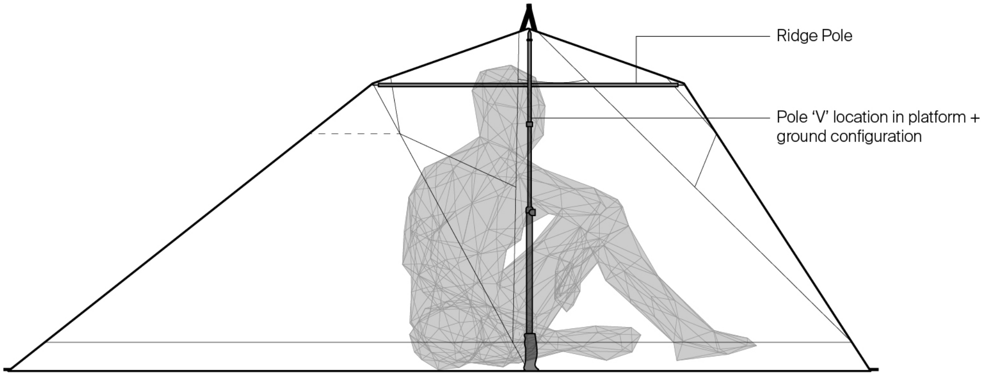


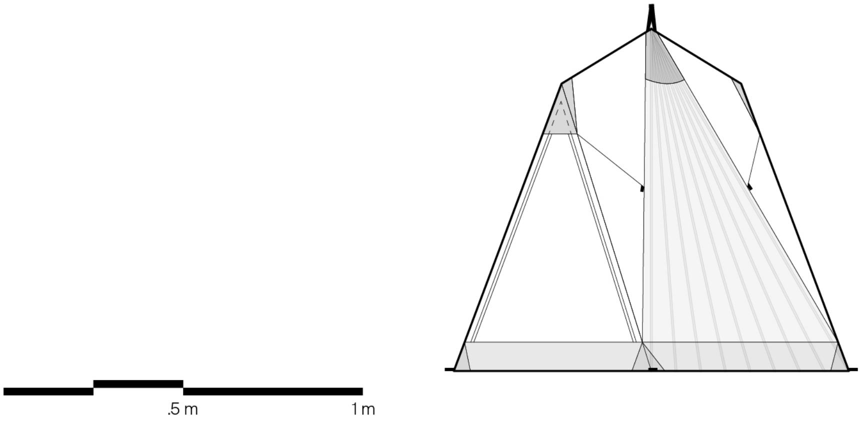




Orthographic Drawings:
Elevations







enclosure’s interior when suspended from its peak. Through the creation and observation of a second half-scale Tyvek® model, this scheme was successfully validated.

FIG 4.18 *Previous Page:* Orthographic drawings of tent concept.

FUNCTIONAL LO-FI PROTOTYPE

In order to test against the functional requirements of an adaptable ultralight shelter, a 1:1 prototype was created with a soft-structure Tyvek® fabric. A pattern for this prototype was created by unfolding the geometry created in Rhinoceros 3D and importing this geometry into a digital prototyping software for fashion and soft goods design called CLO[4]. With this software, a simple sewing pattern was created and sent to be plotted. Next, the paper pattern was used as a template to cut out pieces of Tyvek® by hand, and the cut pieces were sewn together using a standard industrial lockstitch sewing machine. Webbing loops were added to each corner for anchoring. The assembled prototype, not including the rigid structural components, weighed 286 grams and, when compressed, could be packed into a volume of 1.2 litres.

FIG 4.19 Functional prototype suspended at rock climbing area.

Soft-structure Tyvek® has a tensile strength of 11 psi (pounds per inch). This value is less than the tensile strength of DCFs, which vary in tensile strength from 29 psi to 104 psi for the materials used in this thesis. Knowing the strength of the soft-structure Tyvek® would not be able to hold an occupant; it was assumed that the failures of this prototype would illustrate the areas that would require the highest level of reinforcement.

Various form factors of the “V” connector piece were designed using the parametric 3D modelling application *Fusion 360*. The joint was designed to accommodate the tips of standard hiking or ski poles in order to leverage essential equipment that the user may carry. The connector piece was printed on a low-cost resin 3D printer for testing with the prototype enclosure.

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[4] CLO Virtual Fashion LLC, *CLO*.

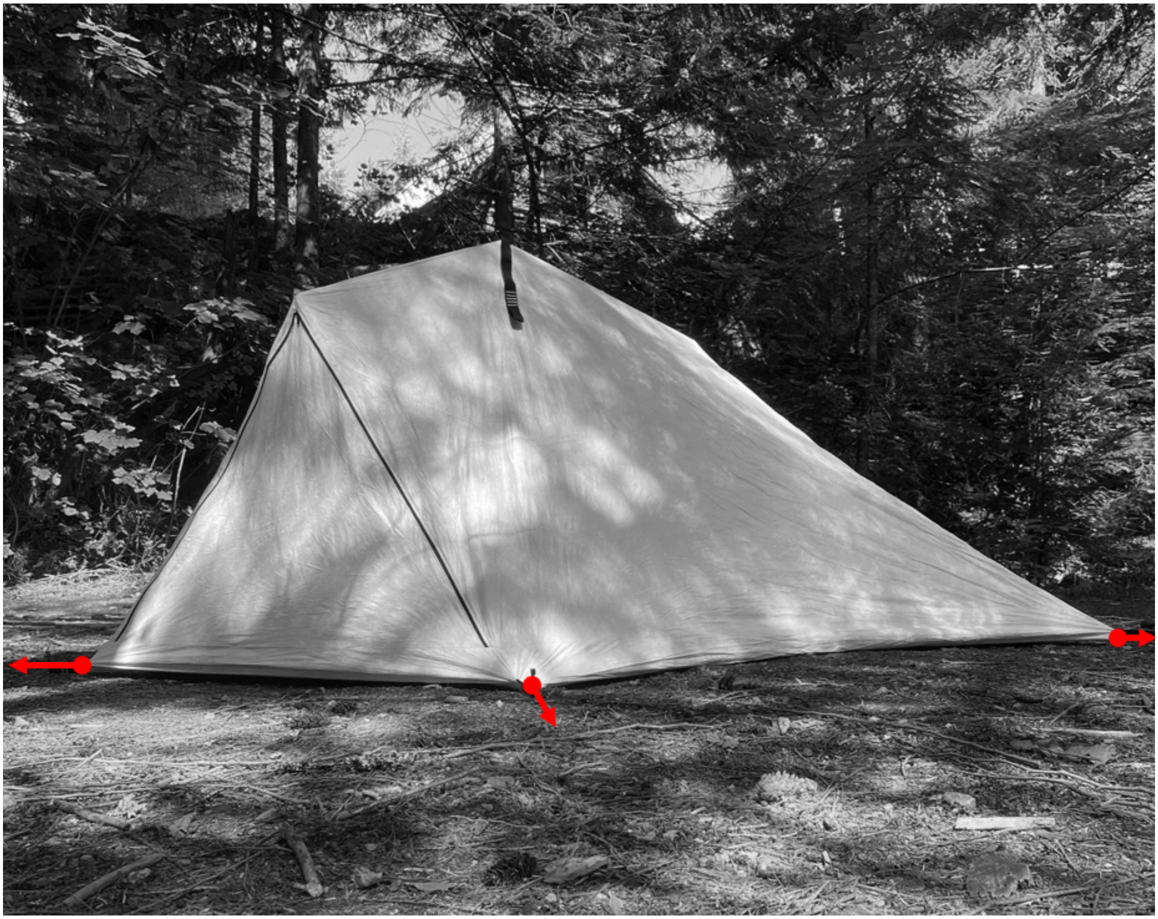


FIG 4.20 Anchoring of ground-pitch condition.

The prototype was then taken outside for field testing. Three different conditions for the shelter setup were attempted. First, the enclosure was used as a standard tent bivvy, pitched on the ground. In this configuration, the four corners of the enclosure's base were pinned to the ground with small aluminum stakes, and the hiking pole frame was tilted up vertically to apply tension to the peak of the enclosure. Lastly, a ridge pole was inserted to increase the internal volume of the shelter. The entire assembly process was complete in two minutes, and the resulting shelter was comfortable for both sitting and lying down.

FIG 4.21 Structural diagram of ground-pitch condition.

Structural Diagram
Ground Configuration

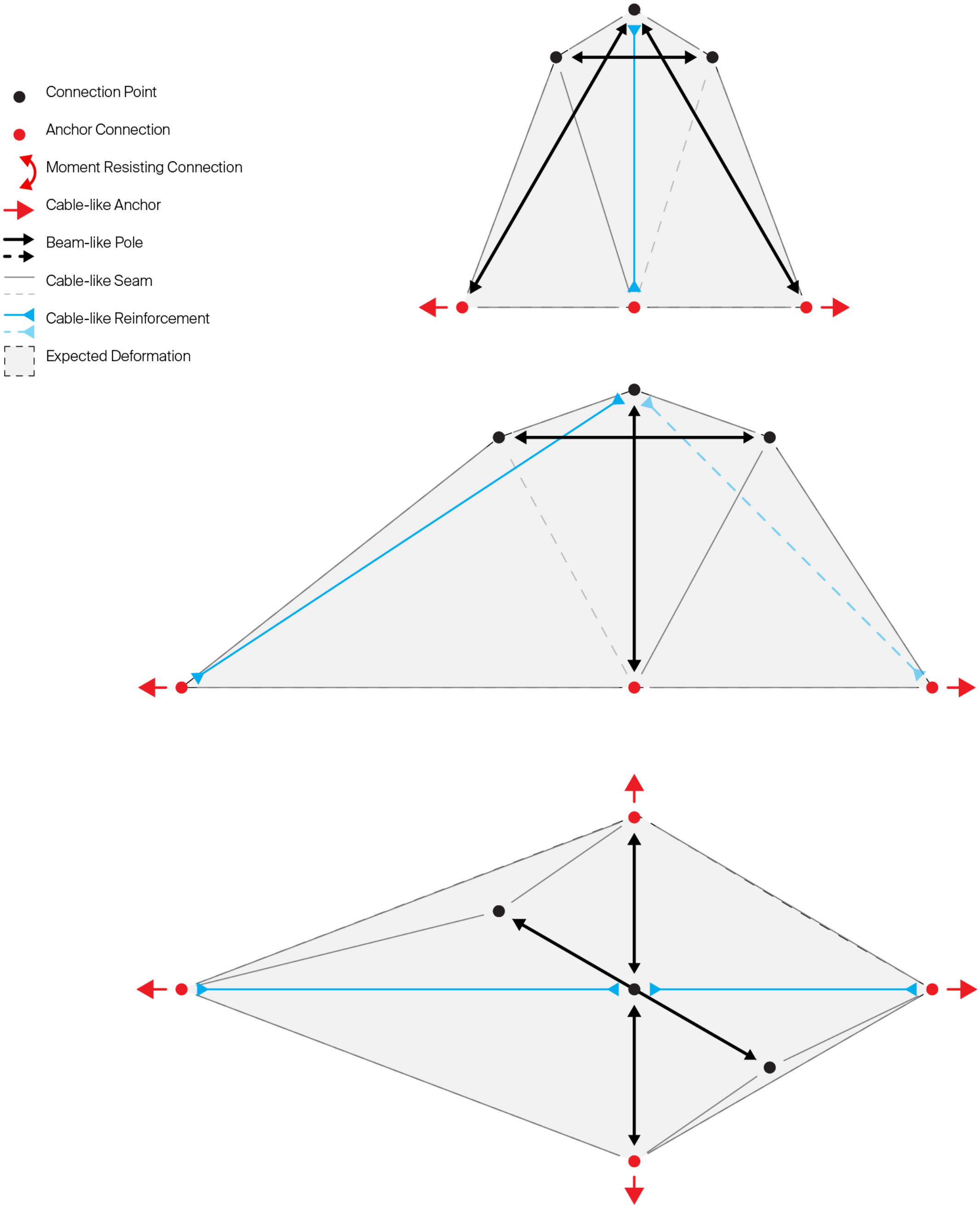


FIG 4.22 Anchoring of tensioned platform condition.

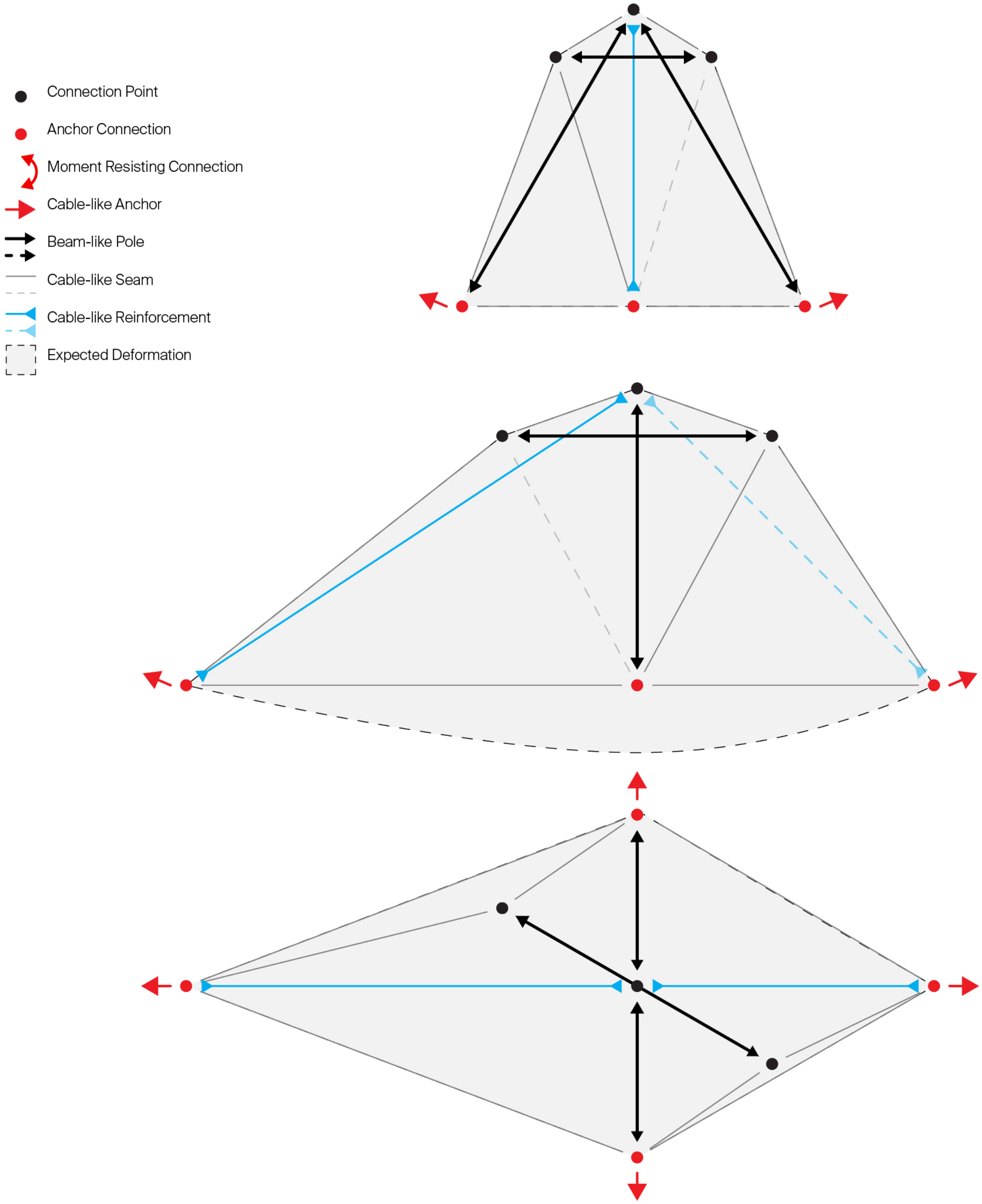
FIG 4.23 Structural diagram of tensioned platform condition.

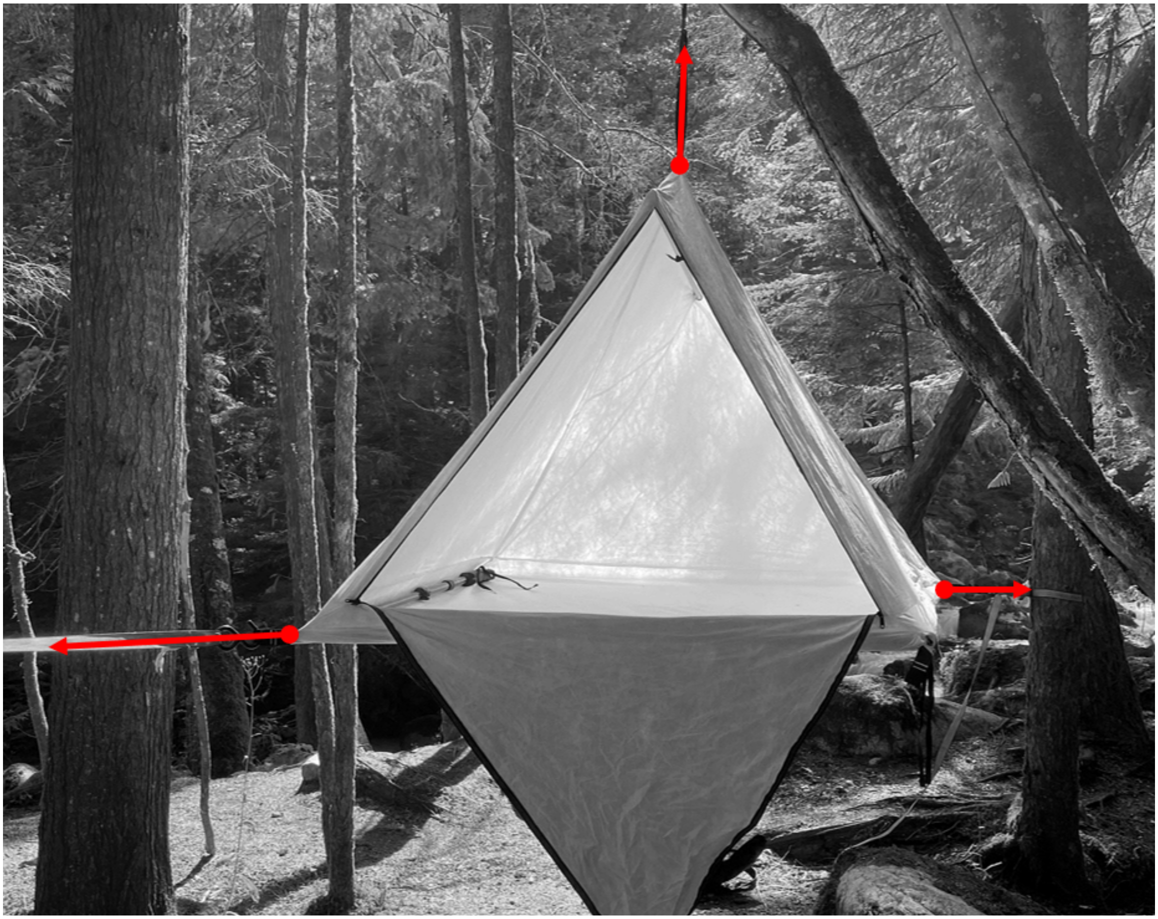
Next, the shelter was tested as a tensioned platform shelter, with the four tent base corners attached to ratcheting straps fastened to tree bases at the height of one metre. This scenario also leveraged the vertical pole configuration to support the peak of the shelter. Although the shelter appeared to hold its form in this configuration, the pressure on the enclosure at the base of the hiking poles created visible failures in the textile, indicating an area that would require considerable reinforcement.

Finally, the prototype was evaluated in a third configuration, suspended from its peak and secured at only two of the four corners of its base to extend its length. This condition leveraged the hiking pole frame in its parallel-to-ground position, which successfully

Structural Diagram

Platform Configuration





maintained the internal volume of the shelter. As this scenario places a large amount of force on the designed connector, the enclosure was loaded with a 30-litre water container to observe the behaviour of the connection when pushed to failure. By watching slowed down footage of this failure, it was noted that the failure began with the tearing of the Tyvek® material at the previously weakened area on the base of the enclosure. The sudden tearing of the enclosure caused a rapid springing out of the "V" frame — previously held together by the deformation of the loaded enclosure base — causing a fatal fracture in the connection joint. From this exercise, it was discovered that the flange of the connector needed to be thicker, and this was applied to the next design iteration.

FIG 4.24 Anchoring of suspended condition.

FIG 4.25 Structural diagram of suspended condition.

Structural Diagram
Hanging Configuration

- ● Connection Point
- ● Anchor Connection
- ⤸ Moment Resisting Connection
- → Cable-like Anchor
- → Beam-like Pole
- — Cable-like Seam
- ◀ Cable-like Reinforcement
- ▨ Expected Deformation

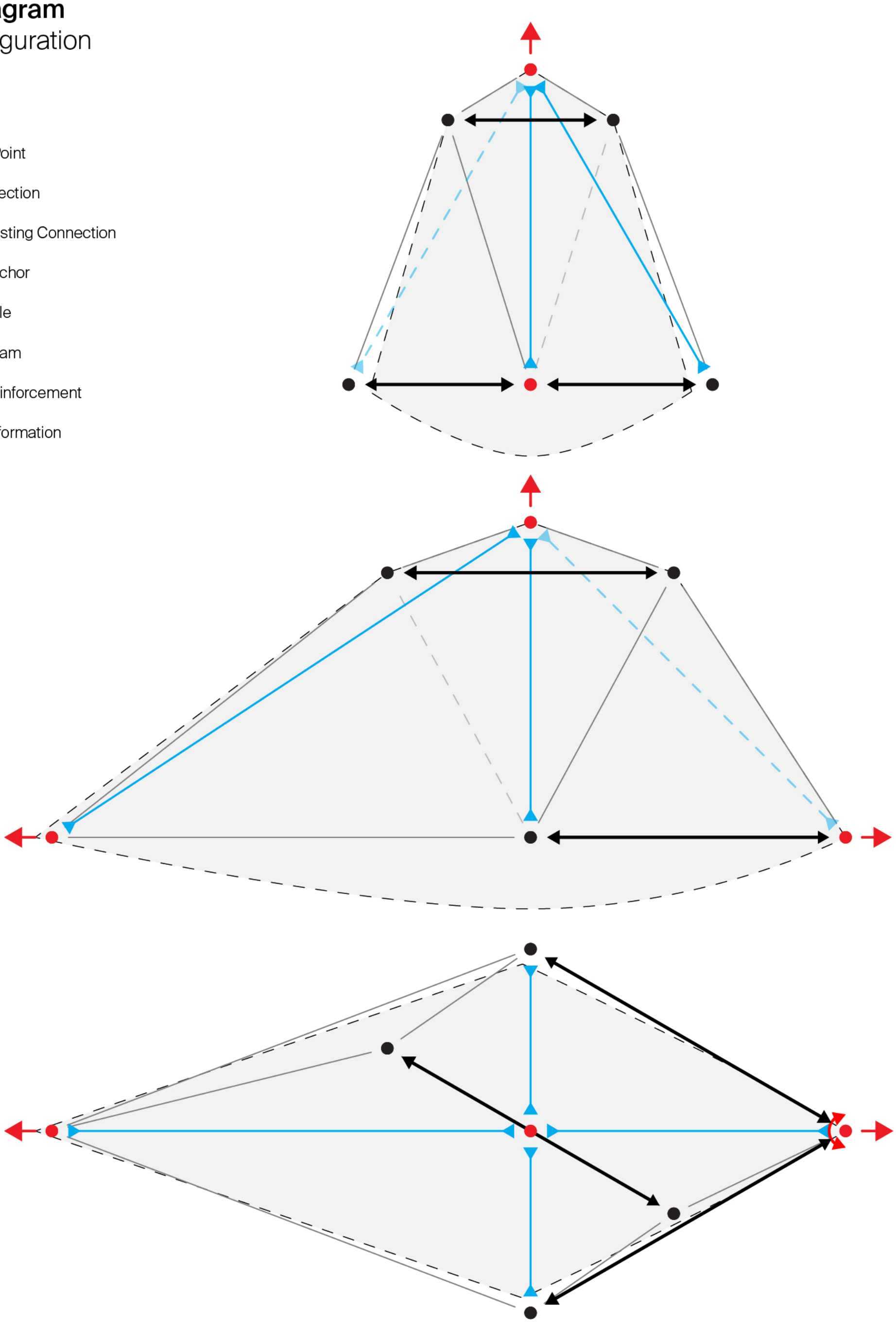


FIG 4.26 Placing the 30-litre water container into the hanging prototype.

FIG 4.27 Initial failure of the secondary support (left).

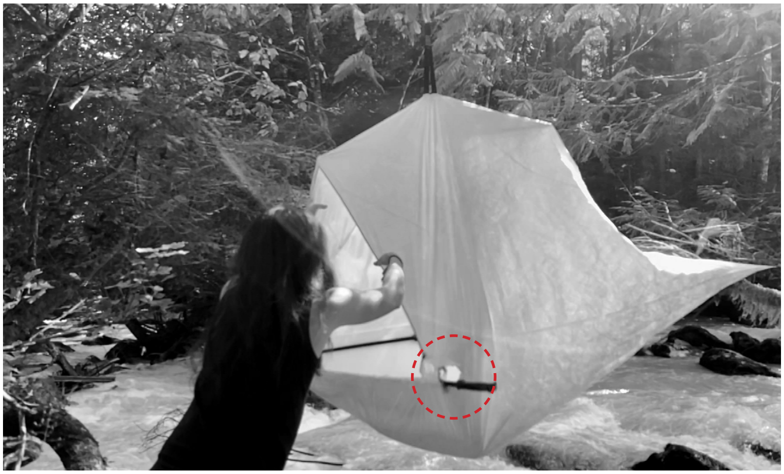


FIG 4.28 Failure of the membrane at right corner where pole handle applies pressure to the membrane (centre).

FIG 4.29 Failure of membrane at right corner created substantial springback in pole 'V' connector.

FIG 4.30 Springback causes 'V' connector to fracture and break apart.

FIG 4.31 Despite regional failures in the membrane, the top anchor remained intact.

MEMBRANE SIMULATION

FIG 4.32 *Opposite Page:* Kiwi!3D Simulation sequence from 75 pounds of loading to 300 pounds of loading.

To better visualize the regional loading and deformation of the enclosure and prevent the type of structural failure witnessed in the testing of the first 1:1 prototype, a simulative modelling exercise was introduced into the design workflow. This process involved another parametric design tool called Kiwi!3D, an isogeometric analysis plugin for Grasshopper 3D.[5] *Isogeometric analysis* (IGA) is a subset of finite element modelling used to simulate the performance and failures of a design digitally, often through visual mappings and animations of dynamic material behaviours within the 3D environment.[6] Kiwi!3D's IGA platform was especially useful in this pipeline because it leveraged the native modelling format of Rhinoceros 3D software, *NURBS* (Non-Uniform Rational B-Splines), and did not require the conversion of geometry to meshes, which could require additional time and processing power during simulation. Using Kiwi!3D tools, the 3D enclosure model was sorted and defined into structural elements (membranes, cables, and beams) and forces (surface loads and supports). These components were fed through an analysis model, which outputted a deformed geometry and stress map, and associated animations to show how these outputs changed with the increase in surface load.

Significant stress and deformation were observed in the simulation outputs, and an additional cable network was added to the surface of parts of the membrane to simulate the effects of added reinforcing filaments. The addition of these cable members dramatically impacted the simulation results, significantly lowering both the stress and deformation of the enclosure. The remaining high-stress regions were noted as sites for reinforcing patches of adhesive and additional DCF layers.

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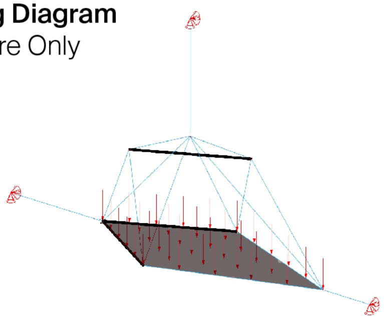
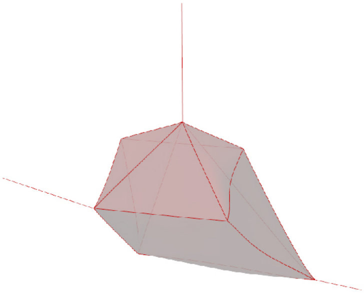
[5] Anna Bauer and Philipp Längst, *Kiwi!3D*.

[6] La Magna et al., "Isoropia."

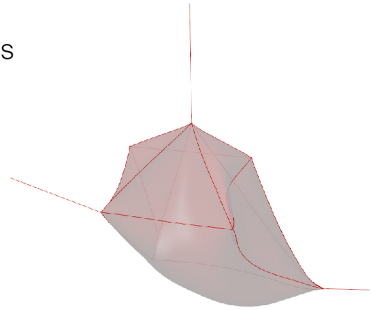
Loading Diagram
Enclosure Only



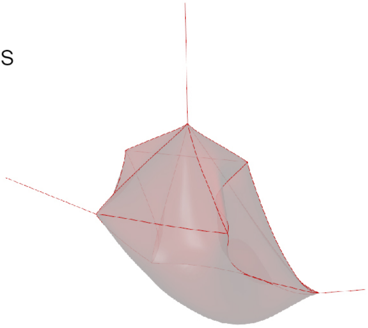
@75 lbs



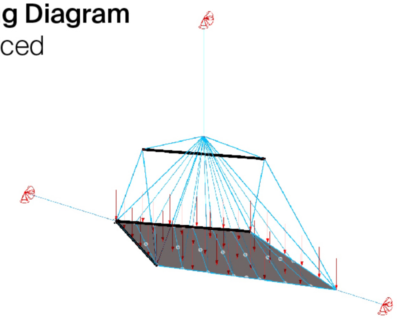
@225 lbs



@300 lbs



Loading Diagram
Reinforced



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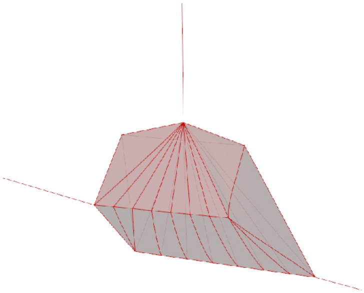

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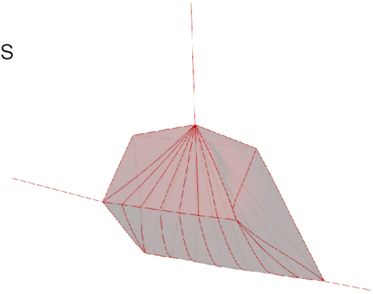

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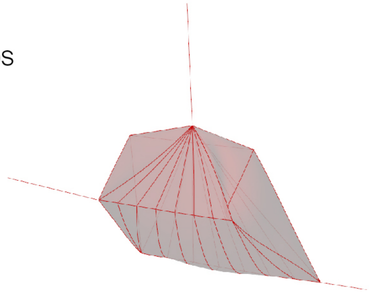


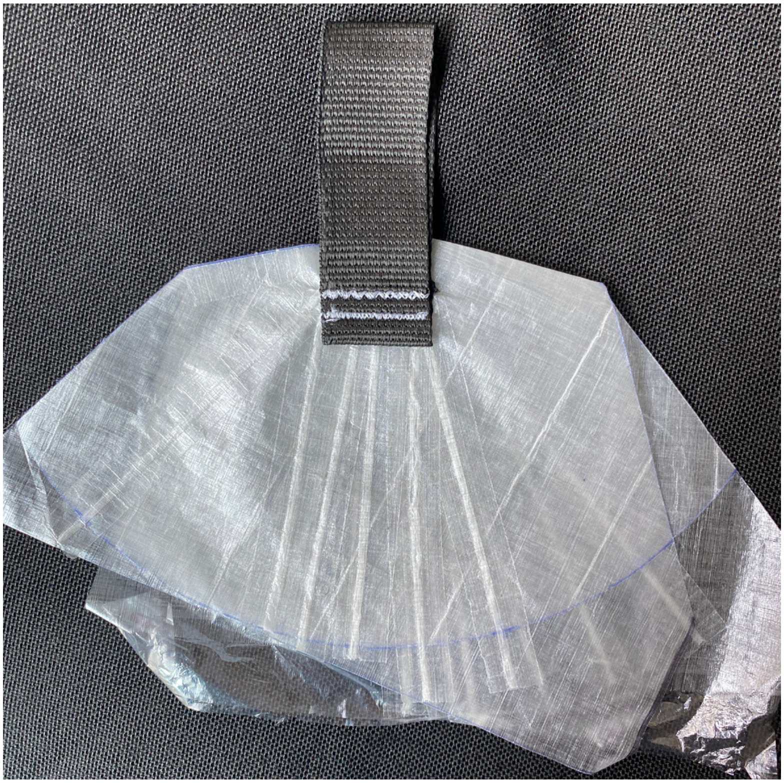


FIG 4.33 Prototyping the connection between filament paths and anchoring points.

MATERIAL STRUCTURE REFINEMENT

The results of the IGA model were used to place seams and filament tape in the enclosure's reinforced membrane. When dividing the enclosure into pattern pieces, the orientation of seams and shape of pattern pieces was created in a manner that would allow all surfaces involved in supporting the weight of an occupant to be sewn, seam-taped, and laid flat in a single composite piece to receive the continuous filament tape that would wrap back and forth between anchoring points. The specific path for the taping was designed to pass through high-stress areas as it passed between anchors so that stresses could efficiently be transferred from membrane to anchor. These paths were drawn in Adobe Illustrator using the stress maps as a base. The Illustrator files were mapped onto the sewing pattern and visualized in 3D using CLO. Once the design refinement was complete, the sewing pattern was sent to a plotter for print.

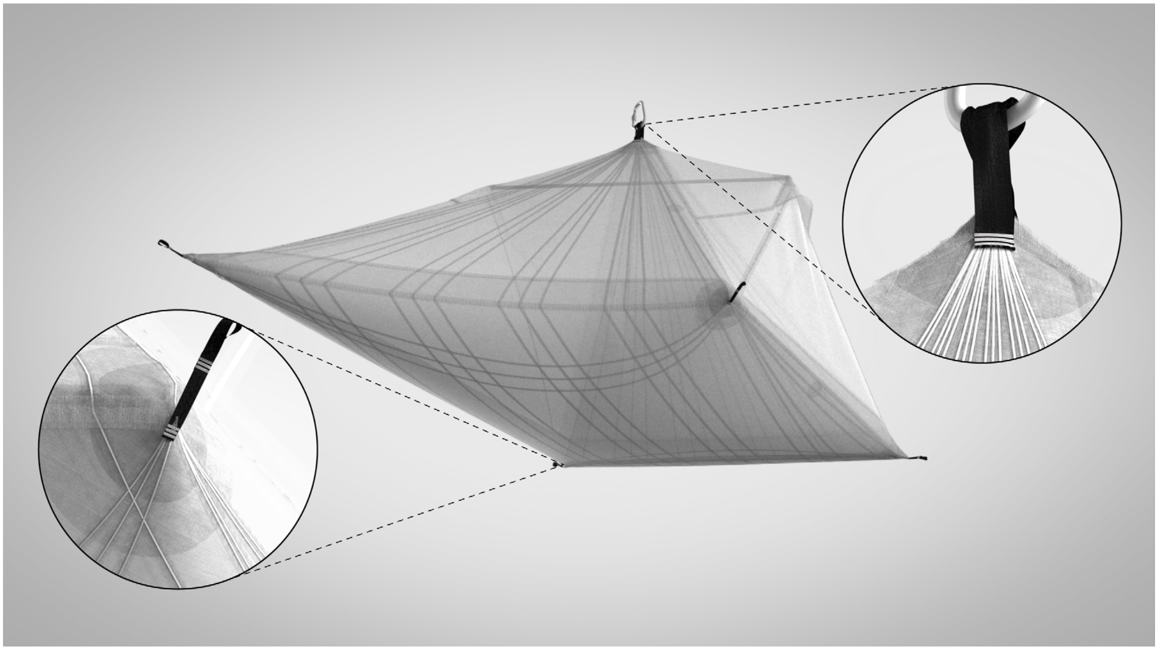


FIG 4.34 Rendering of connection point details.

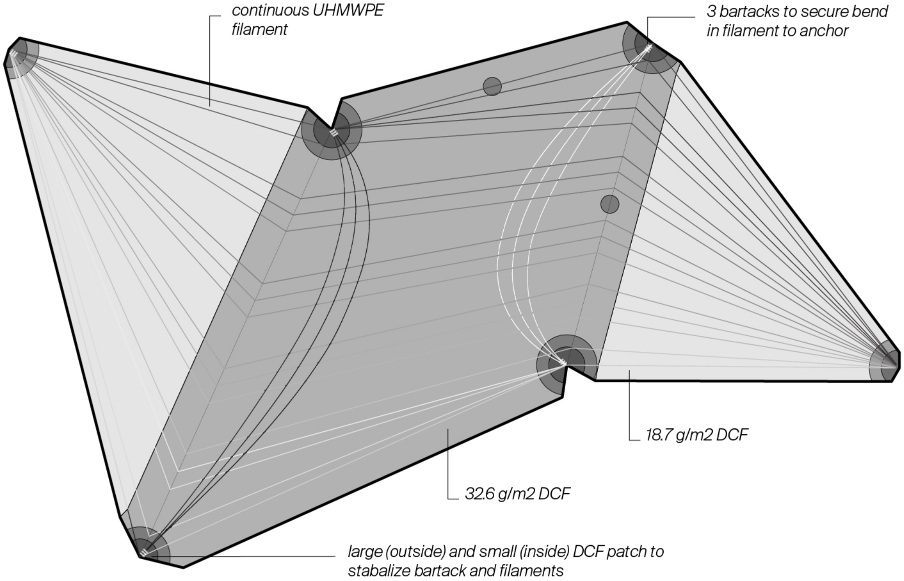


FIG 4.35 Filament structure arrangement.

At this point in the fabrication process, the critical detail of where the filament tape was attached to the sewn-in webbing loops needed to be resolved. The locations for these anchoring points were also where the filament tape would fold on itself and change direction, so it was crucial that load-bearing zig-zag stitches, known as bar tacks, be used at this exact location to prevent excessive strain on the membrane fabric. This detail was prototyped to validate its strength and feasibility for sewing.

FIG 4.36 *Previous Page, Left:* Rendering of tent interior and occupant.

FIG 4.37 *Previous Page, Right:* Rendering of refined material structure from viewpoint of a supine occupant.

FABRICATION OF HI-FI PROTOTYPE

The first step in the fabrication of the final prototype was creating the filament tape. This process was highly time-consuming and required the careful laying out of continuous UHMWPE filament onto adhesive strips, placing the filament and adhesive across the width of the lightweight DCF fabric, and then cutting the DCF to the width of the adhesive. This process was repeated in 1.2-metre sections (the width of the DCF roll), which kept the UHMWPE continuous and breaks in the material backer to a minimum. Each section of tape took roughly 20 minutes to complete, leading to a total fabrication time of 20 hours to produce the 75 metres of continuous filament tape required to reinforce the entire enclosure.

FIG 4.38 Making the filament reinforced tape by hand.

Next, the load-bearing pieces of the pattern were sewn, taped, and laid flat on the printed paper pattern, which was annotated with the path of the filament tape. Masking tape was applied to the back face of the pattern pieces to mark the filament paths for taping. The tape was then applied along the marked path using a silicone roller to begin the adhesive curing process. Reinforcing patches were applied to the front and back face of the membrane material at locations where webbing anchors would be sewn in place, followed by the light application of heat to these crucial areas using a heated clamshell press. Anchors and trims were then sewn into the reinforced pieces and patched with adhesive-backed DCF to prevent tearing and maintain a continuous waterproof enclosure. Next, the remaining pattern pieces were assembled, and seam-taping and reinforcing patches were applied to seams and critical connection points to complete the enclosure.

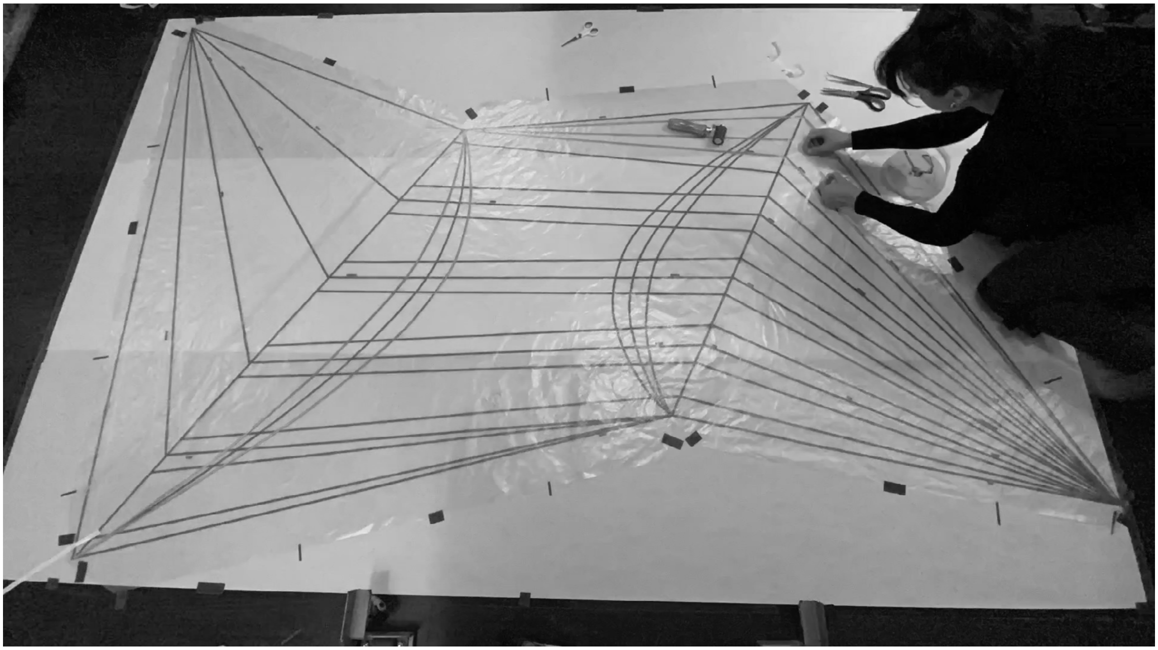


FIG 4.39 Following marking tape guides to lay out filament tape.

FIG 4.40 Assembling the pattern pieces of the enclosure.

FIG 4.41 Previous iterations of the ‘V’ joint connector.

FIG 4.42 3D Printing the final ‘V’ joint connector.

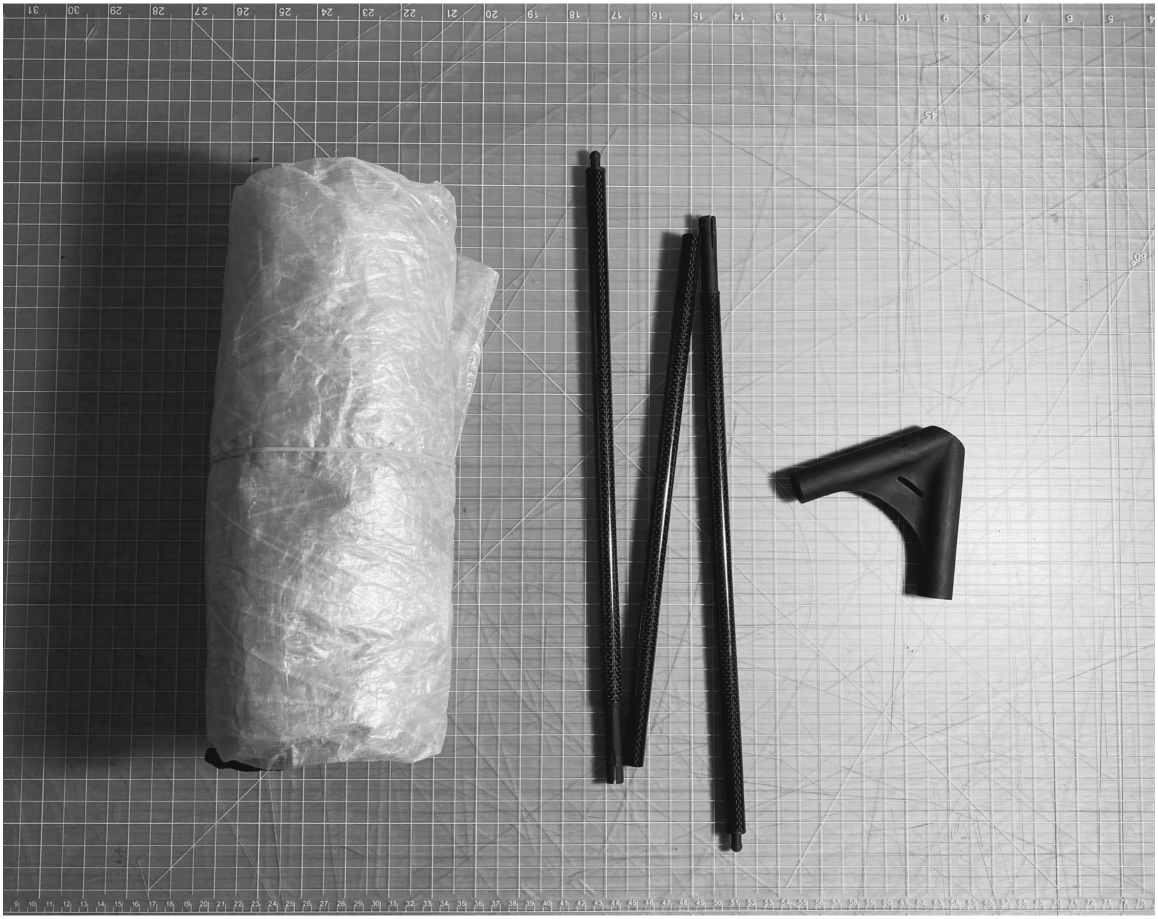
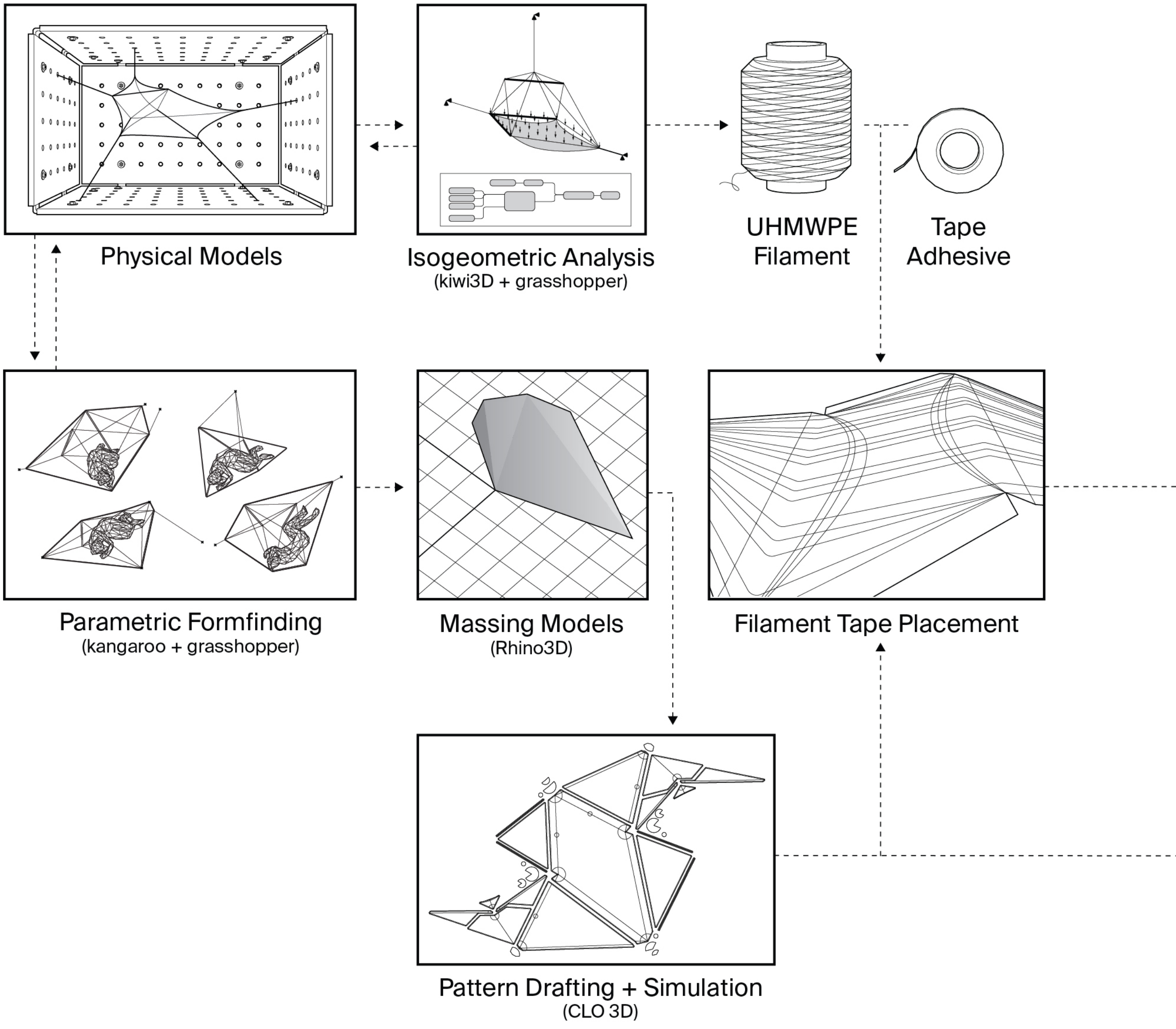


FIG 4.43 The completed components of the shelter system: enclosure, ridge pole, and pole connector.

The final form factor for the pole connector was 3D printed while the enclosure was being assembled. Other miscellaneous pieces for the final design, like connectors for a collapsible carbon fibre ridge pole, were also 3D printed for the final prototype. Printing custom parts saved time and allowed for affordable low-profile components to be used.

Prototyping Workflow

Tools + Processes



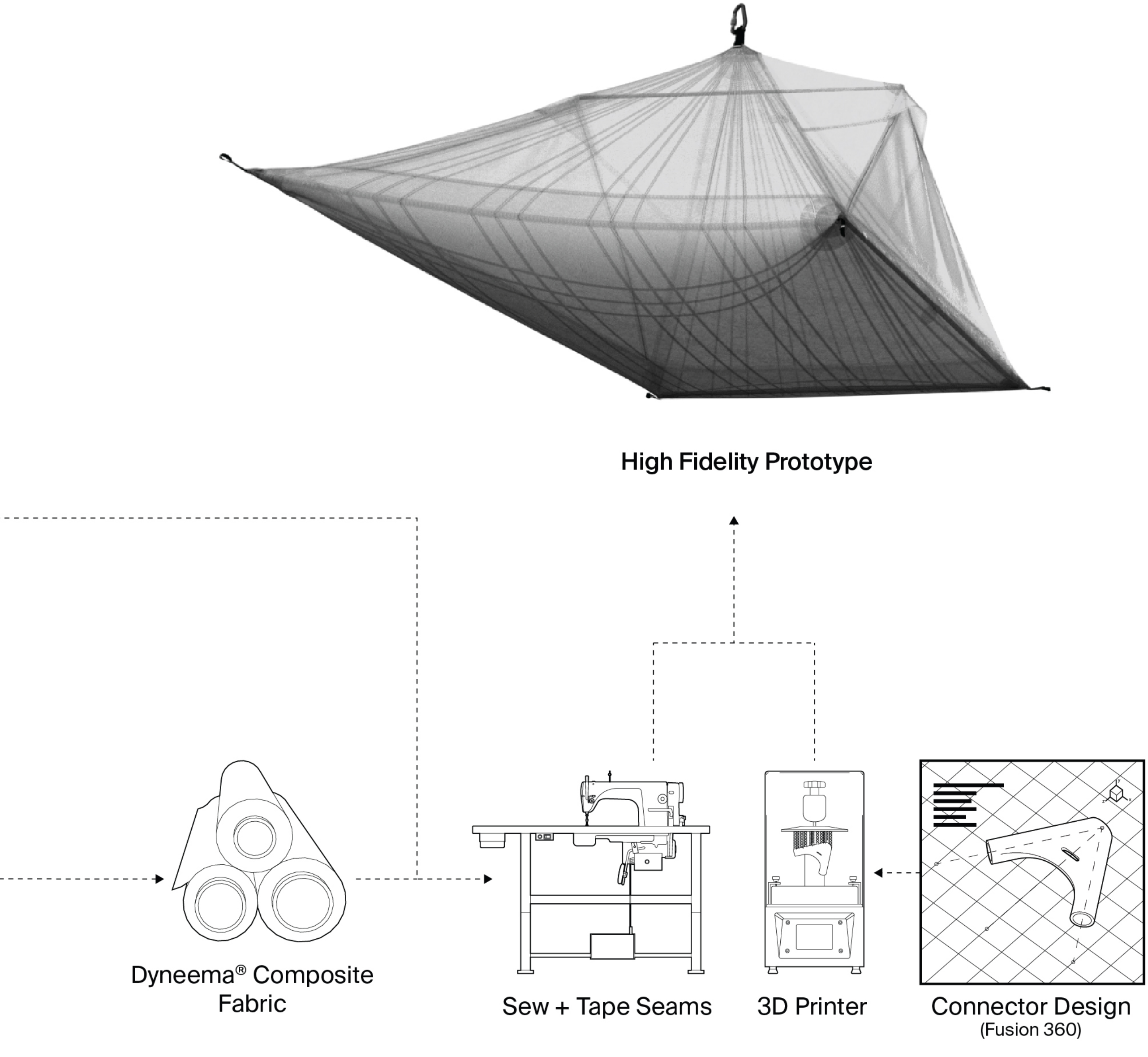


FIG 4.44 Diagram of prototyping tools and processes.

FIG 4.45 Setting up the completed prototype.

Part 5

Results and Reflections

PROTOTYPE PERFORMANCE

The complete high-fidelity prototype had a crystalline aesthetic that appeared surprisingly delicate for a structure designed to bear the weight of its occupant. The enclosure alone weighed 368 grams (480 grams including the pole connector and collapsible ridge pole). This lightness was also unexpected considering that most ultralight shelters, even those designed strictly for use on flat ground, do not typically weigh in at less than 800 grams for the enclosure alone. For comparison, state-of-the-art shelters and their enclosure weights are listed below:

Manufacturer/Model	Shelter Type	Weight
Black Diamond, Single Portaledge	Portaledge	9900 grams
G7, Pod + Storm Shelter	Portaledge	2400 grams
Tentsile, Una	Hammock	3200 grams
Sea-to-Summit, Pro Hammock + Tarp	Hammock	858 grams
Hyperlite Gear, Echo 2 Shelter System	Ground Tent	823 grams
Tarptent, Aeon Li	Ground Tent	490 grams
Hybrid Bivouac	Adaptable	480 grams

FIG 5.01 Shelter weight comparison by type.

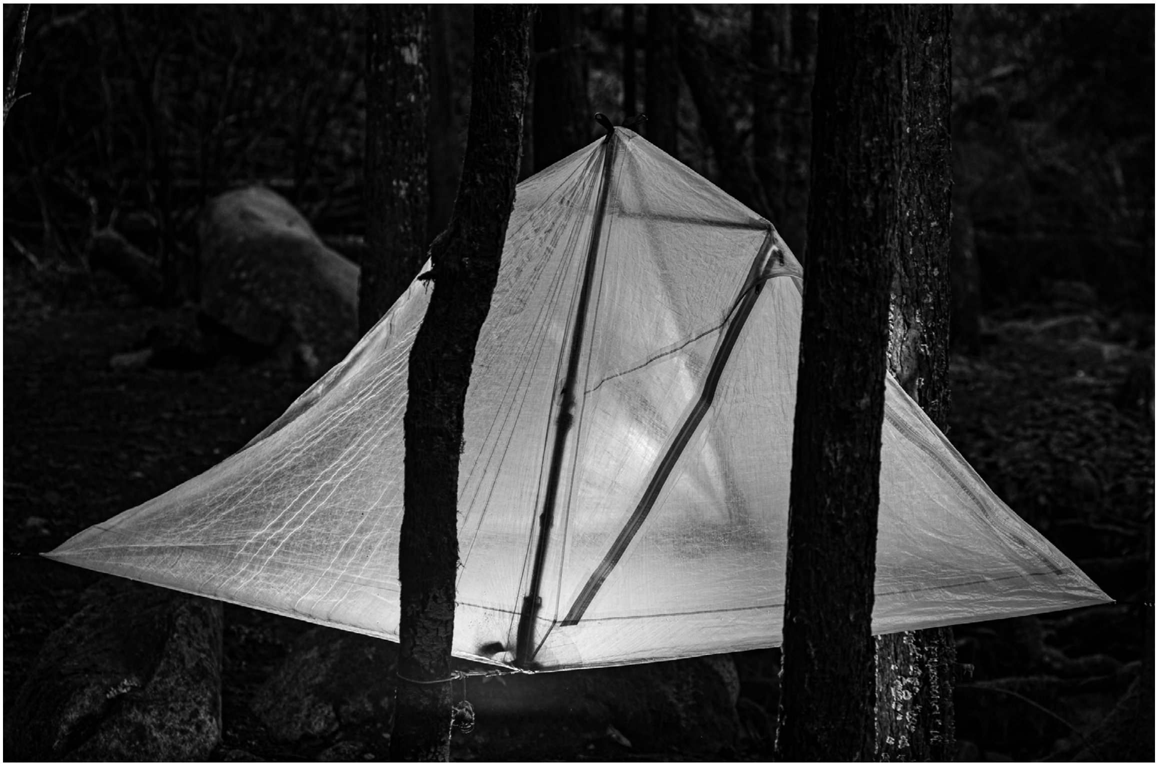
In the first weight-bearing test of the Hybrid Bivouac, the shelter was rigged from its peak in its most minimally anchored configuration. Then, a 25-litre water container (used previously to test the low-fidelity prototype to failure) was placed inside. With this weight on the bottom of the enclosure, the filament tape was visibly engaged in tension, with the hiking pole frame maintaining volume inside the shelter despite the internal loading. The structure was then configured in its tensioned platform condition, and the water container test was repeated. With the membrane successfully supporting this load, the structure was then tested with a human occupant. Like the water container test, their weight was successfully supported by the membrane. It was also observed that the transparency of the membrane, which allowed for views of the sky between the thin strands of reinforcing filament, and the gentle arc of the shelter's tensioned base resulted in a comfortable experience for the occupant (FIG 5.02).

Over the course of a week, the Hybrid Bivouac was tested in various outdoor settings in the local mountains and valleys surrounding Pemberton, British Columbia. This qualitative testing included bringing the bivouac rock-climbing to experiment with suspended

FIG 5.02 *Previous:* Looking out from the Hybrid Bivouac.

FIG 5.03 *Right:* Weighing the compressed enclosure.

FIG 5.04 *Below:* Tree Rigging.




480
PCS
T
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FIG 5.05 Pitched on the snow.

FIG 5.06 Tensioned from each corner to create a floating shelter between trees.

FIG 5.07 Suspended from above in a rock cave.

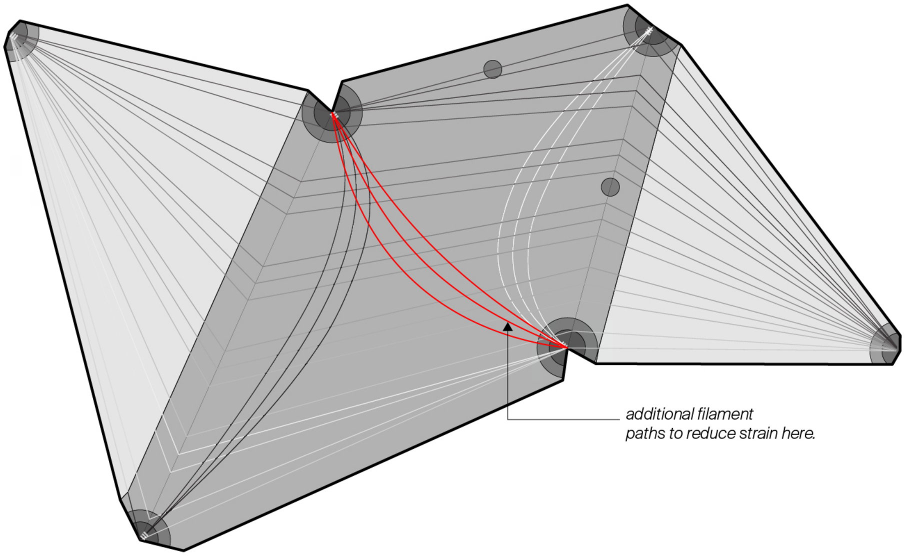


FIG 5.08 Proposed revision to filament paths.

riggings in caves among the rock bluffs, ski touring to trial the shelter pitched in the snow, and hiking in the forest to experiment with the ideal rigging for a set up between trees. During this time, problems in the design of the filament tape path were observed. The primary concern was the failure to add a tape array across the width of the enclosure's base, which was leading to an isolated region of membrane *creep* (visible and permanent deformation of the fabric) where entering and exiting the enclosure placed a high amount of stress on the material. In the diagram above, a resolution to the filament paths is shown that would prevent this creep from occurring through effective transfer of loading between anchoring points with minimal impact on the overall weight and design.

Overall, the Hybrid Bivouac performed exceptionally well with respect to its functionality and strength-to-weight ratio. While improvements to the filament paths and connection points would have a positive impact on the use and lifespan of the shelter as a product, the overall design and resolution of the high-fidelity prototype successfully adapted to a range of site conditions, was straightforward and quick to set up and take down, and the entire system compressed into a small and lightweight package.

FIG 5.09 Filaments wrapping up from bottom of shelter.

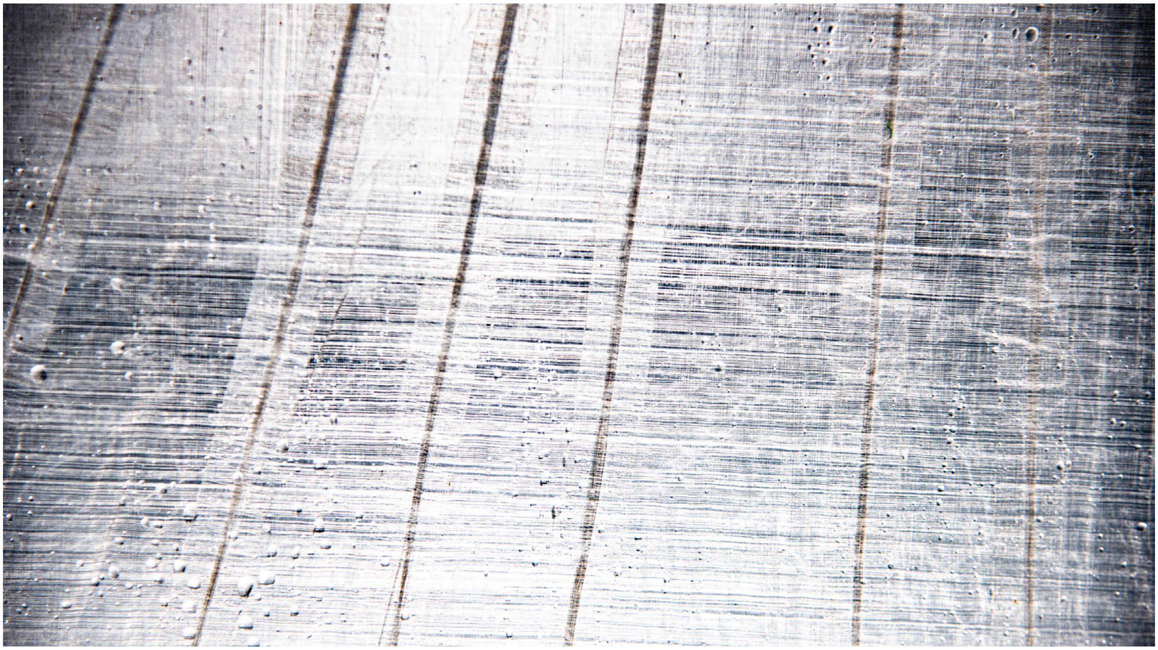


FIG 5.10 Detail of UHMWPE filaments embedded in membrane.

FIG 5.11 Front and back openings unzipped.

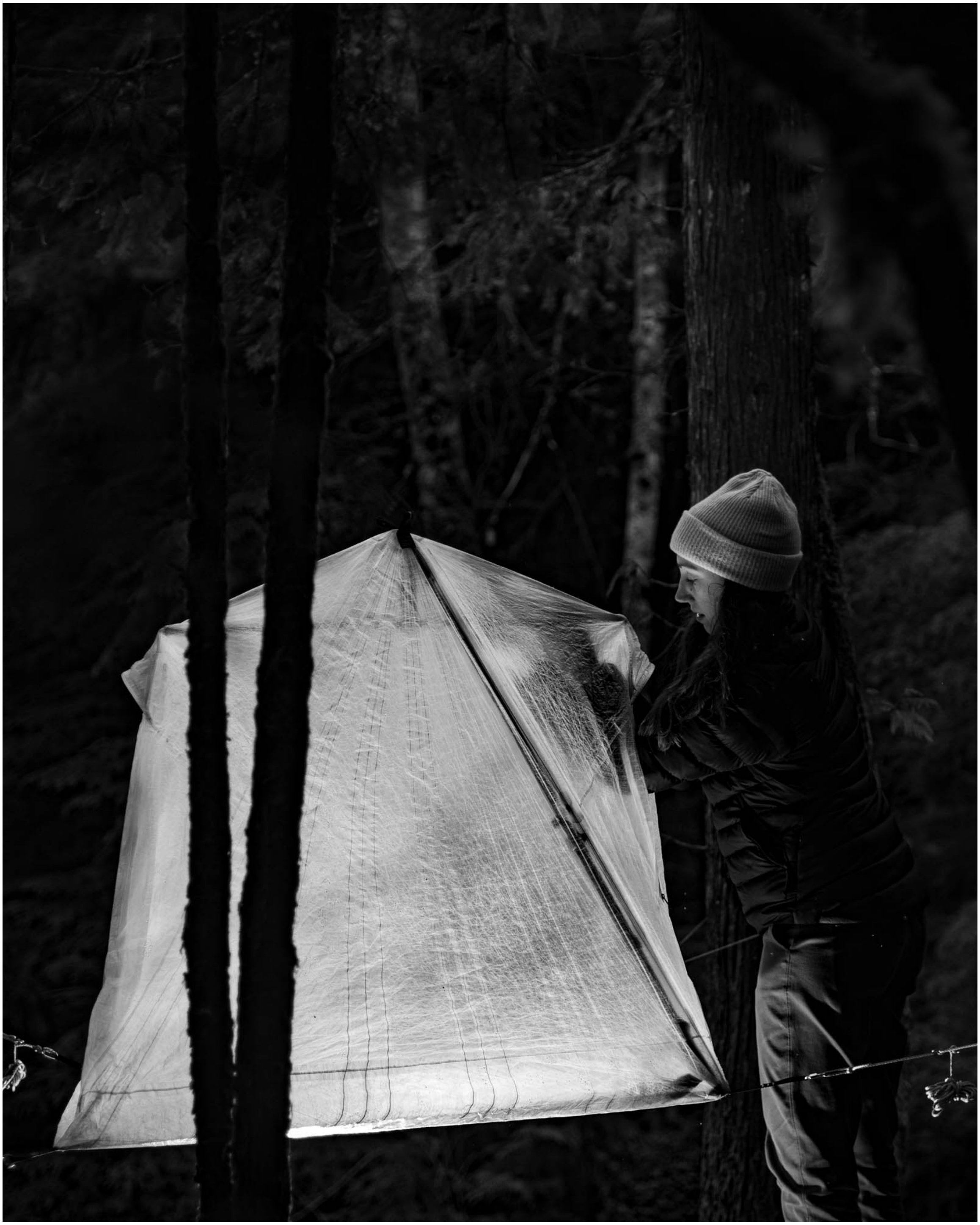
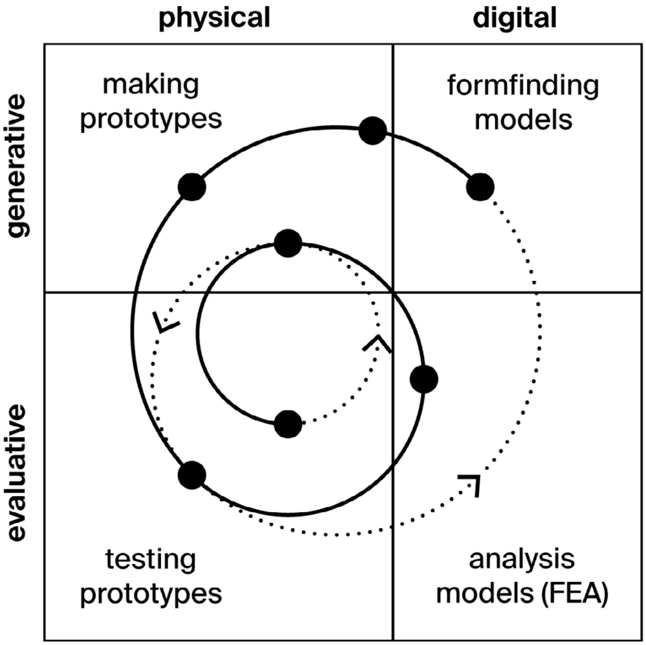


FIG 5.12 Cyclical process model.



DESIGN PROCESS MODEL

The cross-disciplinary approach to this design exploration left me with a scalable process. To break this process down, the activities involved in this project can be categorized by two axes: physical vs digital and generative vs evaluative modelling. Cycling through the four quadrants created by these axes allowed design problems emerging from the work to be viewed through a constantly shifting lens, encouraging multi-faceted solutions. This cycle can be legibly traced through various aspects of the design. For example, the geometry of the enclosure began with a physical model that was used to generate a form. This form was then translated to a digital model used to expand the possibilities of this geometry. The outputs of the digital model were then evaluated based on the functional constraints of a habitable tent, and finally, a form was chosen to build a scale model to evaluate further whether this form was structurally successful in the real world. This loop is illustrated in the diagram above.

FIG 5.13 *Left:* Opening the zippered door to enter the shelter.

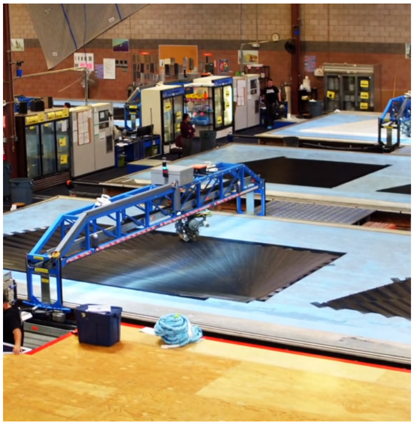


FIG 5.14 Large CNC beds of the North Sails Automated Taping System (ATS).

MASS CUSTOMIZATION

In the creation of a proof-of-concept prototype, labour-intensive fabrication methods are often used to avoid the risks of setting up a more sophisticated fabrication infrastructure before the validity of the product is confirmed. In most cases, it is also important to keep scalable manufacturing methods in mind to avoid creating a product that is not commercially viable later in the development process. In the case of the Hybrid Bivouac prototype, the process of bonding reinforcing filaments to the membrane by hand was too time-consuming to be considered for a mass-manufactured product or a large membrane structure. However, there are many precedents for automating this process. As mentioned previously, this fibre reinforcing method is modelled on the manufacture of high-performance sails for racing yachts, and out of this field, many automation methods for fibre-reinforced composites have been perfected. The sail manufacturer, North Sails, uses a large CNC system consisting of a warehouse fitted with overhead gantries and a robotic arm.[1] This robot arm receives various tools, one being a 6-axis fibre deposition head that can precisely plot the location of reinforcing filaments or a unidirectional fibre-reinforced tape onto a sail membrane and 3D mould.

It is not hard to imagine this process being adapted for architectural membrane composites, as yacht sails, membranes for small buildings, and panels within a larger architectural membrane are similar in scale. Adapting automation from flexible composites to architecture allows for both a scalable model for highly tuned tensile structures and mass customization within these structures. Like the structure explored in this thesis, the use of CNC-deposited filament structures within a membrane allows for textile architectures that are both materially efficient and optimized for their function.

FIG 5.15 *Left:* Robotic arm depositing carbon fibre filament on the membrane of the 2014-2015 ICD/ITKE Pavilion.

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[1] Pearson, "Textiles to Composites: 3D Moulding and Automated Fibre Placement for Flexible Membranes," 313.

FIG 5.16 Looking through the transparent enclosure.

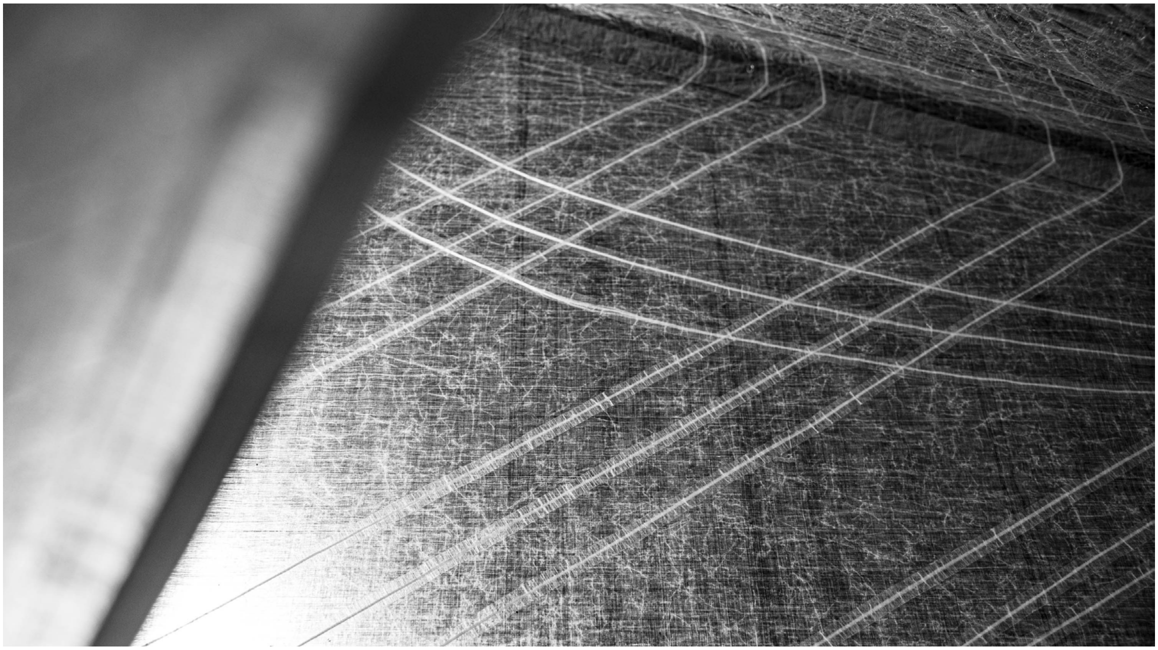

FIG 5.17 Filament paths intersect across the tent bottom.

FIG 5.18 *Next Page:* The Hybrid Bivouac in the trees.

TOWARD A LIGHTER ARCHITECTURE

“The roof had a charm of its own. It was a strict minimum energy surface, like a soap bubble...It was white and transparent like a spider web in the morning dew. We had helped it come into being, we had not designed it.”

Frei Otto, 1957, Speaking of his dance pavilion
tent at the Cologne Garden Exhibition.[2]

The embedding of fibre architecture into tensile membrane enclosures creates opportunities for highly materially efficient and structurally resilient portable shelters. As material consumption is put under increased scrutiny, efficient fabric architectures should also be considered for more permanent buildings. However, flexible architecture is materially complex and dynamic, and more research and experimentation are required to develop new and better practices for designing, constructing, and maintaining these types of buildings. With less opportunity for structural redundancy and the safety factors resulting from this material inefficiency, precise material placement and construction tolerances need to become more stringent to incorporate these new building typologies into the urban fabric. Even still, the shift away from the heavy, immobile, and materially intensive construction of our current built environment to building systems based on light, adaptable, and efficient enclosures is compelling. From inside the suspended enclosure of the Hybrid Bivouac, with the sky visible through its translucent walls, it is easy to see why Frei Otto dedicated his career to the organic openness of tensile membrane structures. Like the spider web, these delicate structures are no matter of show and aesthetics. These light constructions are, as described by Frei Otto, “an architecture of survival.”[3]

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[2] Yousufi, “Fabric Structures,” 5.

[3] Hassel, *Frei Otto: Spanning the Future*.

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GLOSSARY

America's Cup: A prestigious yacht race dating back to 1851 that is globally acknowledged for being a catalyst of new sailing technologies.

avatar: A digital twin of an anatomical human.

ballistic (textile): Referring to a material that has undergone robust mechanical testing for durability; often related to impact protection against projectiles.

bar tack: A load-bearing stitch consisting of overlapping rows of zig zag machine stitches; often used in climbing harnesses, slings, and bags.

bivouac (shelter): Commonly referred to as a "bivvy"; a small tent or body-sized enclosure used for taking temporary or emergency shelter or for sleeping.

buckling resistance: A structural engineering term referring to a material's ability to resist sudden deformations such as the wrinkling of a sheet material or the bowing of a column.

CAD: Computer-aided design.

carbon fibre: A synthetic fibre commonly used in performance composites manufacturing that is characterized by its high strength-to-weight-ratio and tensile modulus.

CITA: Centre for Information Technology and Architecture at the Royal Danish Academy of Fine Arts.

CLO: A 3D fashion and soft goods design software that leverages 2D CAD and dynamic 3D textile physics simulations.

CNC: Computer numerical control, referring to a machine or process where a computer autonomously operates a tool based on numeric inputs.

composite: A material produced through combining two or more materials with differing and typically complementary material properties.

computational models: Digital approximations of physical forms and phenomena represented in a CAD environment.

creep: A material phenomena in which a substrate undergoes an irreversible deformation with continued loading over time.

DCF: Dyneema® Composite Fabric; a family of composite fabrics manufactured and trademarked by DSM; comprised of several alternating layers of UHMWPE filaments.

empirical testing: A means of evaluating the characteristics of a material, assembly or product through observation.

ETFE: Ethylene tetrafluoroethylene; a plastic commonly used for tensile or pneumatic architectural membranes and canopies.

filament: A continuous strand of extruded material produced through spinning.

Fusion 360: A parametric solid modelling tool by Autodesk.

FEA: Finite element analysis; a modelling process by which forces, stress, strain and deformation are simulated and visualized with a computer program.

fly (shelter): The outer weather-resistant layer of a shelter system. In standard ground-pitched tents, the fly is typically bottomless and used in combination with an inner layer comprised of a waterproof base and mesh upper.

form-active: A characteristic to describe the reciprocal relationship between form and loading in a structure.

form-finding: The process of composing a geometry by way of experimentation, often leveraging computational models.

gel-spinning: A filament processing method that uses solvents to convert extruded plastics into a gel and further elongating them through spinning. This method is used to produce the highly aligned polymer structure and resulting high-modulus characteristics of UHMWPE.

generative modelling: A broad classification of procedural modelling through which forms are generated indirectly by the user or with some degree of computational autonomy by specifying goals within CAD software.

goals (computational): Parameters defined in generative models that influence the outputs of an algorithm.

Grasshopper 3D: An algorithmic plugin for Rhinoceros 3D that enables an environment for a range of parametric and procedural modelling tools.

hammock: A spanning textile platform or sling connecting to two or more anchoring points, used for sleeping and resting. A hammock can be open to the elements or covered on top to create an enclosed shelter.

high fidelity prototype: A working model of a product or process with a high level of resolution and investment in its development.

ICD: Institute of Computational Design and Construction at the University of Stuttgart.

IGA: Isogeometric analysis; a type of FEA modelling used in the plugin Kiwi!3D that engages directly with NURBS geometry.

isotropic: A material that has consistent mechanical properties along all axes, regardless of direction.

ITKE: Institute of Building Structures and Structural Design at the University of Stuttgart.

Kangaroo Physics: A physics-based simulation and form-finding solver for Grasshopper 3D developed by Daniel Piker.

Kiwi!3D: Isogeometric analysis plugin for Grasshopper 3D developed by Anna Bauer and Philipp Längst.

laminate: A substrate comprised of multiple layers of material that are bonded together to achieve new material characteristics.

LCD 3D printing: A low-cost resin-based 3D printing method where an LCD screen is used to cure the bottom surface of a resin tank, layering cured resin onto a rising build plate until a 3D object is produced.

low fidelity prototype: A working model of a product or process created as a quick and low-cost way to test a concept before further investment in the development process.

membrane (architectural): A pliable textile layer used to separate environments or provide protection.

mesh (computational): A type of computed 3D geometry that has been subdivided into a finite number of vertices.

modulus: A measure of structural stiffness or resistance to elastic deformation under the application of stress.

NURBS: Non-uniform rational b-splines, a computationally efficient mathematical model for curve representation, used in the CAD software Rhinoceros 3D.

nylon: A common name for polyamide plastic, which is often processed into textile fibres or rigid plastic goods.

parametric modelling: A type of procedural modelling that translates data inputs through an algorithm to edit and generate geometry and associated information that is intrinsically linked to input variables.

PE: Polyethylene plastic, ubiquitous in plastic films and packaging due to its high ductility and low strength. A range of PE subsets with improved mechanical properties, like UHMWPE, is achieved by changing the material's molecular density.

peel strength: A measure for a bond’s ability to resist being pulled apart when opposing forces are applied.

PET: Polyethylene terephthalate plastic, or “polyester” when referring to PET fibres for textiles. This thermoplastic is commonly used to produce textiles, films and rigid goods like plastic bottles.

PU (coating): Rubber-like polyurethane plastic coating for textiles that improves water resistance and durability.

portaledge: A type of suspended sleeping shelter used by rock climbers and mountaineers during multi-day climbing routes.

PSA: Pressure-sensitive adhesive; an adhesive that achieves its bond through the application of pressure.

procedural modelling: A modelling process by which data inputs are entered into an algorithm to produce geometry or other forms of spatial data.

resin (synthetic): Viscous amorphous polymer; in composites manufacturing and 3D printing it is used in a liquid state during processing followed by curing with UV light or heat to achieve a solid or stable polymer.

Rhinoceros 3D: A NURBS-based 3D modelling software developed by Robert McNeel & Associates.

ripstop (textile): Weaving structure in textiles used to strengthen a material with a grid-like pattern.

silicone (coating): A rubber-like polymer coating often applied to the surface of a textile to enhance water-resistance and durability.

specific strength: The strength characteristics of a material proportional to weight.

station (rock-climbing): An anchor within or at the top of a rock-climbing route that uses multiple connection points to the rock (either pre-drilled bolts or camming devices placed into natural features) to create redundancy.

strut: A rigid length of material.

Tyvek®: A brand of spun-bound PE substrate used extensively in water-resistant packaging and building envelopes.

UHMWPE: Ultra-high-molecular-weight polyethylene plastic; a type of PE that has been altered for exceptional specific strength. When produced as a filament, the process of gel-spinning further increases its tensile strength.

webbing (textile): A fabric woven in robust and narrow strips often used for load-bearing applications.