The Feasibility of CFRP Cables in Long Span Temporary Tensile Membrane Structures

A D.ARCH PROJECT SUBMITTED TO THE GRADUATE DIVISON OF THE UNIVERSITY OF HAWAIʻI at MĀNOA IN PARTIAL FUFILLMENT OF THE REQUIREMNTS FOR THE DEGREE OF

DOCTOR OF ARCHITECTURE

MAY 2019

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Acknowledgments

This dissertation would not have been possible without my committee: David Rockwood, Lin Shen, Do Soo Moon, and Tim Goshi. Thank you for sharing your knowledge and encouragement. All of the time that you all have committed has been incredibly fruitful in helping me complete this dissertation.

I would also like to thank my parents Phil and Tena Ritter, who taught me the tenacious spirit required to complete my doctorate. Without their support I would not have been able to continue my education or get anywhere near where I am today.

Abstract

Carbon Fiber Reinforced Polymer (CFRP) cables have the potential to replace steel in orthogonally loaded tensile membrane structures. Tensile membrane typologies are used in place of traditional compressive structures because of their efficient material use, light weight, mobility, and ability to span long distance without support columns. CFRP cables have the qualities required amplify all of these advantages even further. CFRP cables have been proposed and tested to replace steel because they are five times lighter, twice as strong, resistant to atmospheric degradation, and fatigue at half the rate of steel. These cables are not only lighter than steel, but they require less material to achieve the same ultimate strength. This makes CFRP a better solution for mobile tensile structures to create lightweight, long span structures that are readily mobile. Despite the promise of this material, there are still a number of construction and material problems that must be addressed such as the high cost, wind loads, and low sheer strength of CFRP. This study will evaluate the feasibility of CFRP cables replacing steel based on span capabilities, economic feasibility, and constructability for temporary tensile membrane structures. This criteria will be applied to CFRP Cables in one way cable beam and two way cable net structures. I will make a case that CFRP cables are a better option that steel at a comparable price based on a design system for a long span mobile disaster relief shelter.

Introduction

The advent of steel changed the built environment. Steel challenged the possibilities in building and the limits were pushed skyward. The new material's light weight and high strength enabled buildings to soar higher than they ever had. CFRP has the potential for the same impact, with a tensile strength five times that of steel while maintaining a fraction of the weight. These strong and light weight cables can reduce the building material required for tensile structures while simultaneously lowering the dead load of the cable structure. This allows for the possibility of longer spans than currently feasible with steel cables. Additionally, the low material density and high efficiency can cut time on labor, installation, and transportation of these structures.

CFRP's ability to decrease transportation weight as well as increase the unobstructed span for long span tensile construction make it perfect for mobile, long span tensile construction. Additionally, CFRP cables have an extremely long life span as a result of their high fatigue and atmospheric resistance. I will argue that these properties make a good option for a government owned temporary disaster relief shelter. This structure can take advantage of the large, uninterrupted spans when large amounts of people are displaced in events such as Hurricane Katrina. CFRP cables can create a semi-temporary, lightweight structure with the highest material efficiency possible for ease of transportation and construction. On top of this, CFRP's

resistance to fatigue loads as well as atmospheric degradation mean that this structure can be erected for multiple emergency events with a projected lifespan 2-8 times that of steel. This study will evaluate construction methodology and best practices for CFRP cables in tensile membrane structures through the theoretical construction of this disaster relief shelter.

Cost is a major concern for the application of CFRP in any industry today. With a standard unit price at $10 per pound, it seems impossible that it could replace industrial steel, which costs 40 cents per pound. However, cost per pound is a deceiving metric when it comes to carbon fiber. With of its relative strength and lighter weight, CFRP cables have a much higher value per pound than steel. Additionally, steel cables require a number of processes to increase their overall tensile strength. These processes bring the price of steel cables within a reasonable distance of CFRP cables. This study will show that CFRP cables are comparable in price to long lasting steel cables based off of ultimate breaking strength and life cycle. In order to understand the pricing of CFRP, it is important to comprehend the history and production process of CFRP and how they influence its cost.

History

Carbon Fiber Reinforced Polymer is a composite material made up of carbon fibers and a binding polymer matrix. As a general definition, composite materials consist of two or more constituent materials that, when combined, create a material with better qualities than either precursor.

Some of the earliest examples of composites are Egyptian and Mesopotamian bricks made of mud and straw, created around 1500 BC. In this case, the straw is acting to hold the mud in place, while the mud creates the form and impact resistance that straw lacks. With CFRP, the carbon fiber strands produce tremendous strength, while the polymer matrix creates rigidity and resistance to impact. These two materials work together to create a cohesive material with relatively few drawbacks.

Fiber Reinforced Polymers (FRP) are a specific subset of composite materials brought about by advancing plastics technology and research. Polyoxybenzylmethylenglycolanhydride, or Bakelite, was developed in 1907 and became the first synthetic thermosetting resin. It wasn't until 1935 however, that Owens Corning created the first glass fiber, or fiberglass as it is commonly known. Corning's glass fiber, when combined with quickly advancing polymer resin systems, launched the FRP industry. FRP's high strength to weight ratio, and the arrival of WWII, created a global market for FRPs. Just 12 years after Corning's first FRP, a fully composite body Corvette was created.

Glass and Aramid Fibers

Prior to CFRP, the introduction of fiberglass and aramid composites saw researchers propose uses for non-metallic, non-corrosive, materials in engineered design. Aramid fibers, commonly known as Kevlar, pose an extremely high initial cost and do not offer the tensile strength that CFRP

does. Similarly glass fibers have a higher elastic modulus, but come nowhere near the strength of CFRP. Additionally, it has been found that CFRP outperforms both aramid and glass fibers in its overall lifespan. When early composites such as glass fibers were introduced, the non-corrosive and long life span capabilities were seen as a potential advantage for civil construction applications. The later advent of CFRP saw a new composite with an extremely high tensile strength, low atmospheric degradation, and even longer life span than other composite materials. This makes CFRP the perfect composite for civil engineering applications.[1]

CFRP Precursors

Rayon

Despite the rapid advancement of FRP manufacturing and polymer systems in the early 1900s, viable carbon fibers were not developed until 1956. Dr. Roger Bacon, an American physicist with Parma Technical Center, accidently discovered rayon based carbon fibers while trying to find the melting point of graphite under pressure. The “whiskers” that he produced had a tensile strength of 20 Giga-pascals (GPa) which astounded Bacon. However, the strands that he produced were extremely small and would cost around $10 million per pound to recreate. Despite this, he continued to study

[1] Urs Meier, "Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?" *Arabian Journal for Science and Engineering*, March 2012. Accessed November 18, 2018. doi: 10.1007/s13369-012-0185-6.

the carbon fibers he produced and published a paper in the Journal of Applied Physics in 1960.[2]

PAN

Just one year after Bacon's publication, the Government Industrial Research Institute in Osaka, Japan created carbon fibers using a different precursor, Polyacrylonitrile or PAN. Akio Shindo led the research team and created fibers that were about three times stronger than the current rayon based fibers. Additionally, the PAN precursor offered the ability to create long continuous fibers with a much higher yield. Soon, PAN based carbon fibers succeeded rayon based fibers and, even today, represent a 96% of the carbon fiber market because of their high tensile strength.

Pitch

The final carbon fiber precursor was discovered in 1970, again at Parma Tech, but this time by a scientist named Leonard Singer. Singer worked with a carbon heavy, tar-like substance called Pitch, creating fibers by elongating the carbonaceous pitch substance. By applying stress and

[2] Jason Gorss, *High Performance Carbon Fibers: September 17, 2003: A National Historic Chemical Landmark*. Washington, D.C.: American Chemical Society, Office of Communications, National Historic Chemical Landmark Program, 2003.

pulling the viscus material, Singer was able to orient the material into graphitizable carbon fibers. Singer soon realized that these carbon fibers had slightly different properties than rayon and PAN based fibers. Pitch based fibers showed a lower tensile strength, but offered a much higher elastic modulus as shown in Figure 1.[3] On top of this, these fibers have an ultra-high thermal conductivity, which makes them ideal for high heat applications such as aircraft brakes.

Figure 1: Pan vs. Pitch

Source: Composites Part A: Applied Science and Manufacturing, Volume 91

Early CFRP Cables

The first CFRP Cables were produced in the early 1980s for reinforcement for engineering and building structures[4]. These PAN based cables were used in the Shinmiya Bridge in the Hokuriku region of Japan at the start of 1988[5]. CFRP cable was used as a response to the rapid

[3] Bradly A Newcomb, "Processing, Structure, and Properties of Carbon Fibers." *Composites Part A: Applied Science and Manufacturing*91, no. 1 (2016): 262-82. Accessed October 8, 2018.

[4] "History ACFR." TOKYO ROPE MFG. Co., LTD. Accessed November 12, 2018. http://www.tokyorope.co.jp/english/porduct/acfr/history.html.

[5] Hue Thi Nguyen, Hiroshi Masuya, Tuan Minh Ha, Saiji Fukada, Kazuhiro Kobayashi, and Eiji Koida, "Long-term Application of Carbon Fiber Composite Cable Tendon in the Prestressed Concrete Bridge – Shinmiya Bridge in Japan." Master's thesis, Kanazawa University, 2018. 2018. Accessed November 12, 2018.

environmental degradation of the steel components of the bridge. Tests of the CFRP cables 30 years after the construction of the bridge show no sign of atmospheric degradation or unexpected fatigue. This successful application set the path for 76 applications of CFRP cables in bridge construction by 2014[6]. The early application and testing of these cables is vital for its use in future projects. These CFRP cable systems were heavily monitored, tested, and analyzed for cost efficiency. Despite heavy analysis of CFRP cable in bridge construction, little has been explored for applications in building structures.

[6] Yoshiaki Yamamoto and Kenichi Ushijima. *Field Application of Carbon Fiber Composite Cable Post-Tensioning System* Report. Post-Tensioning Institute. 2016. Accessed November 18, 2018.

PAN Production

Polyacrylonitrile, or PAN, is the most common precursor material to carbon fibers, making up 96% of the carbon fiber market.[7] Polyacrylonitrile is a carbon based polymer that is often used for outdoor awnings, boat sails, and even fiber-reinforced concrete. Carbon fibers produced with a PAN precursor offer a higher tensile strength and longer fiber length than pitch based precursors. Polyacrylonitrile itself has an abnormally high melting point, which lead to research on the heat resistant properties of PAN fibers. This research at the Government Industrial Research Institute in Osaka, Japan lead to the first carbonization of PAN fibers. Later in the 1960s, the Royal Aircraft Establishment in England, and the Union Carbide in the USA correspondingly produced carbon fiber.

Acrylonitrile

The most common production method for PAN starts with the refinement of crude oil. During refinement, 2% of the crude oil is turned into the byproduct propylene, the first chemical required for PAN production. This byproduct is not needed in for the further refinement of crude oil and is readily available for PAN production. After shipment from the refinery, the propylene byproduct is mixed with ammonia in a chemical bath to create acrylonitrile in a process called ammoxidation to create acrylonitrile. Acrylonitrile is a carbon based

[7] Sujit Das, Josh Warren, Devin West, and Susan Schexnayder. *Global Carbon Fiber Composites Supply Chain Competitive Analysis.*Report. Energy and Transportation Science Division, University of Tennessee, Knoxville. May 2016. Accessed November 18, 2018.

monomer, which means that it is stable on its own and does not adhere to other acrylonitrile atoms. In order to change its chemical makeup so that it adheres to itself in a chain, acrylonitrile is put through a process called polymerization.

Polymerization

The standard and most efficient method of polymerization for acrylonitrile is a solution bath. Acrylonitrile is released into a solution bath consisting of a solvent, a catalyst, and other carbon based comonomers. This solution combination forces a chemical reaction to create the chain molecule polyacrylonitrile. The choice of solvent and comonomer for this process will affect both the price and the molecular weight of the PAN fibers produced. Regardless of the variation in solution contents, the end result is a PAN copolymer that can be extracted from the bath.

Spinning

The extraction process of PAN fibers is called spinning. The end of this extraction process produces a continuous PAN fiber. There are five methods of spinning PAN fibers which all vary in expense and product quality. The three most practical methods are wet spinning, dry spinning, and melt spinning.

1. Wet Spinning
2. Dry Spinning
3. Melt Spinning

Wet spinning

Wet Spinning is the most common and viable method of extracting PAN copolymers. This is the only current method to be widely used in the commercial production of PAN fibers because of its lack of byproducts and potential for long continuous fibers. In this process, the PAN polymer solution is pumped through a heated solvent. While submerged in the solvent, the polymer is pumped through a spinneret with thousands of tiny holes. Once pumped through these holes, which are fractions of a millimeter in diameter, the resulting PAN polymer is separated from the solution and is spun into a PAN fiber.

Dry Spinning

Dry spinning is an outdated method that follow the same process as wet spinning, but outside of the solution bath. Without the solution bath, a buildup of byproducts is a common occurrence which both slows down production and decreases quality control. Additionally, fibers have a less efficient "dog bone" shape.

Melt Spinning

Melt Spinning is a new method of fiber production which extracts PAN fibers from a polymer solution which is melted away. This innovative process has a high range of resulting fiber strength and stiffness but is also 1/3 of the cost of wet spinning. If this process can be refined to produce a consistent quality

of material it will become the cheapest method of PAN based CFRP production.[8] However in today's market, melt spinning is not a viable option for mass produced carbon fibers because of the large variation in end product quality.

Oxidization

The oxidation of PAN fibers is a process that changes the chemical structure of PAN fibers to attain higher thermal stability. The PAN precursor fiber is heated in air between 200-300 degrees Celsius. The exact temperature and exposure time vary depending on the specific PAN precursor but this stage can last up to a few hours. This makes it the longest stage in the manufacturing of carbon fibers from a PAN precursor. While the fibers are exposed to oxygen above 200 degrees Celsius, oxygen molecules adhere to the PAN precursor and change the molecular structure from linear to cyclical. The specific reasons for this cyclical rearranging of molecules is argued, but this structure is a major component in the tensile strength of carbon fibers. In addition to the thermal stability and the change in molecular structure, oxidation increases the density of the material. The change from 1.18g/cm^{-3} to 1.36 g/cm^{-3} is likely a result of the molecular rearranging during oxidation.

Carbonization

The carbonization of oxidized PAN fibers is a two-step process that removes up to 99% of non-carbon atoms, shrinking the fiber diameter and greatly

[8] David Warren, *Lower Cost, Higher Performance Carbon Fiber*. Report. US Department of Energy, Oak Ridge National Laboratory. Oak Ridge, TN: Oak Ridge National Laboratory, 2011.

increasing the overall strength of the fiber. In the first stage, the oxidized PAN fibers are heated to 400-600 degrees Celsius in an inert environment, usually made up to N_2. This stage assists in the removal of nearly all hydrogen atoms. The second step heats the fibers up to 1500 degrees Celsius in a nitrogen rich, inert environment. The final temperature during carbonization has a direct impact on the tensile strength of the resulting carbon fibers. It has been shown that temperatures above 1500 degrees start to degrade the tensile strength of the fibers. However, heating fibers above this temperature does have a positive impact on the tensile modulus of the fibers, though it's not as dramatic as the drop off in tensile strength. A proper balance of properties based on the materials end use is vital during the production of carbon fiber at all stages. After the fibers are heated to 1500 degrees, nearly all non-carbon atoms are removed from the polymer chain, leaving only carbon atoms and up to 5% nitrogen and oxygen atoms. Once this stage is complete, the final chemical change has taken place and the PAN precursor material has successfully been transferred into carbon fiber.

Graphitization

An additional heating step during carbonization is an expensive, but feasible option for the further purification of the carbon fibers. Heat treatment above 2000 °C cannot be done with nitrogen anymore due to the high heat. The inert gas used instead is usually argon, which is roughly eight times more expensive than nitrogen gas. Multiple stages of graphitization are possible with the final

temperature usually peaking around 3000 °C. At this stage the fibers can have a carbon content above 99%. Depending on your precursor material, the effect this has on the fiber's properties varies. PAN based precursors will never achieve 99% or "full" graphitization because of the oxygen atoms present in the precursor material that pitch precursors lack. Fully graphitized carbon fibers, containing a carbon content above 99%, are called carbon nanotubes.

Stretching/Washing

Once the spinning process is complete, the PAN fibers undergo a series of postproduction processes to increase the quality and workability of the fibers. PAN fibers are run continuously through a series of rollers, starting with a hot water wash to remove any excess solvent from the fiber. Next, they are stretched in steam at about 65 degrees Celsius. This helps to align the polymer's molecules parallel to one another and subsequently increase the strength of the fiber. Fibers can then be run along a UV light to increase stabilization before being coated with an oil finish that acts as a lubricant and barrier static electricity build up. The next stage has fibers dried through a heated drum roller to purge any excess water as well as increasing density in the fiber. Stretching and washing occurs between every step of CFRP production. After final carbonization, a final stage of heating and stretching up to 150 degrees Celsius decreases porosity and increases strength of the fiber for a final time. From there the fibers are spooled and packaged for use.[9] As a

[9] Peter Morgan, *Carbon Fibers and Their Composites*. (Boca Raton: Taylor & Francis, 2005.)

general rule of thumb, the winding of twisted cables into a spool or reel should not exceed a diameter less than 25 times the cable diameter.[10]

Polymers

The polymer matrixes that encase carbon fibers are typically thermosetting resins. These resins have a chemical structure which gives them a high melting temperature and high stiffness after they are curing. There are three main types of thermosetting polymers: Polyester, Vinyl, and Epoxy. These three polymers each have similar mechanical properties, but epoxy has the lowest density and highest tensile strength of the three[11]. Carbon Fiber is almost always paired with an epoxy for its reinforced polymer because of its higher tensile strength. This is important because CFRP's high tensile strength only applies in the longitudinal direction, such as in a cable. The strength between the layers of carbon fiber is solely based on the polymer's properties. This is another reason why cables, such as CFRP cable, are a perfect application for CFRP. Cables take advantage of the longitudinal strength of CFRP and minimize any problems in sheer to the anchor points.

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[10] *Structural Applications of Steel Cables for Buildings: ASCE/SEI 19-16*. Reston: American Society of Civil Engineers, 2016.

[11] Yue Liu and Bernd Zwingmann. "Carbon Fiber Reinforced Polymer for Cable Structures - A Review." *Polymers*, September 2015. Accessed November 18, 2018. doi:10.3390/polym7101501.

Conclusions

- CFRP is the most suitable FRP for cable production because of its high tensile strength compared to glass and aramid fibers.
- PAN based carbon fibers offer continuous wires up to 4km in length, the highest production rate, and the highest tensile strength. These properties make them the best option for long span CFRP cables where large quantities of continuous, high strength cables are needed.
- While melt spinning is a cheaper extraction method during production, wet spinning creates a more reliable overall product which makes it a cheaper option overall for the large quantities of CFRP required in cable membrane roof structures.
- Graphitization greatly increases the tensile strength of carbon fibers, but is not worth the additional cost required for argon gas and higher temperatures required for CFRP cables.
- Epoxy resin is the most common and best suited thermoplastic polymer for CFRP cables because of its high tensile strength compared to polyester and vinyl polymers

Properties and Characteristics of CFRP

Density

The high tensile strength and light weight of Carbon Fiber Reinforced Polymer materials has created interest in its potential since its inception. It is nearly 5 times lighter than steel, with a density of 1760 kg/m^3 compared to steel's 7850 kg/m^3. This reduction in weight is a huge advantage over steel and even aluminum. The material's light weight has been vital to nearly all applications of CFRP from spaceships to golf clubs. The weight reduction of CFRP cables can greatly reduce the live load of tensile structures, creating the potential for fewer cables and longer spans in tensile membrane construction. Additionally, the low density of CFRP will directly translate into a saving in labor and construction costs. Smaller, lighter cables can be spooled more efficiently for a savings in transportation costs in temporary and semi-temporary structures. During construction, lighter structural members can be moved into place faster and with fewer laborers than heavier steel cables. Finally, the weight savings of CFRP cables translates to lighter dead load requirements for the overall structural system. This dead load reduction diminishes the quantity and size of compressive support members required such as beams and masts. A dead load reduction also translates to a savings in the quantity and size of the heavy machinery, such as cranes need for construction and erection. The weight savings of an

efficient structural roof material such as CFRP cables creates a trickledown effect that reduces the load requirements for the entire structure.

Tensile Strength vs. Modulus

Standard strength carbon fiber has a tensile strength of 3.5 GPa. while steel is rated close to 0.5 GPa. Additionally, standard modulus CFRP has an elastic modulus of 230 GPa, comparable to steel's 210 GPa. Despite its natural advantage over steel, the tensile strength of CFRP can be raised even further, as high as 7 GPa. This increased strength comes from additional carbonization and graphitization of the fibers during production. Furthermore, high modulus CFRP can be made from pitch based precursors, creating the potential for a tensile modulus to 440 GPa. However, a general rule of thumb is that as the modulus of CFRP increases, the tensile strength decreases.[12] This relationship shows how the carbon precursor material for CFRP can affect the material's properties as much as the production method. Pitch based carbon fibers have a higher tensile modulus while PAN fibers have a higher tensile strength.[13] Yue Liu's study on the application of CFRP cable in cable net structures showed that a higher tensile strength carries importance

[12] Yue Liu and Bernd Zwingmann. "Carbon Fiber Reinforced Polymer for Cable Structures - A Review." *Polymers*, September 2015. Accessed November 18, 2018. doi:10.3390/polym7101501.

[13] Kimiyoshi Naito, Yoshihisa Tanaka, Jenn-Ming Yang, and Yutaka Kagawa. "Flexural Properties of PAN- and Pitch-Based Carbon Fibers." Master's thesis, University of California, Los Angeles, 2008. *The American Ceramic Society*, 2008.

than a high modulus based on production costs[14]. This is why CFRP cables in production are made with PAN based fibers.

Thermal Expansion

One issue with steel in the built environment is its rate of thermal expansion. All materials are effected by the temperature, expanding and contracting with heat and heat loss. This movement is taken into account through expansion joints, creating additional openings in the structure's waterproofing. These expansion joints create points of access for water infiltration, creating the potential for structural failure. CFRP has a minuscule thermal expansion coefficient of 0.2×10^{-6} m/m/C, a figure which is essentially negligible.[15] CFRP cable applications in concrete benefit from this quality because of thermal movement in cured concrete. The thermal expansion of steel cables in tensile membrane roofs creates additional deflection and sag across the span. This additional sag can cause fluttering in the attached membrane which increases live wind loads. Additionally, increased sag in cables can cause creases and folds in the membrane which can lead to water ponding and increased dead loads. The negligible rate of thermal expansion for CFRP can help to mitigate these issues in cable stayed membrane roof structures.

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[14] Yue Liu "Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures." *Structural Engineering International*, August 15, 2014. Accessed November 18, 2018. doi:10.2749/101686614X14043795570534.

[15] Urs Meier, "Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?" *Arabian Journal for Science and Engineering*, March 2012. Accessed November 18, 2018. doi: 10.1007/s13369-012-0185-6.

Atmospheric Degradation

One major disadvantage of steel is the reduction of ultimate strength that comes from exposure to oxygen and road salting. To combat this issue in steel cables, additional expensive processes are undergone to increase the overall life span of the material. CFRP cables do not require these additional processes. The carbon heavy makeup of CFRP gives it an excellent resistance to environmental exposure because carbon molecules do not react with oxygen or salt. Studies on the earliest application of CFRP cables in Japan have shown that CFRP's performance and life cycle in harsh, coastal environments is far superior to steel.[16]

Water Resistance

CFRP materials have no need for direct waterproofing due to the tight chemical structure of the polymer matrixes. A study conducted at Swansea University immersed CFRP in water for three years to determine water absorption rates and degradation of CFRP under a variety of different water temperatures. Even at water temperatures above 90 degrees Celsius, the carbon fibers makeup showed no signs of micro-cracking. The resin polymer, however, was shown to absorb water over long time periods. A longer immersion time slowed the water absorption rates of the resin polymer,

[16] Hue Thi Nguyen, Hiroshi Masuya, Tuan Minh Ha, Saiji Fukada, Kazuhiro Kobayashi, and Eiji Koida, "Long-term Application of Carbon Fiber Composite Cable Tendon in the Prestressed Concrete Bridge – Shinmiya Bridge in Japan." Master's thesis, Kanazawa University, 2018. 2018. Accessed November 12, 2018.

seeming to max out at a 5% weight gain. This water infiltration into the epoxy resin would lead to relaxation over time in CFRP structures.[17] However, this figure assumes a total immersion underwater over a period of three years. The relaxation rates of structural CFRP cables have been tested to be about 3.5% after 30 years at 80% load. This is about 50% less than the relaxation rate of steel cables under the same parameters.[18] CFRP's rate of relaxation, combined with its natural chemical resistance to water, salt, alkaline, and acid, give CFRP an operational life span up to eight times longer than steel. The operational lifespan of CFRP products is often calculated at 100 years, but with the relatively recent emergence of this material, it is possible that this lifespan can be even greater.

Fire Resistance

Similar to steel, CFRP has a relatively poor fire resistance and requires fire additional prevention measures. The carbon fibers themselves can withstand temperatures above 600 degrees Celsius, but the polymer matrix will begin to degrade around 100 degrees Celsius. At temperatures exceeding 300 degrees Celsius, polymers start to combust and evaporate. This polymer failure causes the CFRP to lose strength and will likely result in the failure of CFRP structures.[19] One solution is to increase the critical temperature of the

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[17] C. Arnold, F. Korkees, and S. Alston. "The Long Term Water Absorption and Desorption Behaviour of Carbon Fibre/Epoxy Composites." Master's thesis, Swansea University, 2012. *European Conference on Composite Materials*, June 2012.

[18] Kunal Joshi, *Investigation of Carbon Fiber Composite Cables (CFCC) in Prestressed Concrete Piles*. Master's thesis, Florida State University, 2013.

[19] Yue Liu, and Bernd Zwingmann. "Carbon Fiber Reinforced Polymer for Cable Structures - A Review." *Polymers*, September 2015. Accessed November 18, 2018. doi:10.3390/polym7101501.

epoxy itself by using additives such as bisphenol-a-diglycidylether or magnesium hydroxide. A study on these additives by Atif Javaid show that they improve the burn rates of CFRP, but not enough for structural applications of CFRP[20]. A more standard method of fire prevention is an external intumescent spray or paint coating, similar to fire protection methods for steel. However, without any fire prevention methods, CFRP has a worse fire resistance than steel. Testing at Tongji University studied the application of painted fire resistant coatings on CFRP to determine the fire resistance compared to steel. This study showed that externally applied intumescent fire coatings on CFRP will resist fire for 2.5 hours before failure.[21] Externally applied fire coatings are already a part of the construction process in steel cables and, while CFRP has a lower tolerance to heat, there is relatively little difference in the application of fire protection in steel and CFRP cables.

UV degradation

CFRP cable has excellent resistance to water and salt corrosion, but wire protection against ultraviolet radiation attack is required. UV rays cause the gradual chemical breakdown of most thermosetting resins, weakening

[20] Atif Javaid and Ayesha Afzal. *Carbon Fiber Reinforced Modified Bisphenol - A Diglycidylether Epoxy Composites for Flame Retardant Applications*. Master's thesis, University of Engineering and Technology, 2018. Pakistan: IOP Publishing, 2018. Accessed November 20, 2018. Materials Research Express.

[21] HU Kexu, HE Guisheng, and LU Fan. *Experimental Study on Fire Protection Methods of Reinforced Concrete Beams Strengthened with Carbon Fiber Reinforced Polymer*. Master's thesis, Tongji University, Shanghai, 2006. Higher Education Press. Accessed November 20, 2018. DOI 10.1007/s11709-007-0054-7.

the ultimate strength of CFRP over time. Similar to fireproofing protection, additives introduced to the polymer before curing can slow the chemical degradation caused by UV rays. However, a more cost effective method uses a protective barrier or shielding for CFRP. This method was used for the first application of CFRP cable for bridge cable stays. Stork Bridge in Switzerland protected the exposed CFRP cable members with a black polyethylene pipe for UV and wind shielding. Tests over the life of the bridge have shown that the black polyethylene barrier is an adequate shield for UV radiation.[22] With fireproofing methods already required for CFRP cables, it would be a prudent design solution to choose a fire protection method that also protects from UV radiation.

Impact Resistance

One negative aspect of CFRP is its low impact resistance. Laminated CFRP is vulnerable to direct impacts, but CFRP cables have a higher resistance due to their structure. A crack in a composite wire does not spread across the entire cable as it would in a solid laminate. When a cable fiber is embedded in the polymer matrix is can take up the full load a short distance away from the crack. A flaw in a single fiber will not lead to the failure of the cable structure.[23] This is another reason why cables are a reliable structural

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[22] Urs Meier, "Structural Tensile Elements Made of Advanced Composite Materials." *Structural Engineering International*, 99th ser., 9, no. 4 (March 23, 2018). Accessed November 18, 2018. doi:10.2749/101686699780481817.

[23] Urs Meier, "Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?" *Arabian Journal for Science and Engineering*, March 2012. Accessed November 18, 2018. doi: 10.1007/s13369-012-0185-6.

application for CFRP. Applications of steel cables where impact failure is a possibility use a protective metal tube to absorb any unexpected impact loads. A relatable example being the impact threat that a car possesses on a bridge stay cable. CFRP cables that are anchored near the ground need to employ a similar protection method to avoid impact failure. The main distinguishing factor between a system for CFRP cables and Steel cables is the possibility of galvanic corrosion. While protective impact sheathings do not perform structurally, unnecessary corrosion should be avoided by placing a non-conductive barrier between the CFRP cable and any surrounding metals.

Cost

The high initial cost of CFRP members is the main barrier for its use in the built environment. At its first conception in 1960, the manufacturing was upwards of $1,000,000/lb. Over the next 40 years, the production process was streamlined and improved to lower the cost of CFRP to $30/lb. in 1998. By 2018, the unit price of CFRP lowered even further to $7-10/lb. This significant drop in price is a direct result of a 50-fold improvement in speed for the pultrusion process in production[24]. This continued decrease in price has been coupled with an increase in demand, creating market incentives

[24] Urs Meier, "Structural Tensile Elements Made of Advanced Composite Materials." *Structural Engineering International*, 99th ser., 9, no. 4 (March 23, 2018). Accessed November 18, 2018. doi:10.2749/101686699780481817.

and competition to lower the price even further through quicker and more efficient production methods.

Carbon Fiber and other Fiber Reinforced Polymer (FRP) materials are still objectively new compared materials such as steel and concrete. While the production methods of steel have been refined over decades to optimize performance, production methods for CFRP are still being explored. A study funded by the US Department of Energy researched the potential future cost of PAN processed CFRP based on emerging production technologies. Demand predictions for CFRP show a stead trend of demand and production increase[25]. This study, conducted at Oak Ridge National Laboratory, looked at high volume production savings, emerging PAN spinning techniques, and savings in precursor materials. With these emerging technologies, and a higher demand for carbon fiber, the supply production cost of PAN based CFRP could lower by up to 40%[26]. This could see the unit price of CFRP drop from $7.8/lb. down close to $4.6/lb.

Even if the price of CFRP were reduced below $5/lb., still seems like an expensive option next to steel at $.40/lb. However, the price per pound is a deceptive figure due to the light weight of CFRP. The difference in strength per pound can be shown in the respective breaking lengths of the materials. The breaking length is defined as the maximum length of a hanging bar that

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[25] Martin Kokoshka, *Value Chain of Carbon Fibers.*Report. 2002. Accessed November 18, 2018.

[26] David Warren, *Lower Cost, Higher Performance Carbon Fiber*. Report. US Department of Energy, Oak Ridge National Laboratory. Oak Ridge, TN: Oak Ridge National Laboratory, 2011.

could suspend its own weight. This can be calculated by dividing the tensile strength (σ_u) by the density (ρ) and the acceleration of gravity (g) together in the equation $\sigma_u/(\rho g)$. As can be seen in the graph below, the breaking length of CFRP is at least 8 times that of steel.[27] This metric shows that, while CFRP has a higher cost per unit, CFRP offers more value per unit than steel. This means a reduction in material required to achieve the same design loads. For CFRP cable, I will review two different studies that show that CFRP cable can be an economically feasible option, even at initial construction, based on the superior strength and lighter weight of the material.[28] [29]

[27] Yue Liu, and Bernd Zwingmann. "Carbon Fiber Reinforced Polymer for Cable Structures - A Review." *Polymers*, September 2015. Accessed November 18, 2018. doi:10.3390/polym7101501.

[28] Yue Liu, "Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures." *Structural Engineering International*, August 15, 2014. Accessed November 18, 2018. doi:10.2749/101686614X14043795570534.

[29] Urs Meier, "Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?" *Arabian Journal for Science and Engineering*, March 2012. Accessed November 18, 2018. DOI: 10.1007/s13369-012-0185-6.

Material	Material Type	Density ρ (kg/m²)	Tensile Strength σ_u (GPa)	Elastic Modulus (GPa)	Breaking Length (km)
Carbon Fiber	Standard	1760	3.53	230	205
Carbon Fiber	High Strength	1820	7.06	294	396
Carbon Fiber	High Modulus	1870	3.45	441	188
Steel	S335	7850	0.50	210	6
Steel	Wire	7850	1.77	210	23

Figure 2: Material Properties

Source: Author

Life Cycle

In addition to the high strength properties of CFRP, it also has an extremely long life cycle. Steel loses strength over the years due to corrosion, relaxation, and fatigue. Tests conducted at the Swiss Federal Laboratory for Materials Testing and Research (EMPA) studied the performance of wire CFRP cable bundles under cyclic loads. Two million test cycles showed that CFRP cables can withstand stress amplitudes and mean stresses three times higher than steel.[30] This test shows the superior fatigue

[30] Urs Meier, "Carbon Fiber Reinforced Polymers: Modern Materials in Bridge Engineering." *Structural Engineering International*, 92nd ser., no. 1 (1992). Accessed November 18, 2018. Researchgate.

capabilities of CFRP over steel, which has been confirmed by the first application of CFRP cables at that Shinmiya bridge in Japan. Tests conducted in 2017 showed the expected amount of fatigue over the bridge's 30 year life.[31]

According to a study by the Federal Highway Administration (FHWA) in 2000, 29% of the 587755 bridges in the United States were structurally or functionally obsolete. A majority of these due to material fatigue and environmental degradation.[32] If the structural steel cables had been replaced with CFRP, the life span would be significantly improved. CFRP has a fatigue resistance three times higher than steel and half of the rate of relaxation[33]. Most importantly, CFRP has a high corrosion resistance and has no reactions with salt in the air or on its surface. CFRP members are often designed for 100 years of life with a single maintenance operation every 50 years. The high corrosion resistance of CFRP was the first reason that it was used in replacement of steel. A study by Nabil Grace showed that in bridge construction, a CFRP reinforced bridge will become the least expensive option between 20 and 40 years of service.[34]

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[31] Hue Thi Nguyen, Hiroshi Masuya, Tuan Minh Ha, Saiji Fukada, Kazuhiro Kobayashi, and Eiji Koida, "Long-term Application of Carbon Fiber Composite Cable Tendon in the Prestressed Concrete Bridge – Shinmiya Bridge in Japan." Master's thesis, Kanazawa University, 2018. 2018. Accessed November 12, 2018.

[32] Halvard E. Nystrom, Steve E. Watkins, Antonio Nanni, and Susan Murray. "Financial Viability of Fiber-Reinforced Polymer (FRP) Bridges." *Journal of Management in Engineering*, 2-8, no. 19 (January 2003). Accessed February 22, 2018. doi:10.1061/(ASCE)0742-597X(2003)19:1(2).

[33] Yoshiaki Yamamoto, and Kenichi Ushijima. *Field Application of Carbon Fiber Composite Cable Post-Tensioning System.*Report. Post-Tensioning Institute. 2016. Accessed November 18, 2018.

[34] Nabil Grace, Elin Jensen, and Vasant Matsagar. *Life Cycle Analysis of CFRP Prestressed Concrete Bridges.* Master's thesis, Lawrence Technological University, 2009. Accessed November 14, 2018. Researchgate

Conclusions

- The low density of CFRP compared to steel will translate to thinner primary support members and a lighter overall dead load of a CFRP cable structure.
- CFRP has a tensile strength over twice that of steel, resulting in smaller, more efficient structural members.
- CFRP fatigues at half the rate of steel. This will reduce cable sag created over time by cyclical live loads, lowering maintenance costs and improving the overall life span of the structure.
- CFRP has a negligible rate of thermal expansion, reducing the possibility of cable sag, membrane folding, and water ponding in tensioned membrane roof structures.
- The atmospheric degradation issues of steel, such as corrosion, do not effect CFRP because of the relative inertness of covalently bonded carbon atoms that make up CFRP. This creates a large disparity in the life span of steel when compared to CFRP and was the first reason for the use of structural CFRP cables.
- No additional waterproofing is required for CFRP as a result of its encasement in a polymer matrix.
- For fireproofing applications, carbon fibers can withstand extremely high temperatures as a result of the high temperatures in their production process. However, epoxy polymers will degrade and de-bond at temperatures above 300 degrees Celsius. Intumescent fire coatings similar to ones used for steel cables have proven to give CFRP a fire rating of 2.5 hours.
- Ultraviolet rays will cause the degradation and yellowing of polymer matrixes, causing CFRP cables to relax over time. UV protective paints or coverings are a simple solution and can often be combined with fire prevention efforts.
- Impact resistant sheathing must be employed for CFRP cables near ground level where high impact loads such as moving vehicles have the potential to damage structural elements.
- Studies have shown that, even in cases where the initial cost of CFRP is higher than steel, the high life cycle of the material makes it the cheaper structural option after 20-40 years' service.

CFRP Cables

CFRP cables were first used for structural applications in the late 1980s. The Carbon Fiber Continuous Cable (CFCC) was the first brand of CFRP cables created. These cables are still in production today, made by Tokyo Rope manufacturers in Japan. Tokyo Rope uses a thermosetting resin polymer combined with a PAN-based carbon fiber made by Toray. Toray manufacturers were the first producers of PAN based carbon fiber in the world. Two of the other major CFRP cable manufacturers are Mitsubishi Chemical Company and Nippon Steel Advanced Carbon Fiber Composites. These three companies all make their individual brands of CFRP cables that have been designed, manufactured, applied, and tested in structural applications all over the world. [35] The CFRP cables that these companies produce are designed as structural replacements for steel cables and have been used in over 10 countries across the world.

[35] Kunal Joshi, *Investigation of Carbon Fiber Composite Cables (CFCC) in Prestressed Concrete Piles*. Master's thesis, Florida State University, 2013.

Configurations

CFRP cable cables are configures in twisted arrays of 5mm diameter strands. The cables are twisted for flexibility and ease of construction. Additionally, CFRP cable are 1/5th of the weight of traditional steel cables. These two qualities make CFRP cable easier to handle on site than steel. The different radial configurations of CFRP cable range from one to four radial rings of 5mm CFRP strands. These specified configurations can be noted in figure 3 with standard configurations holding 7, 19, or 37 strands.

Figure 3: CFRP Cable Configurations

Source: Tokyo Rope

Tensile Strength

The twisting of the cables to is a necessary step for large scale applications of CFRP cable for transportation and workability of the material. However, there are some adverse effects such as a slight reduction in tensile strength. The tensile strength of CFRP cable is reduced to 2.7 GPa. The steel that is used for cables undergoes a series of processes to increase its overall tensile strength. Even after the production of high tensile strength steel, CFRP's tensile strength is still almost twice that of steel cables at 1.6 GPa.

Modulus of Elasticity

The modulus of elasticity of CFRP cable is similar to steel cables, both close to 1.5 GPa depending on the configuration of the cables. However, it has been found that the modulus of elasticity in steel cables decreases as the length increases. This creates elongation and sag in longer applications of steel cables. CFRP cable has an elongation at rapture of 1.6% while steel cables have an elongation of 6%.[36] Figure 4 demonstrates the difference between the equivalent modulus of a CFRP cable stay cable and one made of steel.[37] The reduction of sag in CFRP cable compared to steel offers more advantages than simply being more taught. Less displacement in a cable creates a horizontal loading condition closer to true 90 degrees. Moreover, less sag in tensile structures results in a higher ceiling. This can lead to longer internal spans without adding any height to the primary structural systems. In addition to stronger anchoring instances and long spans, less sag in a tensile canopy can create a more visually impressive structure and more physical space within the building.

Figure 4: Cable Sag in Brides

Source: EMPA, 2011

[36] Ife Olorun Olofin and Ronggui Liu. "The Application of Carbon Fibre Reinforced Polymer (CFRP) Cables in Civil Engineering Structures." *SSRG International Journal of Civil Engineering*2, no. 7 (July 2015). Internationaljournalssrgijce.

[37] Switzerland. Swiss Federal Laboratories for Materials Science and Technology. EMPA. *20 Years of Practical Experience with Carbon Fiber Reinforced Polymers in Structural Engineering*. By Urs Meier. 2011.

Sheer

The amazing properties of CFRP stated are only valid in the longitudinal direction. The lateral properties of CFRP are taken advantage of well in the application of CFRP cable, but the lack of sheer strength is still an issue compared with steel cables. This weakness in sheer becomes an issue for CFRP cables at the anchor points. The anchoring of CFRP cable has been tested over the years to determine best practices and any issues with sheer stresses. A conical, resin filled steel socket imbedded with a Load Transfer Media (LTM) has shown to offset any issues with sheer stresses and creep at the anchor points of CFRP cables.[38]

Anchoring

One main deterrent in the widespread use of CFRP cable in suspended structures is a widespread and proven anchoring system. An anchoring system developed by Urs Meier at the EMPA has been applied to anchor CFRP stay cables on Stork Bridge. These anchors, being the first application of its kind, were monitored closely by sensing systems based on fiber optic Bragg gratings (FBGs) and electrical resistance strain gauges (RSGs). These sensing

Figure 5: Sheer Stress in CFRP Anchors

Source: Liu, 2018

[38] Yue Liu, and Bernd Zwingmann. "Carbon Fiber Reinforced Polymer for Cable Structures - A Review." *Polymers*, September 2015. Accessed November 18, 2018. doi:10.3390/polym7101501.

systems examined the strain on the wires as well as monitoring for creep due to sheer failure. The systems on all of the cable anchors have had no failures due to strain. Additionally the anchorage cones developed at the EMPA are matching calculated expectations for creep displacement.[39]

This anchoring system uses conically aligned load transfer media (LTM) filled with epoxy resin to create radial pressure on the CFRP cables, as demonstrated in figure 5. The LTM is composed of 2 mm Al2O3 ceramic granules with varying elastic modulus. The modulus increases the further away from the load side of termination to take advantage of the conical anchor shape. This system of ceramic LTM also helps to insulate the CFRP wires from the steel to avoid galvanic corrosion in the anchor.[40]

Additional new FRP anchors have tested with an efficiency factor of 97%. All of the anchorage systems proposed take advantage of the superior concrete adhesion properties of CFRP cables. The bond strength of CFRP cable to concrete has shown an average of 9.7 MPa, ranging from 8-12.5 MPa. As a comparison, the average bond strength for steel is 3 MPa, nearly is three times lower than CFRP[41]. The proposed anchor system for CFRP cables is a wedged mechanical gripping anchor made of ultra-high performance

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[39] Rolf Bronnimann, Urs Meier, and Peter Anderegg. "Long Term Behavior of Carbon Fiber Reinforced Polymers Recorded with SHM." *5th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, December 11, 2011. Accessed November 18, 2018.

[40] Urs Meier, "Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?" *Arabian Journal for Science and Engineering*, March 2012. Accessed November 18, 2018. Doi: 10.1007/s13369-012-0185-6.

[41] Nolan Domenico, *Bond Properties of CFCC Prestressing Strands in Pretensioned Concrete Beams*. Master's thesis, University of Manitoba, 1995. Winnipeg: Department of Civil and Geological Engineering, 1995. Accessed November 18, 2018.

concrete. The development of this anchor system is an attempt at a metal free mechanical anchor to avoid galvanic corrosion caused by CFRP cable while taking advantage of the adhesive properties of CFRP cable.[42] As a result of the higher adhesion, CFRP cable cable anchors are smaller and cheaper than their predecessors for steel.[43]

Economic Feasibility

The production process of creating a cable from its raw material creates an opportunity for CFRP cables. Steel cables, similar to CFRP cables, are made of twisted, radial strands of 3-7mm steel wires. These steel wires undergo extra processes to become stronger and stiffer than standard steel. The steel in standard bridge cables today has a tensile strength of 1.57 GPa and a yield strength of 1.18 GPa. These values are about four and five times higher respectively and come with a cost increase as well.[44] The cost of steel cables used for tensile construction ranges from $2.5 to $4 per pound depending on the application and service life of the cable.[45] The range of

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[42] Reda Taha, Mahmoud M., and Nigel G. Shrive. "New Concrete Anchors for Carbon Fiber-Reinforced Polymer Post Tensioning Tendons - Part 1: State of the Art Review/Design." *ACI Structural Journal*, 10th ser., 100, no. 1 (February 2003).

[43] Yue Liu, "Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures." *Structural Engineering International*, August 15, 2014. Accessed November 18, 2018. doi:10.2749/101686614X14043795570534.

[44] Jean-Pierre Michel Chacar, "Design of Cable Systems for Cable Suspended Bridges." Master's thesis, Massachusetts Institute of Technology, 2001. June 2001. Accessed November 28, 2018. https://dspace.mit.edu/bitstream/handle/1721.1/84254/49398523-MIT.pdf.

[45] United States. Department of Transportation. Florida. *Structures Design Guidelines*. By FDOT. FL: FDOT, 2019.

price is a result of the different corrosion protection methods used for steel cables including resin coating and zinc galvanization.[46]

The price per pound of CFRP cables varies as well, but not as a result of corrosion protection. As explained above, CFRP already possesses extremely good resistance towards corrosion. With CFRP cables, the price varies depending on the tensile strength and modulus. While steel cables have to undergo extensive processes to increase its tensile strength, CFRP already possesses the high tensile strength required. However, as a result of the production process required for higher quality, the relationship between cost and strength of CFRP cables is not linear.

Production Process and Price of CFRP Cables

A scientific paper in Structural Engineering International examined the cost efficiency of CFRP cables based on their tensile strength and modulus of elasticity. This study found that the ultimate load bearing capacity of orthogonally loaded CFRP cables is always determined by the tensile strength. Therefore the extra cost for a higher tensile modulus isn't necessary. Additionally, this study showed that additional carbonization and graphitization for a higher tensile strength CFRP fiber is not fiscally worthwhile. This is due to the high costs of heating the fibers to temperatures past 2000 degrees Celsius in order to further improve tensile

[46] Jean-Pierre Michel Chacar, "Design of Cable Systems for Cable Suspended Bridges." Master's thesis, Massachusetts Institute of Technology, 2001. June 2001. Accessed November 28, 2018. https://dspace.mit.edu/bitstream/handle/1721.1/84254/49398523-MIT.pdf.

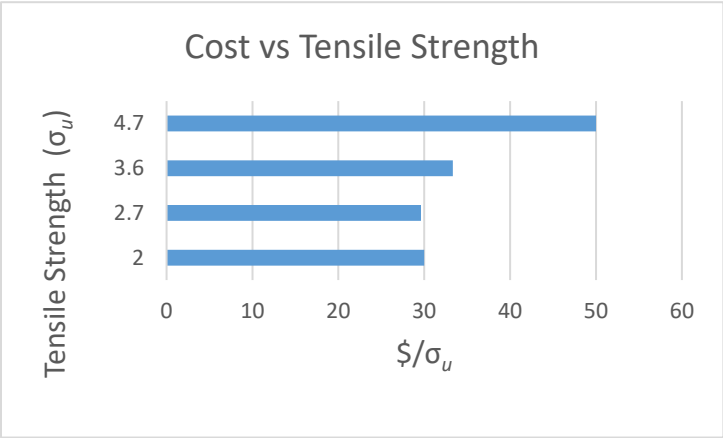

Figure 6: Cost vs Tensile Strength

Source: Author

Figure 7: Cost vs Properties

Source: Liu, 2018

strength. The high tensile strength of standard carbon fibers are still significantly higher than steel. The study showed that CFRP cables with a tensile strength of 2.7 GPa and elastic modulus of 120 GPa are the most cost efficient compared to their breaking strength.[47] As a result of the tensile strength being the deciding factor of breaking length, it is a simple calculation to see which tensile strength is the most cost effective. I have analyzed his study on the price and strength of carbon fibers in the graph below by dividing the tensile strength by the price of CFRP cables with different tensile strengths. The figures used in the study are noted in figure 7. The graph in figure 6 confirms that CFRP cables with a tensile strength of 2.7 has the lowest cost per strength compared with the stronger fibers.

[47] Yue Liu, "Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures." *Structural Engineering International*, August 15, 2014. Accessed November 18, 2018. doi:10.2749/101686614X14043795570534.

Cable Bearing Capacity per Meter Comparison

The price comparison between CFRP cables and steel cables still seems like a daunting figure. However, the production processes required for steel cables create a 1100% increase on cost compared to the raw material, increasing from $0.22/lb to $2.5 – 4/lb. Whereas CFRP cables only rise by about 580%, increasing from $7/lb to $41/lb. Due to the inherent strength of CFRP, no further strengthening is needed for its use in cables, as it is in steel. This cost increase for steel cables alone is another advantage for CFRP in wire cables, bringing the relative material price closer together.

However, even compared with the more expensive, epoxy coated, galvanized steel cables; CFRP is still nearly ten times the price per pound.

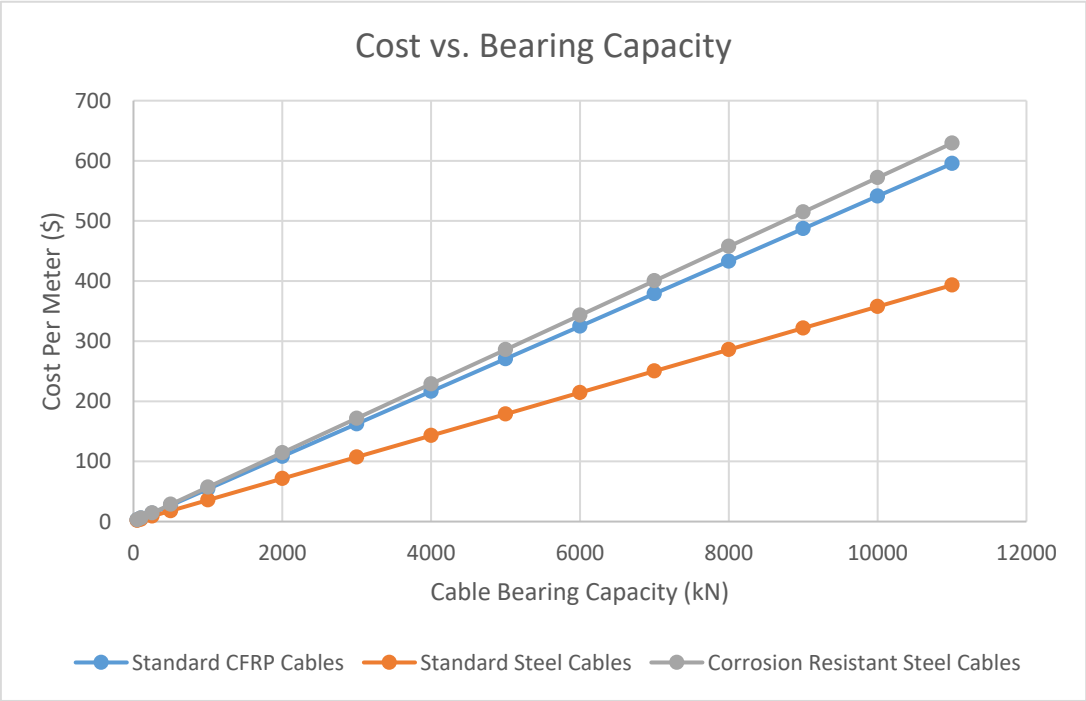

Figure 8: Cost vs Bearing Capacity

Source: Author

While this metric seems daunting, it is actually right in the range of cost comparison for steel and CFRP. This is a result of the high strength and light weight of the material. Basically, CFRP offers more value per pound. For a cost assessment of these CFRP and steel cables, I compared the price per meter of cables with the same ultimate bearing capacity. It is worth noting that the ultimate capacity differs from the guaranteed capacity because of factors of safety and standard redundancy ratios. The ultimate bearing capacity can be calculated by multiplying the cross sectional area of the cable by the yield strength of the material. I compared the cost per meter of standard CFRP cables, standard steel cables, and corrosion resistant steel cables. These cables have an aforementioned price of $41/lb., $2.50/lb., and $4/lb. respectively. For this study, I analyzed cables of each type with an ultimate bearing capacity ranging from 50 kN to greater than 10,000 kN to find the price per meter of each respective cable. After converting the price per pound into dollars per gram, I found the total area of one meter cable by

Standard CFRP Cables							
Ultimate Yield Capacity (kN)	Effective Cross Sectional Area (mm2)	Yield Strength (kN/mm2)	Density (g/mm3)	Nominal Mass (g/mm)	Dollars/g	Dollars/mm	Dollars/m
50	18.58736059	2.63	0.0016	0.029739777	0.031	0.00270632	2.706319703
100	37.17472119	2.63	0.0016	0.059479554	0.031	3.575	3575
250	92.93680297	2.63	0.0016	0.148698885	0.031	0.013531599	13.53159851
500	185.8736059	2.63	0.0016	0.29739777	0.031	0.027063197	27.06319703
1000	371.7472119	2.63	0.0016	0.594795539	0.031	0.054126394	54.12639405
2000	743.4944238	2.63	0.0016	1.189591078	0.031	0.108252788	108.2527881
3000	1115.241636	2.63	0.0016	1.784386617	0.031	0.162379182	162.3791822
4000	1486.988848	2.63	0.0016	2.379182156	0.031	0.216505576	216.5055762
5000	1858.736059	2.63	0.0016	2.973977695	0.031	0.27063197	270.6319703
Standard Steel Cables							
50	41.66666667	1.2	0.0078	0.325	0.0055	0.0017875	1.7875
100	83.33333333	1.2	0.0078	0.65	0.0055	0.003575	3.575
250	208.3333333	1.2	0.0078	1.625	0.0055	0.0089375	8.9375
500	416.6666667	1.2	0.0078	3.25	0.0055	0.017875	17.875
1000	833.3333333	1.2	0.0078	6.5	0.0055	0.03575	35.75
2000	1666.666667	1.2	0.0078	13	0.0055	0.0715	71.5
3000	2500	1.2	0.0078	19.5	0.0055	0.10725	107.25
4000	3333.333333	1.2	0.0078	26	0.0055	0.143	143
5000	4166.666667	1.2	0.0078	32.5	0.0055	0.17875	178.75
Corrosion Resistant Steel Cables							
50	41.66666667	1.2	0.0078	0.325	0.0088	0.00286	2.86
100	83.33333333	1.2	0.0078	0.65	0.0088	0.00572	5.72
250	208.3333333	1.2	0.0078	1.625	0.0088	0.0143	14.3
500	416.6666667	1.2	0.0078	3.25	0.0088	0.0286	28.6
1000	833.3333333	1.2	0.0078	6.5	0.0088	0.0572	57.2
2000	1666.666667	1.2	0.0078	13	0.0088	0.1144	114.4
3000	2500	1.2	0.0078	19.5	0.0088	0.1716	171.6
4000	3333.333333	1.2	0.0078	26	0.0088	0.2288	228.8
5000	4166.666667	1.2	0.0078	32.5	0.0088	0.286	286

Figure 9: Graph Data

Source: Author

multiplying the cross sectional area by the length. I then multiplied the area of each cable by the respective material density to find the nominal mass in grams. From there it was a simple multiplication of the price per gram and the nominal weight per meter of the material to find the price per meter of each respective cable. The calculations and exact numbers for this study can be found in figure 9.

Upon analysis of the price per meter for comparable bearing capacities, it was found that CFRP cables are 5% cheaper than corrosion resistant steel cables of the same strength. The results shown in figure 9 show that, while standard steel cables are still cheaper, CFRP cables are the better option when faced with a long term application. Even with the extra galvanization and epoxy coating, the cheaper CFRP cables have a much

longer projected life span due to their natural chemical, corrosion, and fatigue resistance.

Precedents

Shinmiya Bridge

The use of CFRP cables for used in pre-stressed concrete and suspension bridges has been modeled and applied, but there is little research on the advantages of CFRP cables in tensile canopies. However it is still vital to analyze these pre-tensioned CFRP cable applications to determine accuracy of projected models in real life applications. The first use of CFRP cable was in 1988 in the new construction of the Shinmiya Bridge in the Hokuriku region of Japan. This region has a high level of salinity as a result of the seasonal winds and proximity to the ocean which causes steel to corrode rapidly. The first Shinmiya Bridge showed signs of failure due to the corrosive salt environment after 12 years. This caused its full replacement in just 20 years. The new Shinmiya Bridge was designed with 24 concrete girders, pre-stressed with eight longitudinal CFRP cable tendons. These seven-strand tendons have a diameter of 12.5 mm

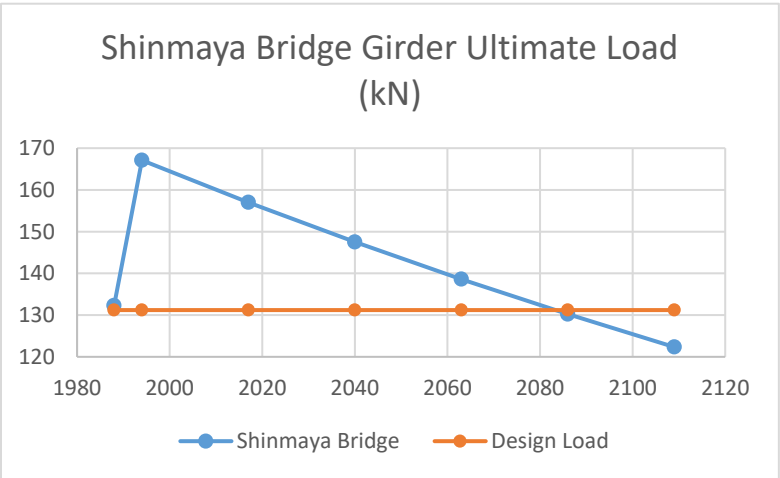

Figure 10: Shinmaya Bridge Ultimate Load Capacity

Source: Author

and were used in the design for their long life span and lack of corrosion. Figure 2 shows the corrosion of both the old and new Shinmiya Bridges after 20 years of use.

Being the first application of CFRP cable in the built environment, two test girders were built and placed on the ocean side and mountain side respectively. The 26 identical girders, made of concrete with a compressive strength of 59.8 n/mm2, were each rated with an ultimate design load of 131.2 kN. At the time of Construction, the ultimate load of the individual girders tested at 132.3 kN. After six years, the first test girder was given the destruction test by bending load. This test showed that after 6 years the ultimate load raised to 167.1 kN. Finally, in 2017 the final test girder was removed and given the same bending load test. After 29 years, the ultimate load was 157 kN, still well above the design load. Assuming that the initial load increase was the result of the continual curing of concrete (great band name), the continuing degradation of ultimate load was close to 6% over 23

Figure 11: Shinmaya Bridge Condition
Source: Nguyen et al. 2018

years.[48] If this trend continues, it will take approximately 97 years for the ultimate load to dip below the design load. The original Shinmiya Bridge was finally replaced after 20 years, but showed signs of needing replacement due to salt corrosion and rust after only 12 years. CFRP cable cables made it possible for this bridge to increase its life span by a factor of 8.

Life Cycle Cost Analysis

As previously stated, CFRP cables in orthagonally loaded tensile structure do not require a high modulus of elasticity, but post-tension cables imbedded in concrete do. As a result, the intial cost of these CFRP cable cables is higher than steel in every pre and post tension application. While this study is not about CFRP cable cables in concrete reinforcemnt, these cables have the same physical and material properties as cables used in tensile structures and are therefore comparable in their respective applications.[49] Many financial feasibility studies have been constructed to assess the cost dispartiy between CFRP cable and steel in this application. A Life Cycle Cost Analysis (LCCA) is a vital step in determining the feasibly of CFRP cable replacing steel in the built environment. This analysis is undergone using the equation:

$$\mathrm{LCC} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

[48] Hue Thi Nguyen, Hiroshi Masuya, Tuan Minh Ha, Saiji Fukada, Kazuhiro Kobayashi, and Eiji Koida, "Long-term Application of Carbon Fiber Composite Cable Tendon in the Prestressed Concrete Bridge – Shinmiya Bridge in Japan." Master's thesis, Kanazawa University, 2018. 2018. Accessed November 12, 2018.

[49] Jean-Pierre Michel Chacar, "Design of Cable Systems for Cable Suspended Bridges." Master's thesis, Massachusetts Institute of Technology, 2001. June 2001. Accessed November 28, 2018. https://dspace.mit.edu/bitstream/handle/1721.1/84254/49398523-MIT.pdf.

Where

C_t = the sum of all costs incured at time *t;*

r = the real discount rate for converting time *t costs;*

T = the number of time periods in the study period.

NCHRP Report 483 cites this equation as the acceptable formula for LCCA in bridge construction and, in 2009, Nabil Grace used this model to perform over 90 million simulations for box beam bridges transversely pre-stressed with CFRP. This study analyzed bridge spans at 45, 60, and 122 feet at three vehicle traffic variables from low to high. The results of this extensive study show that, despite the higher inital cost, CFRP cable cables will

Figure 13: Bridge Life Cycle Cost vs Year
Source: Grace, 2018

Figure 12: Bridge Life Cycle Cost Comparison
Source: Grace, 2018

become the least expensive option between 20 and 40 years of service.[50] This study took into account the maintenance required on steel cables due to fatigue and atmospheric degradation as well as the cost of regular inspections. The life cycle of CFRP as a material is an important aspect in its use for construction. Even in cases where the initial cost is higher, CFRP can be the better choice because of its durability to the environment and fatigue resistance.

Bridge at the Strait of Gibraltar

As a result of the high strength and low weight of CFRP cables, they have the potential to span greater distances than currently possible with steel cables. These cables can be used in applications where steel is inadequate. This application of CFRP cables has been theorized for long bridge span applications. Urs Meier analyzed the feasibility of using CFRP cables based on the higher strength and weight savings generated from using CFRP stay cables over steel. For this study, he analyzed a theoretical bridge at the narrowest point along the Strait of Gibraltar. Multiple methods of transportation have been proposed for the site, including highway and rail tunnels as well as a steel cable suspension bridge. However, the sea depth of 300 meters as well as the 16,000 meter span required make these options particularly expensive.

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[50] Nabil Grace, Elin Jensen, and Vasant Matsagar. *Life Cycle Analysis of CFRP Prestressed Concrete Bridges.* Master's thesis, Lawrence Technological University, 2009. Accessed November 14, 2018. Researchgate

The current proposal for a steel cable stayed bridge would require over ten different spans, creating a number of concrete footings with enormous depth and cost requirements. The high number of concrete supports required would also cause issues for large boats or freighters in the waters. Additionally, the spans are limited to 2000 meters each because of the high dead load of the steel cables required on a job of this magnitude. In fact, the steel cables required for this project would account for 70% of the weight of the superstructure.

Figure 14: Proposal for a Bridge at the Strait of Gibraltar
Source: Meyer, 2018

The proposal for a CFRP cable bridge at the site would have a main span of 8400 meters between just two concrete pillars, located in much shallower water. For this study, the reduction of material required was analyzed based upon the

Figure 15: Specific Design Load vs. Main Span
Source: Meyer, 2018

increased strength of the material compared to steel. This span is only possible with CFRP cables because of the reduction of material required as well as the weight savings of CFRP cables. The composite material would drastically reduce the dead load of the superstructure, allowing for spans that are impossible with steel cables. Figure 15 shows the limitations of steel suspension spans by comparing the weight of specific design load based upon the length of the bridge span. This exponential curve shows that the weight of steel cables limits the maximum span of steel bridges to around 4000 meters. CFRP cables, however, do not have a high design load at this span as a result of the weight and material reduction required for the cables.[51]

While this study focuses on the cable stay applications of CFRP in bridges, it shows how important a reduction of material and weight can be to long span structures. These principles can be applied to long span tensile membrane structures in the same way. The reduction in the self-weight of a structural cable allows for much longer spans than currently possible with steel cables. I will make a case that these advantages can be as beneficial for CFRP cables in tensile membrane structures as they are for CFRP cables in suspension bridges.

[51] Urs Meier, "Proposal for a Carbon Fibre Reinforced Composite Bridge across the Strait of Gibraltar at Its Narrowest Site." *Proceedings of the Institution of Mechanical Engineers*, B2, 201 (1987). Accessed June 8, 2018. Researchgate.

Conclusions

- Despite the slight loss of tensile strength, the winding of CFRP cables is advantageous for cable net and cable beam applications because of its increased workability on such large scale projects.
- The reduction in sag embodied by CFRP cables can increase ceiling heights and long span abilities without the need for taller and more expensive primary structure supports in tensile roof structures.
- The relatively low sheer strength of CFRP cables requires a conic, resin filled termination at CFRP cable anchor points. This system has been simulated and implemented at Stork Bridge, showing efficiency rates up to 97%.
- The low sheer strength also results in a loss of tensile strength in anchors not loaded at 90 degrees. For this reason, orthogonally loaded tensile systems are the most ideal for CFRP cables.
- When comparing tensile strengths, most cost efficient CFRP cable has a tensile strength of 2.7 GPa. The relatively low strength (compared to 7 GPa CFRP) is justified by the extremely high production costs related to higher strength carbon fibers.
- When comparing the bearing strength per meter of 2.7 GPa CFRP cables to environmentally protected structural steel cables, CFRP cables of the same bearing strength are 5% cheaper because of their high strength and efficient material use.
- Studies have shown that, even in cases where the initial cost of CFRP is higher than steel, the high life cycle of the material makes it the cheaper structural option after 20-40 years' service.
- The application of CFRP cables at the Shinmiya Bridge confirms the projected fatigue and atmospheric resistance of CFRP cables.
- Studies on tensioned CFCC cables in long span bridge stay cable applications show that CFCC cables have the ability to increase long span distances as a result of their high strength, light weight, and dead load reduction.
- CFCC cables in tensile membrane structures undergo the same forces, anchors, and cable configurations tested in bridge applications. Therefore, the concepts from these tests can be applied in tensile membrane structures.

Cable Stayed Tensile Membrane Structures

In order to understand why CFRP cables are ideal for tensile structures, it is important to understand the history and construction methods of cable supported tensile membrane structures. If you have ever hung clothes on a clothes line, you can start to understand the basic physics of a tensile structure. Instead of resisting the load of the clothes by pushing them up (compression), the clothes line cable resists force though a sort of tug-o-war (tension) with a primary structure. The clothesline example expresses many of the basic principles in cable construction.

A clothesline is a cable that is suspended between two primary structural supports. These supports can be wood, steel, concrete, or anything that can resist the force that the wire exerts. In the clothesline example, it is often two trees or metal poles. As a result of gravity and the downward force of hung clothes, the line exhibits sag in a catenary, or parabolic, curve. The sag caused by this curve can be decreased through pre-tensioning (pulling the clothesline tighter) or by using a cable made of a stiffer material. Additionally, the clothes line example shows how wind loads are often the controlling load factor for tensile membrane structures.[52] A simply suspended cable such as a clothesline is easily pushed upwards by wind, exerting much higher loads than the hanging dead load of the structure itself. As a result of

[52] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

CFRP cables' light weight, the impact of wind is an important factor for the design load requirements of the structure.

Cable tensile structures have several advantages when compared to convention compression and bending moment based structures. Firstly, the lightweight fabric and cable system can span greater distances without the need of mid span columns for additional support. This allows for large unobstructed open spaces within the building. Additionally, tensile membrane structures are capable of carrying large applied loads while weighing a fraction of their compression based counterparts. This reduction in weight and material required results in shorter construction times and an overall cost savings. The shorter construction times and light weight of the arrangement make it the ideal typology for mobile structure.

The application of CFRP cables in these systems amplifies all of the benefits that these systems already possess. When replacing steel cables in tensile construction, CFRP cables allow for even lighter buildings that are more easily constructed and mobile. Additionally, the increased strength of CFRP means that even less material is required, for an additional savings in transportation and labor costs. Additionally, cables in tensile construction are more effected by cyclical loading than by dead loads as a result of ever changing wind strength and direction. [53] As previously stated, CFRP cables exhibit nearly twice the fatigue resistance compared to traditional steel

[53] *Structural Applications of Steel Cables for Buildings: ASCE/SEI 19-16*. Reston: American Society of Civil Engineers, 2016.

cables, resulting in fewer re-tensioning maintenance checks required and a longer life span. Finally, since cables work in pure tension, they are extremely efficient structures, making them perfect for long span applications. As shown in the proposal for a bridge at the Strait of Gibraltar, the strength of CFRP cables allow for much longer span capabilities compared to steel. The characteristics of CFRP cables take every advantage in a tensile construction system and improves upon it further, making it the perfect choice for these system typologies.

History

Simple tensile fabric structures have been around for thousands of years. Some of the earliest examples started as early as the ice age, where nomadic people stretched animal skins across tree branches. These early dwellings were used as shelters for the harsh climates, but also because of the nomadic tendencies that go hand in hand with hunter gatherer culture. As early as the ice age, humans were using tensile membrane structures for quick assembly and disassembly of mobile shelters. Many of the earliest human shelters around the world were made in this fashion such as Native American teepees, Asian kibitkas, Middle Eastern tents, and Mongolian yurts.[54] These cultures grew in total isolation from one another and, while the geometries may differ, they all came to the same building solution: tensile membrane structures.

[54] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

Large scale cable membrane structures in modern construction still have the basic building principles as these early structures with fast construction, effective coverage, and lightweight materials. However, with the development of steel and high strength steel cables, these systems attained a stronger structural support system which resulted in longer spans, faster construction, lighter weight, and more efficient material usage for long span structures compared to traditional compressive buildings. CFRP cables offer these same advantages to tensile membrane structures, allowing span length and material efficiency to grow even larger than possible today.

The very first "modern" application of a long span cable net structure was the J.S. Dorton Arena in Raleigh, North Carolina. Built in 1953, this system was used to create a column free interior span. The cable net roof spanned 95 meters between two opposing primary structure arches, depicted in figure 16. The roof is saddle shaped, with upward curves spanning the width and downwards curves running perpendicular along the length of the cable net. These opposing parabolic forces help to stabilize the overall structure of the saddle

Figure 16: Dorton Arena
Source: Vandenberg, 1998

shape at every cable intersection. This application of a cable net roof is said to have influenced Frei Otto in his works with cable membrane structures.

The work of Frei Otto is often the first cited when speaking about tensile cable net structures. Perhaps the most famous cable net building application is his Olympic Stadium in Munich. The most significant aspect of this project is probably the sheer scale of the project for a tensile structure built in 1972. 210 kilometers of cable was used to cover 75000 square meters of total area. The structural system of the cable net was stayed by masts of heights up to 80 meters. This application of cable nets still uses opposing arches to stabilize the structure, but it shows how these nets can be pushed and pulled by external forces such as mast anchored stay cables to create unique forms. [55]

Figure 17: Olympic Stadium in Munich
Source: Feng, 2009

Membrane Fabrics

Membrane fabric systems in tensile structures are high performance fiber composites in their own right. Similar to carbon fibers, membrane fabrics materials such as polyester, nylon, and fiberglass are coated with a

[55] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

protective material to improve the durability, waterproofing, and insulation value of these materials. The most common protective coatings are Polyvinyl Chloride (PVC), Polytetrafluoroethylene (PTFE or Teflon), and Silicone. These fabrics and their protective coatings provide all of the requirements for a standard roof at a fraction of the cost, size, and weight. With the heaviest membrane system combination weighing less than 2 kg/m^2. To reach all of the necessities in a roof design, these membranes must be airtight, waterproof, and fire resistant as well as accounting for acoustics, heat control, lighting, and durability. In the composite combination of coatings, the protective coating helps to improve fireproofing, waterproofing, and airtightness while actually contributing little to the overall structural strength of the fabrics. The fiber material and fiber's weave are the contributing factors to a composite membrane structure's structural properties.

Structural Components of Fabric Weaves

Similar to CFRP cables, structural fabric is made up of a series of individual fibers. These tiny fibers are laid atop one another and twisted together to make long sections of yarn. The act of twisting these fibers enacts the same reaction as twisting strands of CFRP into cables, the twist allows for more elongation under applied axial loads and therefore results in a lower equivalent stiffness. These long twisted yarn fibers are then laid perpendicular and woven into a two-dimensional fabric sheet. As noted in figure 18, the pattern and proximity of the fibers creates a range of finished

fabrics with varying advantages and disadvantages. For roof membrane applications, the weave with the fewest disadvantages is a tightly woven plain weave. While an adhesively bonded plain weave has a higher tensile strength, the adhesion makes the material fold and interact poorly with complex curvature often found in cable beam and net structures. Loosely woven scrims offer a high tear strength, but are more susceptible to failure in tension. Tightly woven fabric weaves offer the high tensile strength needed for roof membrane systems, as well as the requirements for the additional protective coating required for weatherproofing.[56]

Figure 18: Fabric Weave Patterns
Source: Feng, 2009

[56] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

Tensile and Tearing Strength

The two main methods of failure for fabric membranes are tensile and tearing. Tensile failure is a failure in the overall fabric when stretched from opposite ends. Tearing, however, is a measure of local failure where a sudden force is applied and the individual fiber fails in this location. Tearing failure often occurs during material transportation and construction, while tensile failure is often the exhibit of a failure in the entire load bearing system. The relationship between tensile and tear strength is inversely proportional. Therefore an increase in tensile strength will result in a decrease in tearing strength. This relationship can be easily explained through a common real life situation. When cutting a rope, it is easier to cut when it is pulled tight. Similarly, fabric with a higher tensile stress is subject to a higher risk of tearing.

Another factor that is worthwhile to note for fabrics in membrane roofs is that the tensile and tear strengths are affected by non-axial loading. It is common for roof membranes to be shaped into complex curves with multiple warp and fill directions. These fabrics tend to increase in tensile strength in warp while losing tensile strength in fill. While the difference in tensile strength does not vary by an order of magnitude, it does create a range in which the tensile strength of fabrics must be judged.[57] For example, heavy duty PTFE coated glass fabrics have a tensile strength of 130 kN/m^2 in fill

[57] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

and 146 kN/m^2 in warp. These numbers, while based on professional material testing, are still only guidelines because of the varying degrees of curvature possible. For this reason, fabrics are often designed with a safety factor of at least 5. [58]

Stretching and Folding

As mentioned, the weaving of fabrics into yarn increases the elongation of the final fabrics. This is a benefit for the structural properties of the fiber, but causes the material to elongate and deform over time. To mitigate this, fabrics are pre-stretched and pre-tensioned either before installation or to the individual fibers before the weaving process. After installation, these membranes must remain in tension at all times to remain a part of the load resisting system and avoid fluttering.

UV Degradation

An important distinction before choosing between fabric types is the loss of strength over time due to UV rays. While glass fibers are not meaningfully effected, polyester loses 20% and nylon 90% of its strength after two years of direct exposure. If these materials are chosen for roof

[58] Natalie Stranghöner, Faruk Bilginoglu, Jörg Uhlemann, Kai-Uwe Bletzinger, Heidrun Bögner-Balz, Evi Corne, Nick Gibson, Peter Gosling, Rogier Houtman, Josep Llorens, Marc Malinowsky, Jean-Marc Marion, Marijke Mollaert, Meike Nieger, Giorgio Novati, Farid Sahnoune, Peter Siemens, Bernd Stimpfle, Vatyu Tanev, Jean-Christophe Thomas, Silvia Dimova, Artur Pinto, and Steve Denton. *Prospect for European Guidance for the Structural Design of Tensile Membrane Structures: Support to the Implementation, Harmonization and Further Development of the Eurocodes*. Luxembourg: Publications Office, 2016.

membrane systems, UV radiation must be mitigated through the use of light resistant additives or a UV absorbent coating.[59]

Transparency

The light transmittance of tensile membrane fabrics can greatly affect the experience inside of such a structure. For obvious reasons, thicker membranes allow less light to pass though. However, it is worth noting that the different fabrics and coatings have different allowances for light transmittance. Brand new PTFE coated fiberglass allows 5.33% diffused light transmittance while PVC coated polyester was shown to allow 3.8%. Over time, however, the same PTFE coated fiberglass membrane allowed 7.4% transmittance. Over time, these membranes will weather and begin to allow a slight increase in light transmittance. On top of this, the weathered PTFE membrane actually exhibited a 5% increase in reflectance. This increase in reflectance means that these membranes appear to become whiter over time.[60]

Fabric Materials and Coatings

Within the matrix of choices for fiber and coating combinations, the most common are PVC coated polyester, PTFE coated fiberglass, and Silicone coated fiberglass. PVC coated polyester is one of the oldest and most

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[59] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

[60] El Nokalay Amira, *ENVIRONMENTAL BEHAVIOUR OF TENSILE MEMBRANE STRUCTURES*. Master's thesis, School of the Built Environment, University of Nottingham.

commonly used materials for tensile fabric structures. Its main drawbacks when compared to PTFE coated fiberglass are lower tensile strength and shorter life span. However, as previously mentioned, the lower tensile strength is traded with a higher modulus of elasticity. Protection from UV is commonly and more easily applied to polyester than nylon to extend the lifespan of the material. PVC coated polyester is a good choice for structures with steep complex curves that take advantage of its higher modulus of elasticity. This material has been a popular choice since the 1960s, but has a tendency to absorb dirt from water and air. This drawback, when combined with its low durability create a short lifespan of 10-15 years that is difficult to overcome.

PTFE and Silicone coated fiberglass both have a considerably higher tensile strength and durability when compared to PVC coated polyester. However, the main drawbacks are their poor tear strength and higher cost. PTFE coated fiberglass must be handled with care during transportation and construction but offers the highest tensile strength available. Silicone coated fiberglass still retains much of the tensile strength, but is more flexible and less brittle than PTFE, offering a compensation for tear while still resisting UV degradation.

Conclusions

- Tensile roof fabrics must be designed with a high factor of safety as a result of the variations in non-axial tensile strength
- Mechanically woven plain weave fabrics are ideal for tensile roof membranes because of the high tensile strength and flexibility of the weave
- All membranes must be pre-stressed prior to erection to avoid fluttering caused by fabric elongation
- For a temporary long span emergency shelter, fiberglass is the best membrane fabric due to its UV resistance, transparency, and tensile strength
- Despite PTFE's higher tensile strength, silicone is a better coating option because of its superior tear resistance in transportation and construction

Basic Fabric Structure Systems

Tensile fabric structures come in a variety of shapes and sizes, but they can all be broken down and categorized into three basic systems: pneumatic structures, boundary tensioned membranes, or cable net and beam systems.[61] Each of these three systems can be further broken down into categories of construction based on the variations in construction elements. These three systems all share the same basic elements to their construction: a tensioned fabric membrane used as roofing, flexible cable or ties for structure and form, and rigid primary supporting members such as masts, arches, or beams.[62]

Pneumatic

For the application of CFRP cables, pneumatic or air supported structures are tensioned using internal air pressure. Due to the difficulty in creating square geometries air, cables are utilized in nearly 95% of pneumatic systems to push and pull the system into the desired shape.[63] CFRP cables are a viable option for these tensioning systems due to their low density, workability, and long life. These cables, in addition to form finding, help to stabilize the low weight structure against any wind loads.

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[61] Maritz Vandenderg, *Cable Nets: Detail in Building*. (Chichester: Academy Editions, 1998)

[62] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

[63] Alberto Gómez-González, Javier Neila, and Juan Monjo. "Pneumatic Skins in Architecture. Sustainable Trends in Low Positive Pressure Inflatable Systems." *Procedia Engineering*21 (2011): 125-32. doi:10.1016/j.proeng.2011.11.1995.

Additionally, pneumatic systems have the advantage of rapid installation times. These structures have the ability to deflate into a much smaller area because much of its volume is created by internal air pressure.[64] This aspect makes a pneumatic system an interesting solution for a temporary emergency shelter because of its inherent mobility. However, pneumatic systems are not as compatible with CFRP as a material because of CFRP's more viable composite competitors.

As previously stated, pneumatic systems are inflated and supported by air pressure. Like a balloon, this force of air works not because of its immense power, but by its constant uniform pressure. The largest force exerted on these cables occurs in high positive pressure pneumatic typologies, where the force rarely exceeds .0001 GPa.[65] Even the weakest CFRP cables are rated above 2 GPa in tension. This disparity represents an excessive abundance of strength for the cables needed in pneumatic systems. Fiberglass composite cables provide the same weight benefits as carbon fiber and other composites, but does not boast the high strength of CFRP. This trade off, however, does mean that glass composites are considerably cheaper than CFRP. For pneumatic systems, Glass Fiber Reinforced Polymer (GFRP) Cables would be a more viable solution based off

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[64] Bob Martens, and Wolf-Michael Tschuppik. *Exploring the Design and Fabrication of Inflatables*. Master's thesis, Vienna University of Technology. Vienna: Vienna University of Technology.

[65] Alberto Gómez-González, Javier Neila, and Juan Monjo. "Pneumatic Skins in Architecture. Sustainable Trends in Low Positive Pressure Inflatable Systems." *Procedia Engineering*21 (2011): 125-32. doi:10.1016/j.proeng.2011.11.1995.

of the strength required for these systems and cost of the comparable composites.

Boundary Tensioned

Boundary tensioned membrane structures however, do use mechanically tensioned cables as a part of their structural system. These systems are what you would typically think of when you hear the term tensile membrane structure. These structures are comprised of a flexible membrane fabric fastened to tensioned cables along the exterior of the fabric. These cables are strung along four or more primary structure points to create the membrane's shape. The main aspect that distinguishes boundary tensioned membrane structures from cable net and beam systems is that the support cables only appear on the boundary of the membrane system. This means that the membrane itself acts as the protective layer as well as the structure for the system.[66] The main drawback to this typology is that fabric tear propagation is the dominant factor for determining the maximum span.[67] The unsupported span of the fabric itself is rarely greater than 30m due to the tear strength of the fabric itself.[68] While CFRP cables can still offer a lighter dead load and lower material usage than steel in this application, the span length is always going to be determined by the strength of the fabric instead

[66] Maritz Vandenderg, *Cable Nets: Detail in Building*. Chichester: Academy Editions, 1998.
[67] Ben Bridgens, P. D. Gosling, and M.J. Birchall. "Tensile Fabric Structures: Concepts, Practice, & Developments." *Structural Engineer*, July 2004. Accessed December 4, 2018.
[68] Craig G Huntington, *The Tensioned Fabric Roof*. Reston, VA: American Society of Civil Engineers, 2004.

of the cable support system. For this reason, CFRP cables are most effective when replacing steel in cable net and beam systems.

Cable Net and Beam

Cable net and beam structures use systems of cables to span distances which are then covered by a roof system, in this case, a flexible membrane. The distinguishing factor between these systems and boundary tensioned systems is that the cables run throughout the system instead of solely on the outside of the membrane. This means that the cables take the entire roof system load upon themselves while the roof system simply rests atop them. Cable beams exhibit this in a parallel one way system while cable nets run in a perpendicular, two way system. For the sake of this study, I am going to focus on tensile membrane cable net and beam systems because these arrangements take advantage of all of the beneficial properties that CFRP cables possess. Additionally, these systems use orthogonally loaded anchoring systems required for cost competitive carbon fiber cables.

Simply Suspended Cable Structures (one way system)

Simply suspended cable structures are the long span building application of the tensile clothesline example. These structures consist of a series of single cables, individually tensioned between a primary support system. These systems can be hung in both rectangular and elliptical plan arrangements with examples of each shown in figures 19 and 20. In these one way cable systems, structural cables do not overlap, but work individually with the primary supports to create the roof form. These longitudinal systems have a fixed maximum width or radius, but rectangular arrangements can be extended indefinitely for additional length. This fixed maximum width or radius is a product of the weight, sag, and strength of the structural cable as well as the maximum pretension allowances for fabric roofing membranes. CFRP cables can extend this limit through their decreased material usage and weight, as well as the material's sag resistance. However, despite the pre-tensioning of cables, these systems have major drawbacks with regards to wind. If we think back to the

Figure 20: Simply Suspended Cable Roof
Source: Buchholdt, 1999

Figure 19: Radial Simple Suspended Cable Roof
Source: Buchholdt, 1999

clothesline example, the suspended cables in these systems have no stiffness. Simply suspended cable roofs are extremely susceptible to updraft wind loads which cause unpredictable movement. The low density and efficient material usage of CFRP cables would amplify this issue. For systems of this type, the common solution is to reduce movement though an applied load, such as a heavy concrete roof. This weight keeps the cables in place by resisting any updraft. However, these concrete roofs are often poured on site and create heavy, permanent structures as opposed to light, mobile, tensile membrane roof structures. For this reason, simply suspended cable roofs are not the ideal solution for CFRP cables in tensile membrane structures.[69]

Cable Trusses (one way system)

The other way to mitigate wind loads in one way cable systems is to create a cable truss. These trusses use a second set of cables with an opposite curvature to resist both uplift and dead load forces. In this system, the upside down arch carries the dead load in tension while the upward arch sits in compression. This upward arch carries a light dead load, but becomes vital for any sudden live loads. When forces such as suction or updraft push the membrane upwards, the cable truss members reverse their roles and the upward arch holds the form in tension.[70] These opposing convex and concave cables not only work to resist updraft, but mitigate cable vibration by creating opposing periods of vibration. These opposing oscillations work

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[69] H. A. Buchholdt, *An Introduction to Cable Roof Structures*. (London: Thomas Telford, 1999.)

[70] Ben Bridgens, P. D. Gosling, and M.J. Birchall. "Tensile Fabric Structures: Concepts, Practice, & Developments." *Structural Engineer*, July 2004. Accessed December 4, 2018.

together to cancel each other out and mitigate fatigue caused by wind vibration[71] Standard cable truss arrangements are shown in figure 21. The main distinguishing factor between these systems is the force enacted on the ties between the two opposing cable arches. In the first, convex cable beam these ties sit in compression. In the second, concave cable beam they are in tension. In the mixed convex and concave cable beam, the outer two cables are in tension with the rest in compression. The final cable truss in figure 22 shows a system designed by the Swedish engineer David Jawerth. This appropriately named Jawerth uses diagonal pre tensioned ties to create a system of pre tensioned triangles. With the application of various live loads, certain diagonals go slack as the rest help the lower cable to resist the loads in pure tension. This truss,

Figure 21: Cable Trusses

Source: Buchholdt, 1999

Figure 22: Jawerth Truss

Source: Buchholdt, 1999

[71] Frederick S. Merritt, *Building Engineering and Systems Design* (Springer Verlag, 2014.)

using conventional steel cables, has been successfully implemented in buildings with spans ranging from 15-100 meters.[72] With the implementation of CFRP cables, this cable truss the potential to span even greater distances.

Cable Net Structure (two way system)

Cable net systems consist of a grid of perpendicular overlapping cables to create an interlocking system of structural cables. Cables are typically anchored to either the ground or a primary structural system to resist the tensile loads. These cable net structures are the typical design solution for long span fabric membrane roofing systems because of their light and efficient material use. CFRP cables in this system will allow for longer span capabilities as well as improving upon the system's efficient material use.

Flat

A flat, or synclastic, setup of a cable net structure is a two way representation of a simply supported cable system. An array of simply supported cables are arranged

Figure 23: Anticlastic Structures
Source: Vandenberg, 1998

[72] H. A. Buchholdt, *An Introduction to Cable Roof Structures* (London: Thomas Telford, 1999.)

perpendicular to one another create a shape similar to an inverted bowl. This inverted bowl shape is a synclastic surface, with both sets of cable arrays curved in the same direction. Similarly to simply suspended cables, these synclastic shapes are vulnerable to live wind loads such as updraft and must rely on a heavy mass to counteract the flutter induced by these loads. Without this mass, tensioned flat nets are only resist flutter and wind loads for spans of up to 30 meters. CFRP cables in these systems would amplify these issues because of the reduced density and surface area compared to steel cables.

Saddle

The typical design solution to offset these wind issues in lightweight membrane roof structures is to create an anticlastic shape. Anticlastic surfaces gain geometrical stiffness though the individual node connections on opposing perpendicular curves. A typical, two way anticlastic cable geometry creates a saddle, or barrel vault shape to the cable net structure as depicted in figure 23.[73] At each intersecting node of these anticlastic surfaces, one cable pulls up while the perpendicular cable pulls down. This creates a vertical equilibrium at each intersecting node which creates the required tensile reistance for downward loads such as snow, as well the upward loads create by wind.[74] Additionally, the geometric shape of the cable net structure

[73] Maritz Vandenderg, *Cable Nets: Detail in Building* (Chichester: Academy Editions, 1998)
[74] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

is more infuential to the overall geometric stiffness of the system. This means that increasing the pre-tension forces and tensile strenght of the cables is more infuential in reducing the deformation of the structure than the elastic modulus. This is an important point for the use of CFRP cable cables in cable net systems because of their high tensile strength and relitively low modulus compared to steel cables.

With the increased tensile strength of CFRP cables, the cable cross sectional area required for the ultimate bearing load capacity is reduced. This weight reduction, on top of the low density of CFRP, results in an increased material efficiency and lower structural dead load. Additionally, the smaller radius required for CFRP cables results in smaller and cheaper anchoring systems. Cable net structures already attain near orthogonal anchor loads as well as a high efficiency in the number of anchor required.[75] For these reasons, CFRP cables in cable net structures can prove to be a suitable replacement for steel.

Conic

Simple or inverted cones create another common anticlastic form. While saddle shaped cable net structures bear their load against a primary support along the perimeter of the structures, cone shapes have an additional primary mast support to pull the form into a variety of possible

[75] Yue Liu, "Carbon Fibre Reinforced Polymer for Orthogonally Loaded Cable Net Structures." *Structural Engineering International*, August 15, 2014. Accessed November 18, 2018. doi:10.2749/101686614X14043795570534.

shapes. A typical example of a mobile conic membrane structure is the traditional peaked circus tent. These tents often radial cable net or beam systems that radiate around a central primary support mast. Conic cable net cone shapes with multiple masts allow for an infinite number of vertical or inverted cone configurations to create unique membrane forms. One typical example of a multiple mast cable net system is found in Frei Otto's iconic Olympic Stadium in Munich.

These conic shapes, while unique and playful in form, do have a series of drawbacks. The first of which is the disturbance of a column free span caused by additional supporting masts. Additionally, these unique forms require a number of additional anchor points, many of which necessitate one of a kind anchoring solutions where a series of cables terminate at a single point. This adds considerable design and labor costs to these iconic forms. Finally, one of the main aspects of tensile roof structures is the efficiency in material use for a long span form. When compared to saddle systems, conic forms have a high fabric and cable material usage relative to their plan area due to the increased slope of the structure.[76]

[76] Craig G. Huntington, *The Tensioned Fabric Roof*. Reston, VA: American Society of Civil Engineers, 2004.

Construction

Primary Structure Systems

While net and beam construction, like all tensile structures, do not act in pure tension. The cables themselves are under a solely tensile load, but these cables must be fastened and anchored against primary support systems. With the exception of soil anchoring, these primary support systems resist all of the cable's tensile force through compression.[77] Typical primary support systems for tensile structures include masts, arches, and beams. As a result of these structures acting in compression, concrete, steel, and even wood have been used to resist cable forces.

It is important that the primary support system is designed to be capable of resisting the large forces exerted by these cables. These primary support systems have the same influence on form finding as the tensile cables themselves. Arch and beam support systems create flat and saddle shaped cable geometries while masts have the ability to pull cables into conical forms. These variations and choice of support system is pivotal for the efficiency and form of tensile membrane structures.[78] Cable nets that use masts or edge cables have a tendancy to be less stiff and require more complex details than nets with stiff boundaries. For structures with very large

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[77] Vandenderg, Maritz. *Cable Nets: Detail in Building*. Chichester: Academy Editions, 1998.
[78] Ibid, Huntington

spans, it is good practice to use fixed, stiff primary support boundaries to ensure maximum stiffness.

Cable Saddles

As previously discussed, terminations for CFRP use a conical cold poured polyester resin fill technique with an imbedded load transfer media to stabilize the cable. This technique has been tested and verified to work to offset the low sheer strength of CFRP cables. These terminations are commonly made of stainless steel or galvanized steel to protect from corrosion at these vital anchor points. The external shape of these conic sockets are sized to accommodate the individual design requirement based on the radius of cable used. Generally, the length of the conic socket is 6 times the cable diameter and the larger diameter of the cone is 2-3 times the cable diameter.[79]

Figure 24: Cable Terminations

Source: Buchholdt, 1999

As a result of the poor sheer strength of CFRP cables, eye or looped cable terminations are not feasible anchor terminations. Even if sheer strength were not an issue, these eye terminations are more reliable for small scale construction as opposed to the Instead, conic resin terminated

[79] H. A. Buchholdt, *An Introduction to Cable Roof Structures*. London: Thomas Telford, 1999.

sockets can be fitted with more permanent threaded, jaw end, or closed end terminations as depicted in figure 24. These terminations are then secured between pairs of plates or onto clevises. Jaw and closed end terminations allow for rotation about a single axis while threaded terminations must be fixed at the correct dead load angle. These three systems are all adequate for the high tensile loads associated with resin terminated CFRP cables.

Cable Anchors

Figure 25: Cable Anchor

Source: Buchholdt, 1999

In order to take advantage of the high tensile strength of CFRP cables, termination anchors must be able to withstand the large forces acting upon it. Cable anchors for threaded, jaw end, or closed end saddles are typically galvanized steel plates with plates, clevises, or threads to attach the saddles. These anchors can either be bolted to a primary structure, a concrete footing, or ground anchors. For this application, ground anchors are the most temporary, but also offer the least resistance and strength. Even experimental ground anchors in the most optimal soil conditions only offer a resistance of .004 GPa.[80] After design load reductions

[80] Kuangyi Zhang, Zhi Fang, Antonio Nanni, Jianhua Hu, and Guoping Chen. "Experimental Study of a Large-Scale Ground Anchor System with FRP Tendon and RPC Grout Medium." *Journal of Composites for Construction*19, no. 4 (2015): 04014073. doi:10.1061/(asce)cc.1943-5614.0000537.

and factors of safety for the overall structure, this number comes nowhere near CFRP cables' ultimate breaking strength of 2.7 GPa. A bolted anchor baseplate is the more reasonable solution for these systems. Therefore, any cable terminations, including ground termination, must be attached to a primary structural system such as an arch, mast, beam, or footing.

Pre-tensioning

Cable pre-tensioning is vital for cable net and beam structures. While CFRP cables have a higher stiffness and fatigue resistance than steel, tensioning systems ensure that they remain stretched under any combination of applied loading. Pre-tensioning is vital to improving vertical stiffness and avoiding any excess deflection.[81] Pre-tensioning systems vary by structure but are always carried out by either the shortening of cables, or increasing the length of ridged compressive members. A typical system for the shortening of cables employs either mechanical or hydraulic jacks. While it is possible to tension cables from a single end for cable beams, it is best practice to tension cable net systems from both ends simultaneously to avoid creating an imbalance in the cable grid.[82] One tensioning system involving the elongation of a primary support structure can be found in a typical circus tent construction. In this system, the fixed cables are lifted and stretched by

[81] Katherina Santoso, "Wide Span Cable Structures." Master's thesis, Massachusetts Institute of Technology, 2004. 2004. Accessed December 7, 2018. https://pdfs.semanticscholar.org/81e6/79d6384d5561ed1d003d75d018dcb2a658f8.pdf.

[82] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

a central mast. This mast, when at full height, tensions the cables and fixes the system in place.

Overlap Conditions

Cable to Cable

Figure 26: Cable to Cable Overlap
Source: Vandenberg, 1998

While cable beam systems do not have any instances of cable to cable interaction, these overlapping conditions are in integral part of cable net systems. As previously discussed, each of these overlapping nodes are balanced by opposing, anticlastic curves to create a vertical equilibrium at each intersection. These intersections are commonly fitted with U-bolt or cable clamp connections such as the ones found in figure 26. These connections hold each node in place while simultaneously mitigating fretting, or rubbing, of the cables.

For the application of CFRP cables, the material makeup of these clamps is a concern due to the conductivity of CFRP cables. These clamps are commonly made of steel or aluminum, which will corrode over time when in direct contact with CFRP. To mitigate this issue, these clamps must have a protective layer of an insulating material on any surface that comes into direct contact with CFRP cables.

Cable to Fabric

Cable to fabric connections are an integral part of cable tensioned membrane roofs. To avoid any membrane flutter, these connections must be pulled tight at all times after construction. It is common for fabric membranes to be sectioned and subdivided to facilitate ease in the installation process. This subdividing also proves helpful for later fabric maintenance and repair.

Figure 27: Cuff, Fabric to Cable

Source: Fang, 2009

Cable to fabric connections can be done in a number of ways. A common method involves a cuff or sleeve created in the fabric membrane boundary edge which the cables are then slid through as shown in figure 27[83]. This is a common method with PVC coated polyester fabric but can be restricted by the length of the seam for PTFE coated fiberglass.[84] This system uses the tensioning of the cables themselves to pull the fabric taught. A majority of cable and fabric tensioning systems use this technique for simplicity of design, but it creates an instance where the fabric strength will limit the level of pre-stress. Typical fabric pre-stress loads range from 2 kN/m to 10 kN/m depending on the fabric material.[85]

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[83] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

[84] Rogier Houtman, and Harmen Werkman. "Detailing and Connections." In *European Design Guide for Tensile Surface Structrues*, 147-62. TensiNet.

[85] Jean-Pierre Michel Chacar, "Design of Cable Systems for Cable Suspended Bridges." Master's thesis, Massachusetts Institute of Technology, 2001. June 2001. Accessed November 28, 2018. https://dspace.mit.edu/bitstream/handle/1721.1/84254/49398523-MIT.pdf.

Another method for fabric to cable connection is an external belt strap system. In this instance, the edge cable is placed outside of the membrane edge and linked at intervals through a sequence of straps and clamp plates. Fabric belts are stitched or welded along the perimeter to fasten the cable to the primary membrane. The advantage of this system is that it allows for flexible curved edges and can be implemented for an indefinite length. Additionally, this system allows for multiple membranes to converge on a single cable, as the belts are attached at regular intervals as opposed to covering the entire length of the cable. For waterproofing purpose, these connections require an additional membrane section to be stitched or welded to the primary membrane to cover the exposed cable-fabric connection.

Figure 28: Belt Loop, Fabric to Cable
Source: Houtman et al., 156

Fabric to Fabric

As previously mentioned, tensile roof membranes are often cut and sectioned off site for ease of handling and installation. To rejoin these subdivisions and any other required seams, the fabric must be reattached by stitching, welding, lacing, or clamping. The most commonly used is a simple welded overlap because of their inherent water tightness and seam strength. This technique uses applied heat to fuse the overlapping fabrics together. These connections are commonly single or double butt seams, or a simple

overlap seam. The only downside to this method is that on site applications are difficult, with most seam welding taken place in the shop.

Stitching and lacing techniques are commonly used for small scale membrane structures because of their relieve ease and on site constructability. However, laced seams depend heavily on the reinforcement of the holes through which the laces pass, making them vulnerable to tearing in long span applications. Stitching or sewing techniques can provide adequate strength for any load with a reasonable overlap length. However, this method only works reliably on nylon and polyester membranes. The stitching of fiberglass fabrics causes considerable strength loss because of the tight weave required for such products.

Figure 29: Fabric to Fabric Lacing

Source: Houtman et al., 154

The final method for fabric to fabric connections is a clamped seam. These seams are made of overlapping plates clamped together by bolting. These clamps are often used on edge conditions for ease of fabric tensioning during construction. These connections can be installed on site and can be made of steel, aluminum, or even wood. These clamp connections are capable of carrying extremely large loads and are commonly used to connect large subdivided fabric fields on site. One example of these clamp connections can

Figure 30: Fabric to Fabric Clamp

Source: Houtman et al., 155

be seen in figure 30. This clamp plate connection is secured by a bold and uses a bolt rope called a keder to transfer the load of the membrane across the clamp.[86]

[86] Rogier Houtman, and Harmen Werkman. "Detailing and Connections." In *European Design Guide for Tensile Surface Structrues*, 147-62. TensiNet.

Conclusions

- Pneumatic membrane systems would be more viable with GFRP cables instead of CFRP cables because of the low strength required for cables in these systems.
- The span distance of boundary tensioned membrane systems are limited by the strength of the membrane as opposed to the strength of the cable and therefore have little benefit in using CFRP cables.
- Simply suspended cable roofs require heavy roofing systems to avoid updraft issues, making inadequate for membrane roof applications
- Cable net and cable beam roof structures are orthogonally loaded cable roof structures which can benefit from the use of CFRP cable's low density, high strength, and material efficiency.
- The low weight of CFRP cables makes them more vulnerable to updraft wind loads. Cable beams and anticlastic cable nets offset this issue through opposing arch geometries.
- Saddle shaped cable net structures present a better use of CFRP cables than conic shapes. This is on account of their higher rigidity, longer span capabilities, and fewer anchor points when compared to conic shaped anticlastic cable nets.
- Silicone coated fiberglass is the most viable membrane composite for a long span mobile roof structure using CFRP cables. Fiberglass has a much longer life span than nylon or polyester which is better suited for the long life of CFRP cables. The silicone coating works to protect the fiberglass from environmental conditions, but also offers more flexibility and ease of transport than Teflon coatings.
- Cable to cable U-bold or clamped connections must have an insulating buffer to avoid galvanic corrosion caused by CFRP cable
- For fabric to fabric connections of long span fiberglass membranes, clamped and welded seam connections are best practice for on and off site conditions respectively.

Design Framework

Disasters and Displacement

Fires, earthquakes, floods, tsunamis, and hurricanes occur throughout the world, displacing people of all walks of life every year. In the United States alone, four different events each displaced nearly 200,000 people in 2017.[87] Hurricane Katrina alone displaced over 1,000.000 Americans, with 600,000 households displaced for longer than a month after the event.[88] The Federal Emergency Management Agency (FEMA) has a dedicated strategic plan for 2018-2022 which emphasizes building a culture of preparedness and preparing for disasters in advance of emergency situations.[89] One major aspect of emergency preparedness is the availability of temporary shelters and housing. In order to accommodate the large numbers of displaced population, these temporary and semi-permanent solutions need to be easily transported, simply erected, and be able to support thousands of people.

Disaster Shelters

Guidelines for disaster shelters have been administered by government agencies like FEMA as well as humanitarian organizations such as The Sphere Project. The following guidelines set by the Humanitarian

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[87] International Displacement Monitoring Centre. "United States Disasters and Displacements." IDMC. Accessed January 30, 2019. http://www.internal-displacement.org/countries/united-states.

[88] Allison Plyer, "Facts for Features: Katrina Impact." *The Data Center*. Accessed January 28, 2019. https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.

[89] United States. Federal Emergency Management Agency. *FEMA Strategic Plan 2018-2022*. By FEMA. Washington, DC: Federal Emergency Management Agency, 2018.

Charger and the Minimum Standards in Humanitarian Response are important, but understandably generalized to accommodate for any number of disaster typologies and scales. By definition, an adequate shelter must provide an immediate environment for all aspects of family life, providing protection from the elements, secure tenure, personal safety, and access to clean water and sanitation, proximity to places of employment and educational and health care facilities. It is imperative that they are easily transported and erected on the emergency site, despite a possible lack of vehicle access. The ability to respond to climate variations is crucial as these emergency shelters may be required for periods that span months or years after the corresponding disaster. Survivors will need fuel and cooking appliances available, beds and clothing supplied on site, as well as adequate ventilation and shade from the sun. Additionally, these shelters must provide its users with dignity and security in the face of the unexpected disaster. Current solutions for disaster relief are broken down into four categories: emergency shelters, temporary shelters, transitional shelters, and temporary housing.[90]

Emergency Shelter

An emergency shelter is the most basic type of shelter used for emergency situations. These shelters are generally existing buildings, used

[90] Abdulrahman Bashawri, Stephen Garrity, and Krisen Moodley. "An Overview of the Design of Disaster Relief Shelters." *Procedia Economics and Finance*18 (2014): 924-31. doi:10.1016/s2212-5671(14)01019-3.

for a temporary period to deliver the most basic shelter and lifesaving support. An example following the category 5 Hurricane Katrina is the use of the New Orleans Saints' Superdome football stadium to house displaced families after the storm.[91] This stadium housed thousands until temporary shelters and housing were brought to the inflicted area. Ideally, emergency shelters should be in use for less than one week but in catastrophic events such as Hurricane Katrina, they are sometimes required for longer periods of time.

Transitional Shelter

Transitional shelters are temporary shelter solutions developed by the displaced individuals themselves. These shelters can range from backyard tents to abandoned warehouses and are understandably required to relocate to official temporary shelters as soon as possible.

Temporary Shelter

Temporary shelters are meant for medium to short term use. These systems range from plastic tents to public mass shelters erected in a short time and used for a period of weeks. The stay period in such shelters is often limited as a result of the high volume of users and understandable lack of space in the days immediately following a large disaster event. These shelters must prioritize environmental protection as well as speed of

[91] Adham Hany Abulnour, "The Post-disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." *HBRC Journal*10, no. 1 (2014): 10-24. doi:10.1016/j.hbrcj.2013.06.001.

construction in order to quickly accommodate the large influx of displaced population. In August 2005, FEMA provided Hurricane Katrina survivors with temporary trailers, ranging from 18-40 square meters of floor area. These trailers were made of fiberglass so that they would be driven in on wheels to the disaster site. However, the quick construction of these trailers have been retrospectively criticized. On top of the understandably cramped quarters, the low quality materials used to fabricate these units provided a poor indoor air quality for its residents. Additionally, the low quality of these trailers meant that they were unable to be reused, making them relatively expensive as a result of their short life span.[92] Creating a shelter with higher quality, long lasting materials such as CFRP, allows for continual reuse and can create cheaper solutions in the long run.

Temporary Housing

Finally, temporary housing is often distributed following large disaster events across the globe. These shelters are designed for periods of six months up to three years in order to allow people affected by the disaster to return to their daily lives. These housing typologies are often rental houses or mobile prefabricated units. One main differentiating factor between shelters and housing is the privacy offered for each family unit. While shelters often have open plans and promote safety over privacy, temporary

[92] Adham Hany Abulnour, "The Post-disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." *HBRC Journal*10, no. 1 (2014): 10-24. doi:10.1016/j.hbrcj.2013.06.001.

housing is designed with each individual family unit in mind.[93] Following Hurricane Katrina, larger mobile homes were brought to the affected area to allow families to transition back into normal life for the years following the disaster. It is not uncommon for temporary shelters to transition into longer term housing over the duration of the displacement. [94]

Physical and Psychological Effects

An emergency shelter is more than just a protection from the surrounding climate. These shelters house thousands of people under one roof, people of different cultures and backgrounds, people whose homes have just been destroyed, people who may have just lost friends and family. Yes, these structures must protect their inhabitants from the climate, must provide hygienic air and water, and must be erected quickly. However, the gravity and trauma of these situations must be addressed. Facing a disaster and losing a home can cause serious, long term physical stress including traumas such as posttraumatic stress disorder.[95] In a study of the 2013 Typhoon Yolanda Victims in the Philippines, it was found that 20% of the survivors admitted to high levels of anxiety, stress, and depression. The most alarming part of that statistic is that it is spread evenly across all ages,

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[93] Abdulrahman Bashawri, Stephen Garrity, and Krisen Moodley. "An Overview of the Design of Disaster Relief Shelters." *Procedia Economics and Finance*18 (2014): 924-31. doi:10.1016/s2212-5671(14)01019-3.

[94] Adham Hany Abulnour, "The Post-disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." *HBRC Journal*10, no. 1 (2014): 10-24. doi:10.1016/j.hbrcj.2013.06.001.

[95] Abdulrahman Bashawri, Stephen Garrity, and Krisen Moodley. "An Overview of the Design of Disaster Relief Shelters." *Procedia Economics and Finance*18 (2014): 924-31. doi:10.1016/s2212-5671(14)01019-3.

from children to elders, all experiencing anxiety, stress, and depression in the wake of such disasters.[96]

CFRP Cable Net Shelter

A tensile, CFRP cable net system offers the ability to span large areas with minimal weight and material usage. The additional strength of CFRP cables allows for smaller cable diameters, tighter spools, and lighter material than a comparable steel cable system. Additionally, the lifespan of CFRP cables allows for a temporary system to be used and reused for multiple disaster relief efforts. Tensile structures are the most efficient systems for material usage per floor area, maximizing the shelter's occupancy while maintaining minimal material for transportation. During on site construction, the smaller, lighter CFRP cables are easier to handle and pose a lighter dead load for the final erection of the structure. This design study will show how a tensile, CFRP cable net structure can be used to efficiently support disaster victims though multiple phases of the relief effort.

[96] Regan Potangaroa, "Sustainability by Design: The Challenge of Shelter in Post Disaster Reconstruction." *Procedia - Social and Behavioral Sciences*179 (2015): 212-21. doi:10.1016/j.sbspro.2015.02.424.

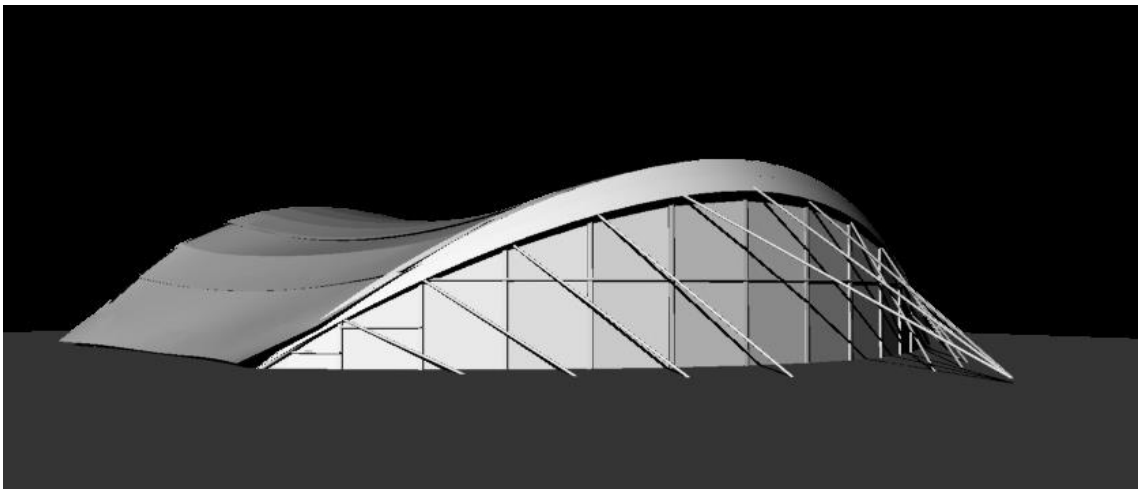

Figure 31: Simple Exterior Render

Source: Author

The design that I have adapted for this structure can be seen in figure 31, a simple saddle shaped cable net hung between two primary structural arches and tensioned back by steel cables. The symmetrical shape and lightweight cable net simplify and streamline the construction and erection process. In the sections below, I will break down the design of the cable net, the construction process, and the interior programmatic spaced used in the emergency shelter.

Simple Saddle Shape

Tensile structures offer the most efficient system to cover large areas with minimal material. However, they are not known for their simple construction. It is imperative that the design of this shelter be something that can be erected in a matter of days in order to fully support the disaster victims as soon as possible. Pneumatic structures offer interesting capabilities for quick deployment but lack the structural strength required for

CFRP cables. One way cable beam can be repeated indefinitely to create large and long structures, but each component needs to be individually constructed upon arrival and tilted into place one at a time. Additionally, once in place, one way cable systems need to be tensioned back and supported in three directions to avoid the collapse of individual components within the one way system.

Upon analyzing the possibilities for tensile structures in previous sections, a cable net system has the ability to be constructed simply and rapidly. The main advantage of cable nets is that they can be fully constructed on the ground before being raised into place as a whole roof structure. This means that, once secured, a majority of the building can be erected all at once. Within the cable net class, the two main structures are saddles and conic masts. As previously discussed, masts give the ability to push and pull the structure of the cable net, allowing a central support for additional structure as well as form. However, these masts require the convergence of the entire system of cables into one spot. This coming together of the cable system necessitates complex anchoring solutions. Additionally, mast systems double the physical number of anchors required compared to saddle shaped cable nets. These anchoring systems are the most complex and skill intensive aspects of constructing a cable net system. Doubling the number of anchors will double the anchoring work required for these cable net systems. While conic mast systems offer interesting possibilities with form finding and erection, additional anchoring

requirements overcomplicate a structure whose first priority is rapid erection and protection. Therefore, a simple saddle cable net is the most efficient, simply erected tensile typology for long span shelters. The result of my studies on the application CFRP cables suggest that a long span saddle shaped tensile roof structure is the most ideal solution. CFRP cables for this structure will use an adequate diameter of the cost efficient, 2.7 GPa tensile strength cables. The anchoring and bearing requirements for these cables have been tested to be sufficient both in simulations and practice.

Scale

Sizing and scale of the cable net, as well as the shelter itself, is a conundrum that I have framed around past disaster precedents as well as scales that can be quickly transported to disaster relief sites. While Hurricane Katrina displaced over 1,000,000 Americans, creating the benchmark for the worst disasters in US history, this event represents a scale of disaster all of its own.[97] The situations surrounding Hurricane Katrina and the low sea level of the area created a natural disaster that was unprecedented in American history. Katrina is the benchmark for large scale disasters in the US, but this one of a kind event does not represent the average displacement in America. In 2017, there were four disaster events which each lead to a displacement of close to 200,000 Americans: the Oroville Dam flooding, Hurricane Harvey,

[97] Allison Plyer, "Facts for Features: Katrina Impact." *The Data Center*. Accessed January 28, 2019. https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.

Hurricane Irma, and the California wildfires. While 2017 was an especially bad year, FEMA's records state that America averages one 200,000 displacement event every year. While most of these displaced see assistance from government programs, only an average of 5-10% require additional support from disaster shelters.[98] These temporary shelter camps are setup in multiple locations across the affected area. With close to 10,000 people looking for a place of refuge split between these areas, each area should look to accommodate at least 1,000 people immediately after a disaster event.

The other issue for sizing comes from the delivery method for disaster relief shelters. Some disaster level events such as hurricanes and fires can present themselves days or weeks before displacement occurs. FEMA describes this phase as "mobilization", which after the identification of a threat but before the event itself. During this phase, evacuations and shelter-in-place operations begin right away to prepare for the event. The goals of this phase are to move as few people as needed the shortest distance to safety.[99] During this time, emergency shelters are transported by ground to the closest possible safe location. Therefore, it is imperative that any emergency shelter can be broken down to fit inside of a ground transport freight container.

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[98] United States. Federal Emergency Management Agency. *Fema.gov.*By FEMA. August 9, 2018. Accessed February 11, 2019. https://www.fema.gov/media-library/assets/documents/168342.

[99] United States. Federal Emergency Management Agency. *Fema.gov.*By FEMA. August 9, 2018. Accessed February 11, 2019. https://www.fema.gov/media-library/assets/documents/168342.

Finally, the rapid construction and erection of this shelter is imperative for a successful design. While CFRP cable nets offer a much lighter system than steel, an excessively large cable net can easily hamper this process. The use of a crane for construction is not a guarantee after the chaos of events such as these. The CFRP cable net offers a lighter solution that can be more easily erected for a long span structure. The final size settled upon for the CFRP shelter has an 8000 ft^2 area with a 100’ span between two 80’ arches. This size was based upon the breakdown of the primary support arches into shipping containers, hygienically sound accommodations for at least 1,000 people, as well as a feasible cable net weight for tilt up construction.

Primary Structure

It can be argued that a pure tensile structure is a technical impossibility. The structural cable roof typologies described do hang in pure tension, however they require a primary support system that, invariably offsets the roof tension loads through compression. Primary structural systems can range from any compressive material in nearly any form. Small scale tensile roofs often hang from boundary tensioned aluminum systems with central masts. Larger examples include the massive concrete arch that spans 300’ across the Dorton Arena in Raleigh, North Carolina. However, as previously discussed, midspan masts add additional anchoring requirements. Moreover, this primary structural system, along with the rest of the temporary building, must be readily mobile, relatively light, and deconstructable. Therefore, any concrete structures are not viable solutions.

With the long span roof cable net system relying on these primary structural supports, weaker aluminum supports would also not suffice. Therefore, with the weight, strength, transit, and constructability requirements, a three dimensional steel truss frame is the solution that seems most adequate.

Steel truss frames have been proven to be capable of holding tremendous amounts of weight as primary supports in cable roof systems. Wembley Stadium in London has a primary support steel arch that spans 315 meters and holds over 7000 tons of roof structure in the cable tensioned roof system. When it was built, the steel arch was the longest single span roof structure in the world. Additionally, this arch was assembled and lifted into place on site. The pulling force required for the tilt up erection equated 12,000 tons of force, nearly seven times the weight of the truss itself at 1750 tons.[100] The design and construction of the Wembley arch shows that this primary structural system has the required strength, weight, transportability, and constructability required for a mobile disaster relief shelter.

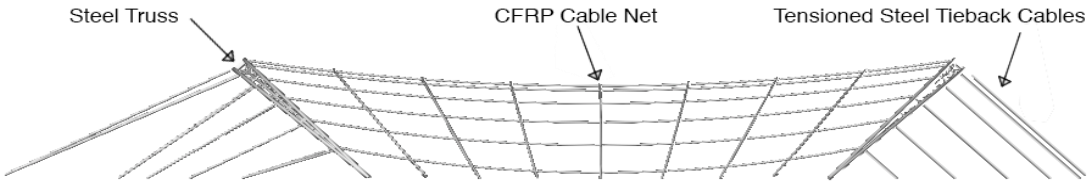

Figure 32: Design Sketch

Source: Author

[100] Christopher Lyles, "Wembley: Facts and Figures." The Telegraph. May 16, 2007. Accessed February 20, 2019. https://www.telegraph.co.uk/sport/2313407/Wembley-Facts-and-figures.html.

Two opposing steel truss arches, depicted in figure 32, are the primary structural support systems that I have chosen to hold the cable net array. These trusses are sized to span an 80’ width built with a height of 25’ to allow for a possible mezzanine level within the central portion of the structure. The CFRP cable net array is hung between the arches angled at 45 degrees, and then tensioned back by traditional steel cables and hydraulic jacking systems in order to attain the proper tension within the cable net.

This primary support system not only opposes the forces created by the cable net, but also helps to tension the cable net itself. Both the tensioning of the steel cables, as well as the weight of the truss itself, pull the longitudinal, negative sloped CFRP cables within the net into the satisfactory sag requirements. For transportation and mobile constructability, these arches can be prefabricated into three sections. These sections can then be fitted together on site through large double lapped mechanical bolt connections and temporary TAC wields. The length and angle of the trussed arches are such that each section from both arches can all fit snugly within a single 40’ shipping container as depicted by figure 38 under transportation. A steel trussed arch as the primary support system in a transient cable net structure poses a logical solution for this typology. The truss can be prefabricated and deconstructed for ease of transportation, has been proven to carry enormous loads at a fraction of the weight, and even helps to simplify the erection and tensioning process.

CFRP Cable Net

The primary long span structural component of this disaster relief shelter is the lightweight CFRP cable net. The longitudinal cables in this net span a distance of 100 feet between the primary support arches while the transverse cables span close to 80 feet. While the longitudinal cables carry both the dead load as well as the live load acting upon it, the transverse cables are simply opposing arches to offset any wind uplift, keeping the longitudinal cables in place. A quick construction and erection of this cable net is imperative for a successful relief shelter and therefore a focus on stronger cables and fewer anchors favors the cable net typology. Additionally, symmetry within the cable net allows for load calculations based on perfect catenary curves.

Saddle Net Form Finding

Guidelines for tensioned cable spans cite a maximum cable sag of 4-6% in order for satisfactory cable stiffness. Additionally, a minimum factor of safety of 3 is required for structural cables.[101] With these guidelines in mind, the form finding of the CFRP cable net falls to the cable radius as well as the

Figure 33: Form Finding Method

Source: Beccarelli, 2015

[101] Mohammad Ossman, *STATIC AND DYNAMIC ANALYSIS OF CIRCULAR CABLE ROOF NETS*. Master's thesis, MANSOURA UNIVERSITY, 2016. Accessed February 11, 2019. https://www.researchgate.net/publication/305407889_Static_and_Dynamic_Analysis_of_Circular_Cable_Roof_Nets.

number of cables in the net's array. In order to find the adequate structural cables, I followed the form finding path depicted by figure 33. As the architectural shape of the structure is measured by material efficiency and construction ease, the structural evaluation is the step required in order to find the adequate sizing for the CFRP cables' radius and net array.

Load Considerations

Longitudinal cables within the cable net array carry both the live, and dead loads distributed across the canopy. For fabric tensile structures, ASCE 7-05 cites the most influential of which as wind and snow loads. While live rain loads will occur, snow loads require much more structural support and are therefore the bottleneck on structural design. Therefore, the worst possible load combination is $L_T=L_D+L_W+L_S$, where L_T is the total load, L_D is the dead load, L_W is the wind load, and L_S is the snow load.[102]

Dead Load

To find the load requirements for the cable net system, I have created a moment diagram based around one cable. Because the basic structural elements of the membrane are perpendicular cables,

Figure 34: Simply Hanging Cable Equation

Source: Feng, 2009

[102] *Minimum Design Loads for Buildings and Other Structures*: ASCE/SEI 7-05. Reston: American Society of Civil Engineers, 2016.

each perpendicular cable presents the same basic behavioral properties. Therefore, I have created a 2D moment diagram to analyze the structural requirements of the system. The shape that a symmetrically hung cable fills is a catenary curve, which is considered optimal because it follow the bending moment diagram. Because the cable cannot resist shear or bending, it will always deflect to carry loads in axial tension only. Considering a uniformly deflected shape, we can find the respective applied forces using the diagram in figure 34. Where *w* is the load per unit length, *L* is the total length of cable, *h* is the maximum vertical deflection at midspan, and *H* and *V* are the horizontal and vertical forces.

In this structure, *H* and *V* are the unknowns, with the cable length (*L*) at 100 feet and, with a 4% sag, the vertical deflection at midspan (*h*) is 4 feet. The load per unit length (*w*) is the uniform dead load across the catenary curve. This unit is derived from the weight of the cable, as well as the weight of the fabric membrane itself. While nearly all fabric membranes weight less than 50 kg/m^2, ASCE Minimum Design Loads for Buildings requires that roof materials are calculated at a minimum of 58 kg/m^2.[103] This, in conjunction with the cable weight, creates the load per unit length across the net.

[103] *Minimum Design Loads for Buildings and Other Structures*: ASCE/SEI 7-05. Reston: American Society of Civil Engineers, 2016.

Using the moment diagram above, vertical equilibrium yields:

$$V = \frac{wL}{2}$$

As cables cannot resist bending, the sum of moments about any point will be equal to zero, therefore, horizontal equilibrium can be found using:

$$\sum M_{midpoint} = 0$$

$$H(h) + w\left(\frac{L}{2}\right)\left(\frac{L}{4}\right) - V\left(\frac{L}{2}\right) = 0$$

$$H = \frac{wL^2}{8h}$$

Finally, the force in the cable is depicted by:

$$F = \sqrt{V^2 + H^2}$$

However, as the radius and number of cables in the array change, so does the dead weight of the cables themselves. Without a set *w*, I created a matrix of varying cable diameters to determine the most appropriate diameter and volume of cables needed. Using the equations above, I tested CFRP and Steel cables with radii of 1 cm, 1.5 cm, and 2 cm and spit the subsequent loads across odd numbered arrays from 3-21 cables. The results can be found in Table x.

Wind Load

As this is a temporary structure that needs to be able to be erected within the proximity of a disaster, wind and snow load factoring must take into account the worst possible condition for satisfactory safety. Unlike the

load per unit length for dead loads, wind load can be calculated without the weight of the cable net and is therefore a stable number regardless of cable size or array. Using the second method depicted by ASCE 7-05, the analytical procedure, wind velocity pressure per square foot is:

$$qh = .00256*Kz*Kzt*Kd*V^2*IV$$

Where *Kz* is a ratio about the building height, *Kzt* is the topography factor, *Kd* is the wind directionality factor, *V* is the wind velocity, and *IV* is the building classification factor.

Though it is enclosed, this emergency shelter typology is instantly put in to the highest building classification because of its use as an emergency facility. Along the same lines, wind velocity is set to an astounding 150 mph and it is assumed that the structure is within a hurricane zone. Temporary structures usually get an allowance from ASCE 7-05 to only account for a certain percentage of the wind load, as they are only up for a certain period of time. However, this does not apply to temporary structures within a hurricane zone. All said, with a topography factor of 1, building height ratio of 1.08, and a direct factor of .85, the wind pressure equates to 60 pounds per square foot. This converts to just under 300 kg/m^2 of wind pressure, making it the highest force acting upon the building by nearly three times.

Snow Load

Some building typologies in certain regions will see snow load as the highest load force acting upon the roof structure. For the same reason as

above, the maximum possible load permissible in the United States must be applied to fully account for snow load at any emergency site. As a result of this, as well as the building typology, wind loads will always be the determining force upon this building within the continental United States.[104] However, combined snow and wind loads must be taken into account to find the total possible live load. ASCE 55-10 states, "Design snow loads shall not be reduced by implementation of snow melting or removal methods except on temporary structures if approved by the authority having jurisdiction."[105] Despite this structure's temporary status, no snow load reductions are available for this structure because in a temporary structures, this reduction is allowed only if the building will be erected during the winter season. Therefore, this cable net must be designed to withstand the maximum snow load within the continental United States.

ASCE 7-3 depicts the calculation for snow loads upon a roof, defined as:

$$p_f = 0.7 * C_e * C_t * I * p_g$$

Where p_f is the snow load, C_e is the exposure factor, C_t is the thermal factor, I is the importance factor, and p_g is the ground snow load. Again, the importance factor places the emergency shelter in category IV as a result of the emergency proceedings within the program. This puts the importance

[104] Rosemarie Fang, *The Design and Construction of Fabric Structures*. Master's thesis, Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering, 2009.

[105] United States. FEMA. Risk Managment Series. *FEMA P-957: Snow Load Safety Guide*. By FEMA.

factor (*I)* at 1.2. As the structure is heated, the Thermal condition (C_t) sees a factor of 1.1. The roof is fully exposed and therefore receives no change, with an exposure factor (C_e) of 1. Finally, the only changing coefficient is based upon standard, non-Alaskan, ground snow loads which ASCE 7 places at 20 lb/ft^2. This translates to the equation $p_f = .7*1*1.1*1.2*20$, which puts the snow load at 18.5 lb/ft^2, or 90 kg/m^2. [106]

Cable Radius and Array

With the maximum live load calculated and the membrane dead load known, the only remaining unknown is the weight of the cable net itself. However, as thickness, strength, and number of cables increase, so does the weight of the array itself. In order to find the optimum cable diameter and number of cables, I created a matrix, using the load equations above while altering the diameter of cable as well as the number of cables within the array. The matrix, depicted in table x, highlights the points at which the ultimate yield strength of the cables is able to withstand the forces exerted with a factor of safety of 3. Additionally, I ran the same numbers for a cable net made of conventional, galvanized steel cables as a comparison.

My analysis found that a CFRP cable with a radius of 1 cm would require 21 longitudinal cables to offset the total load of 178 kN within the comprised factors of safety. However, if the radius were increased to 1.5 cm, only 11 cables would be required to offset the new 181 kN load (due to

[106] *Minimum Design Loads for Buildings and Other Structures*: ASCE/SEI 7-05. Reston: American Society of Civil Engineers, 2016.

increased cable weight). Finally, if the cable radius were 2 cm, only 7 longitudinal cables would be required to offset the 184 kN total force. However, if only 7 cables were used to span the 80 foot longitudinal section, it would see the cables spaced more than 10 feet apart from each other. Excessive spacing within a cable net system will cause unwanted sag within the tensile membrane which spans the cables. Therefore, an array of 11 longitudinal cables each with a radius of 1.5 cm will sufficiently span the structure within the set tolerances.

As previously discussed, transverse cables are only acted upon by any updraft wind loads, simply to keep the longitudinal cables in place. While this force only represents one of many acting upon the building, wind loads are the highest of any within the system. For ease of anchoring and construction, using the same cable size across the entire system is often worth more than the cost saved in varying the element sizes.[107] Therefore, using the same 1.5 cm radius cable, 7 transverse cables can offset the accompanying wind load.

[107] Katherina Santoso, "Wide Span Cable Structures." Master's thesis, Massachusetts Institute of Technology, 2004. 2004. Accessed December 7, 2018. https://pdfs.semanticscholar.org/81e6/79d6384d5561ed1d003d75d018dcb2a658f8.pdf.

Steel Cable Net (with everything CFRP in Parentheses)

For the sake of comparison, I used the same standards and loading requirements to size a cable net system using steel cables of the same diameter. Understandably, steel cables of the same diameter are both heavier, and weaker than comparable CFRP cables. Therefore, it will take more steel cables to overcome the same live load forces while simultaneously increasing the dead load of the overall structure. Figure 35 depicts the number of cables required to overcome the required longitudinal loads for both steel and CFRP cables of the same diameter in the same system. The horizontal lines depict the breaking strength of the respective cables with a safety factor of three. While CFRP cables break the required strength threshold at 11 cables, it would require 23 steel cables to overcome the same

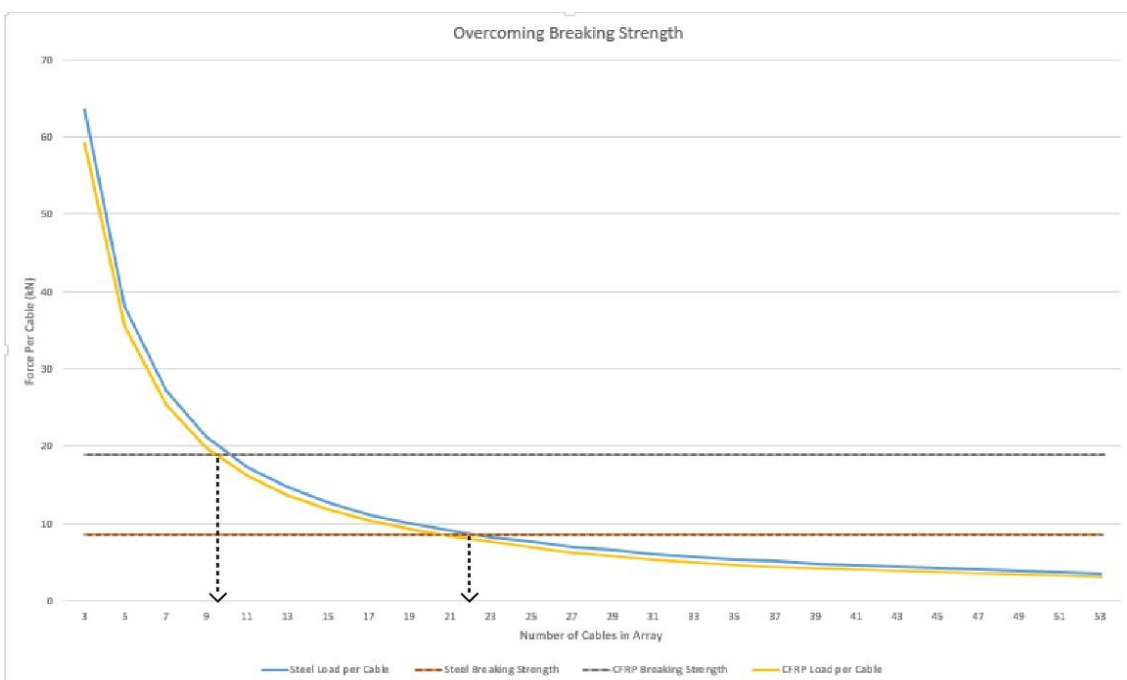

Figure 35: Overcoming Cable Breaking Strength
Source: Author

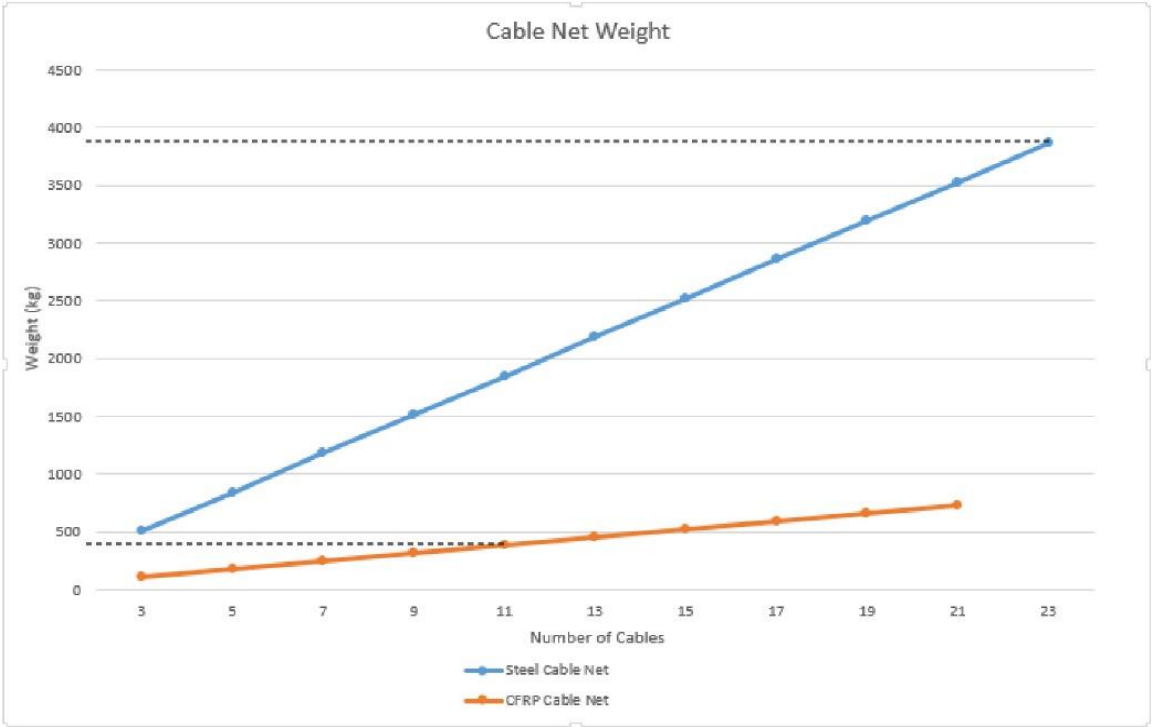

Figure 36: Cable Net Weight

Source: Author

forces. A CFRP cable net system of equal strength uses less than half the number of physical cables. This means half as many anchors, half as many spools to transport, and exponentially fewer cable overlap connections to secure across the array.

Additionally, the weight of the steel cable net system is astronomically higher than a comparable CFRP cable net. Not only are there more than twice as many physical cables within the steel net, each steel cable weighs nearly five times more than a CFRP cable of the same diameter. Figure 36 shows that this two fold increase quickly shows itself in the overall weight of the cable net. When comparing the weight of the cable net over the number of

cables, CFRP has a much more favorable rise/run than steel cables. On top of this, fewer steel cables are required within the system. The results for this structure show that a comparable steel cable net would weigh 4482 kg while a system using CFRP cables only weighs over 10 times less, at 379 kg.

Looking back at figure 36, it is worth noting that despite this sizable weight advantage, the overall dead and live load forces are fairly similar in range. This is a result of the maximized wind and snow loads that are required for disaster relief shelters. In terms of the building's equilibrium and loading, the disparity in weight between the two cable net systems is fairly negligible. However, the advantages start to show themselves as a result of the transient nature required by disaster relief shelters. The rapid construction of this system post-disaster is imperative for a successful disaster relief shelter. Fewer spools and lighter cables translate to simpler and faster transportation. Less weight and material during construction speeds up loading, clipping, and anchoring times. And most importantly, a cable net that is 1/10th the weight becomes vitally important during the tilt up erection of the primary arch system. As previously stated while exploring the cable net's primary structural support, the iconic Wembley arch required nearly seven times the load of the truss in order to lift and tilt the arch into

place. With the cables attached prior to erection, the weight of the cable net system becomes a part of the forces that the tilt up process must overcome. The difference between overcoming 2,653 kg (7*379 kg) for a CFRP cable net versus 31,374 kg (7*4482 kg) is huge. The reduced weight simplifies the tilt up construction process to the point that it can be accomplished without cranes and within the required amount of time to help shelter displaced families.

Transportation

Within the United States, the possible location of a disaster could range across the entire continent. This is one of the main reasons why FEMA has broken down the United States and its territories into 10 risk map regions. Each region has its own risk assessment possibilities as well as one or more FEMA headquarters for

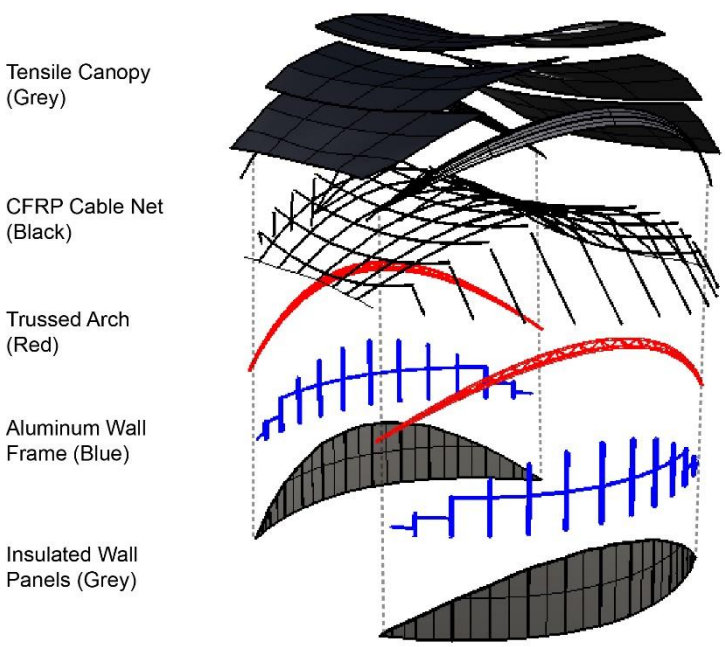

Figure 37: Exploded Axon

Source: Author

operations to stem from.[108] After a FEMA level disaster strikes, they are ready to respond within a few hours, if not before. As previously discussed, FEMA's mobilization phase can start weeks before an event even occurs given proper forward knowledge. Given such proximity and forewarning, even in the face of the worst displacement disaster in our nation's history, Hurricane Katrina, FEMA was able to drive temporary shelters to location on big rig trucks. These fiberglass temporary shelters and homes arrived via roadways, one big rig carrying one 40' home at a time.[109] With this precedent in mind, the design of a CFRP cable net structure must be easily transported within 40' containers on the roadways. Tensile cable net roofs are some of the most efficient structural systems in terms of material use. Breaking down and transporting the prefabricated CFRP cable net shelter follows the same

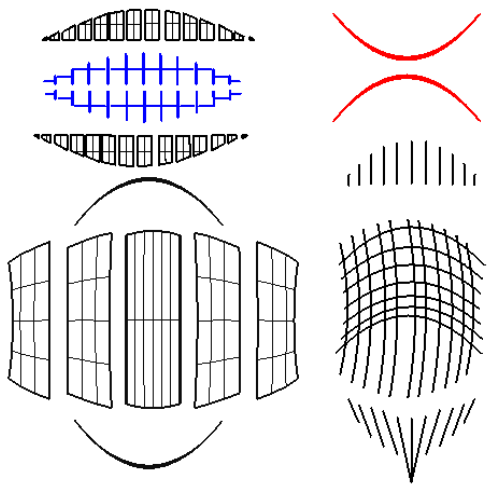

Figure 38: Materials Laid Flat

Source: Author

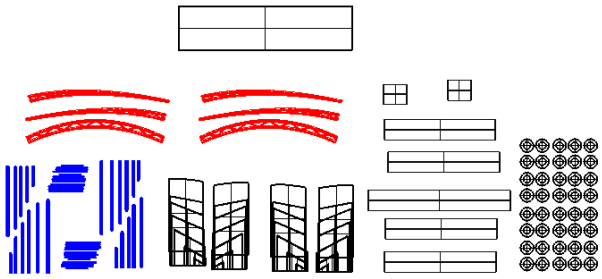

Figure 39: Materials Packaged

Source: Author

[108] United States. FEMA, Risk Mapping, Assessment and Planning (Risk MAP). Emergency Support Function Annexes | FEMA.gov. Accessed February 21, 2019. https://www.fema.gov/risk-mapping-assessment-and-planning-risk-map.

[109] Allison Plyer, "Facts for Features: Katrina Impact." *The Data Center*. Accessed January 28, 2019. https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.

principles of efficiency. After analysis, transporting this prefabricated tensile structure proves to be four times more efficient that current FEMA practices. Instead of having a single 400 sq. ft. shelter transported by a single truck, the entire structural frame and skin of this 8000 sq. ft. shelter can fit into just five container beds.

To demonstrate this, I took my full scale digital model and broke down the primary structural and weatherproofing systems into their individual components. These components I then laid out flat as depicted in figure 38.

Packing the different materials required a case by case analysis. As previously explored, the trussed arch is prefabricated to break down into three sections which can then be fit inside of a 40’ container. For the cables, spooling standards cite a minimum of 25 times the cable diameter.[110] The CFRP cables as well as the steel tensioning cables have a diameter of 3cm, requiring a minimum spool of 6.25’. Using this to size the spools,

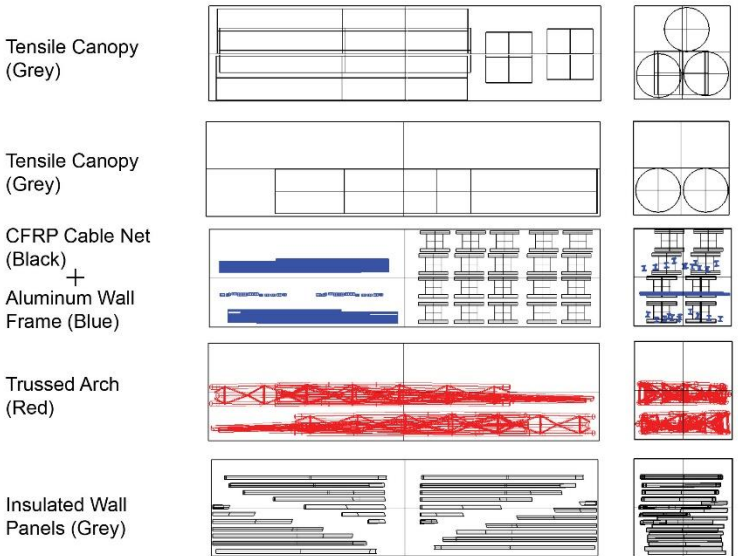

Figure 40: Materials Shipping
Source: Author

[110] *Structural Applications of Steel Cables for Buildings: ASCE/SEI 19-16*. Reston: American Society of Civil Engineers, 2016.

I then added 40 spools, one for each cable, for simplicity as well as redundancy. The aluminum wall frame as well as the insulated wall panels themselves never exceed 8’ in width, and can therefore be simply stacked into one and a half containers, with some room left over. Finally, the tensile canopy, split into seven sections can be rolled into 20’ bundles. These rolled sections, similar to baseball grass covers, can be fork lifted and stored within one and a half containers as well. Altogether, the entire structure can be stored for transportation within five 40’ shipping containers for transportation across the United States.

Construction/Erection

The rapid erection of the roof structure in order to protect families who have just lost their homes takes priority over every design aspect. CFRP cables are able to assist in this because of their lightweight nature and high tensile strength. Without taking additional strength into account, CFRP cables average one fifth the weight of steel cables of the same diameter. After analysis of the comparable steel and CFRP cable nets, CFRP cables reduce construction costs and time with half the required cables. This translates to fewer anchoring points, fewer overlap conditions, and a cable net that is nearly 10 times lighter than its steel counterpart. The high strength and low weight of CFRP cables directly renders into a quicker, lighter erection process with CFRP cables.

While the CFRP cable net's low weight and high strength will help during the tilt up process, it is imperative that the structural supports and weatherproofing membrane are constructed as soon as possible. After FEMA's mobilization phase, they move into the evacuation and shelter-in-place phase. During this phase, the priority objective is the protective action for evacuees as well as the establishment of a command center for the next phase. The evacuation phase is estimated to last 5-7 days before the impact phase begins.[111] In order for this CFRP cable net emergency shelter to be successful, it must be weatherproofed within the estimated 5-7 days of FEMA's evacuation.

Figure 41: Dead Man Anchor

Source: Buchholdt, 1999

[111] United States. Federal Emergency Management Agency. *Fema.gov.*By FEMA. August 9, 2018. Accessed February 11, 2019. https://www.fema.gov/media-library/assets/documents/168342.

Foundations and Anchoring

The first, and most important step in terms of a bottleneck process, is pouring concrete for the required foundations. While most of the anchoring systems for the cable net are drilled ground anchors, depicted in figure 42, two cable dead man concrete foundations are required for structural redundancy. Additionally, concrete must be poured for the four steel arch foundations. For these pours, rapid hardening hydraulic cement with fly ash can be used for an adequate cure within three days.[112] Outside of the poured concrete anchors, there are 36 locations where the cable net and tensioning cables must be anchored. Using my calculations for the CFRP cable net, the highest stress cable undergoes 16 kN, or 3500 lb. of force. American Earth Anchors and other similar companies, make 46" penetrating anchors which have been tested to carry a pullout load of 14,000 lb. on asphalt and 9,500 lb. on gravel and dense sand.[113] These penetrator anchors are installed by predrilling four feet through the asphalt or dense gravel and using a motorized drill to screw the penetrators into the ground. Ground

Figure 42: Ground Anchor
Source: American Earth Anchors

[112] James K. Hicks, and Ryan M. Scott. Rapid Hardening Hydraulic Cement from Subbituminous Fly Ash and Products Thereof. US Patent US 2005/0241537 A1, filed February 11, 2005, and issued November 3, 2005.

[113] American Earth Anchors. *Load Capacity Anchors*. Franklin, MA: American Earth Anchors, 2017.

anchors are relatively easy to use but do also narrow the range of locations possible for this shelter. However, after large events such as Katrina, FEMA has had a history of setting up their command center on large asphalt parking lots.[114] For this, these ground anchors add the additional option of hard packed gravel or dense sand foundations.

Steel Truss

Once the foundations have been poured, the next step is to unload and join the prefabricated sections of the arched steel truss. As discussed in the transportation section, the two trusses are broken down into three sections each, creating six prefabricated sections that all fit within a single shipping container. These individual sections should be driven as close as possible to their final location. They should then be removed and individually placed in their respective position before joining the truss together through mechanically bolted half lap connections and temporary TAC wields. The two arches should be oriented so that they are both laying the same direction,

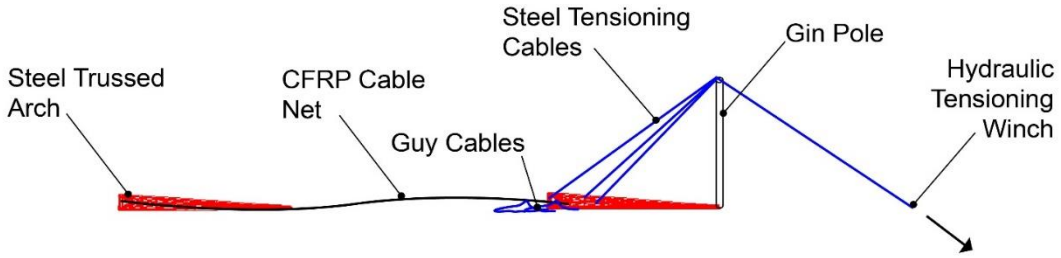

Figure 43: Pre-erection setup

Source: Author

[114] Allison Plyer, "Facts for Features: Katrina Impact." *The Data Center*. Accessed January 28, 2019. https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.

with their foundations ready to connect to the hinged baseplate attached onto the concrete foundation. Once the two trusses are fully assembled two gin poles should be attached to the baseplates and joined vertically at the center point of the trussed arch, creating a vertical triangle pulley to hydraulically winch the arch into position. Additionally, guy cables should be attached to the back of the steel trussed arch for control during the erection process.

Cable Net

Figure 44: Cable Termination
Source: Buchholdt, 1999

After the primary support system is assembled, the cable net can begin to be assembled. CFRP cables must be unspooled, with their permanent cold pour resin anchors already attached tested for fatigue. The attachment of the cable net to the primary support system is performed on the ground, and with the anchors already attached, a relatively low skill level is required for the attachment of the anchors. The jaw, or close end anchors depicted in figure 44 allow for free rotation about a single axis. This is vital for the tilt up construction phase as the cable net is completely slack while assembled on the ground. Once the anchors have all been attached to the sockets, permanently attached to the steel truss frame, the transverse cables must be laid atop the longitudinal cables and attached to their respective ground anchors.

Once the slack cable net is completely laid out, the overlapping cable to cable connections must be secured. With the entire cable net slack, it is important that each of the 77 cable to cable overlap locations is clearly marked on both sets of cables. This mechanically bolted connection can be secured fairly quickly, but the sheer volume of connections required may see this process take a few hours. However, if this construction process were using the comparable steel cable net, 345 cable to cable overlapping conditions would be required. Not only does this save over four time the number of physical clamps, it also sees the labor hours for this process drop by over four times. This is just one iteration of how the CFRP cable net saves money in both material and labor cost through its superior strength and low density.

Figure 45: Cable to Cable Overlap
Source: Vandenberg, 1998

During the cable net form finding process, it is worth noting that all of the tested nets had an odd number of cables within the array. The odd number of cables allows for a symmetrical spread as well as an important central cable. This central cable is pivotal for both the structure of the cable net, as well as aiding to ease the erection process. A central cable allows for a more controlled, even lift for the primary structure arch. Additionally, after

the arch is in place, a balancing act of cable tensioning must take place in order to obtain the required sag. The central cable acts here as a balance and baseline for the rest of the structure to follow.

Tensile Membrane

Figure 46: Fabric to Fabric Clamp
Source: Houtman et al, 155

Figure 47: Belt Loop Fabric to Cable
Source: Houtman et al., 154

After the cable net is secure, the seven sections of tensile membrane fabric should be unloaded. The silicone coated fiberglass membranes are broken into five 20-25’ sections, each overlapping the next by a full span of longitudinal CFRP cables. The 6’ overlap is used to ensure waterproofing about the entire span of the structure. These overlaps are then connected on both ends by mechanical clamp plates depicted in figures 43 and 44. The two remaining sections are weatherproofing covers to attach across the steel arch frame.

The five main sections are tensioned between fastening rods attached to the steel truss arches. The fabric uses a belt connection depicted in figure 46 and discussed in previous sections for its indefinite length. The silicone coated fiberglass can then be secured across the cable net at each of the 77

cable to cable overlap points to ensure proper shape, avoid water ponding, and minimize any flapping.

The first two sections to be unrolled are positioned at the outermost edge of the structure. These membranes are then subsequently overlapped by the next, higher sections before finally being capped by the largest, central section of fabric membrane. The final two, arch covering membranes can then be attached to overlap any gaps created by the truss frame and belt loop connections. These membranes, weighing roughly 10 lb/ft^2 can be unrolled by a crew of volunteers, similar to the way that baseball stadiums unroll their large rain delay tarps. Each connection is made up of overlapping and mechanical bolts for ease of reuse while the fabric itself is tensioned through the cable tensioning process. Additionally, flexible insulating membranes such as Tensotherm allow for acoustic dampening and high insulation values without sacrificing flexibility, translucency, or weight.[115]

Wall Construction

Finally, the last process for the completion of the building shell is the insulated panel wall at the front and rear of the structure. This prefabricated, panelized wall is mounted on an aluminum frame which spans from the top of the arch to the ground. This panelized wall and frame are non-structural, but do offer additional stiffness and sheer resistance for the overall building.

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[115] "Insulated Tensioned Membrane." Birdair, Inc. - Tensioned Membrane Structures, Fabric Roofing. Accessed February 21, 2019. http://www.birdair.com/tensile-architecture/membrane/insulated-tensioned-membrane.

Structurally Insulated Panels (SIP) can be easily prefabricated for ease of construction and continual reuse. Polyurethane SIP panels are commonly manufactured with a depth of 3.5” and an R-value close to 20.[116] These panels can also be used as flooring where needed, but need to be code cleared by the individual manufacturer.[117] By using a mechanically bolted, prefabricated system, this wall construction can be used for multiple disaster events. Additionally, when individual panels become worn past use, they can be replaced one at a time, instead of needing to replace the entire wall. The construction of these wall sections can begin at differing times. The front of the building, with the three cables anchored to the concrete dead man, can begin wall construction as soon as the laborers are available. However, wall at the back of the building cannot be constructed until the steel trussed arch is in position in order to avoid complications during the erection process.

[116] Juan Rodriguez, "SIPs (Structural Insulated Panels) Are an Alternative to Wood Framing." The Balance Small Business. Accessed February 22, 2019. https://www.thebalancesmb.com/structural-insulated-panels-benefits-844842.

[117] Icc. "2018 International Residential Code for One- and Two-Family Dwellings." CHAPTER 11 [RE] ENERGY EFFICIENCY | 2012 International Residential Code | ICC PublicACCESS. Accessed February 22, 2019. https://codes.iccsafe.org/content/IRC2018/chapter-6-wall-construction.

Erection Process

Once all of the above components are in place, and the concrete anchors have cured over three days, it is time to lift the steel trussed arch into position. This is the most technical and difficult process during the construction of this structure and would require a small group of experienced construction workers and foremen. Preferably, this team is practiced and dedicated to the installation process as these events occur, so that their experience can translate into a quick and on time erection of the structure.

For the sake of construction time, nearly all of the above components, with the exception of the far wall, can occur before the lifting of this structure. Many can even be completed at the same time. However, this would require a large number of laborers. Luckily, these large scale disaster events often see thousands of volunteers helping across the country. Additionally, FEMA recommends giving tasks to the displaced population.[118] FEMA states that working towards a common goal can help get people's minds off of what they have lost, and towards what they have to gain. Many aspects of the prefabricated construction are

Figure 48: Hinged Baseplate
Source: Solidsignal.com

Figure 49: Hinged Baseplate
Source: Tboake.com

[118] United States. Federal Emergency Management Agency. *FEMA Strategic Plan 2018-2022*. By FEMA. Washington, DC: Federal Emergency Management Agency, 2018.

fairly unskilled in nature and can benefit greatly from the help of volunteers the displaced population.

The first step in the erection process is to be sure that the trussed arches are secured to their individual concrete foundations. Hinged baseplates, such as the two depicted in figures 48 and 49, are used in many styles of tilt up construction. They help to guide the arch as it is erected, ensuring that it stays within the axis as well as attached to the concrete foundation.

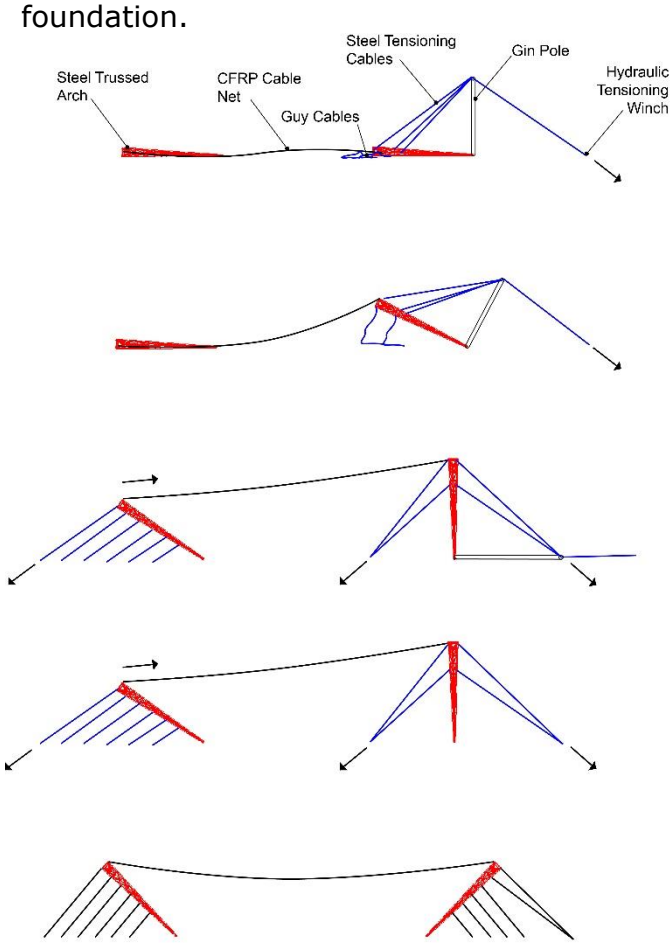

Figure 50: Erection Proccess
Source: Author

Once the baseplates are secured and the cables are in place, the tilt up construction can begin. Following the diagram in figure 50, the tensioning cables are attached to a hydraulic winch. This winch uses the vertical gin pole as a torque arm and the hinged baseplate as the fulcrum. This lift continues, using opposing guy cables as a safety, until the forward arch becomes completely vertical. At this

point, the gin pole is removed and the forward tensioning cables are attached at their anchors. The final step in the tilt up construction uses the guy cables to lower the steel arch into position, raising the other arch up and tensioning both the cable net and fiberglass membrane. Once the steel truss frame and cable net are in position, the individual cables need to be tensioned to balance the tensile structure and ensure proper stiffness within the cable net.

Phasing

As the individual disaster events develop, this structure has the ability to adapt its interior for different phases of displacement within a single event. The long span cable net typology allows for a completely open, column-less floor plan which can be arranged, and rearranged, to suit different needs as the events develop. The construction method above represents the completion of phase 1 for this building: Environmental Protection.

Phase 1: Environmental Protection

The first phase for the interior space of this structure represents a basic human need, environmental protection. This phase represents a basic level of protection from the sun, wind, and rain, which can begin as soon as the cable net has been tensioned.

Priorities

The priorities for this phase are shelter, sleeping arrangement, water, and healthcare. FEMA guidelines state that for health reasons, bed units must

be allowed 10 square feet surrounding. With double bunked cots, this places the capacity of the 8000 sq. ft. building close to 1500 people, allowing for corridors and dead spaces along the exterior of the structure. As needed, multiple structures can be assembled to accommodate any additional displaced population.

Programmatic Space

These shelters and FEMA facilities are not simply sleeping arrangements. Within the FEMA disaster camps, areas are needed for the Red Cross, Salvation Army, Mental Health Clinics, a disaster command center, water tanks, gas tanks, food serving, restrooms, heirloom and item storage, pet and animal facilities, security, parking, generators, garbage, and recycling. For the first phase, the priorities within the cable net structure are sleeping and hygiene. Current FEMA camps, depicted in figure 51, contain the rest of the programmatic spaces outside of the sleeping area. With the use of the long span CFRP cable net structure would see the scale of the sleeping area greatly increase compared

Figure 51: Current FEMA Disaster Shelter

Source: FEMA, 2018

to current FEMA arrangements.[119]

These emergency shelters may be required for periods that span months or years after the corresponding disaster. Additionally, they must have provisions for any type of disaster, such as earthquakes, hurricanes, tsunamis, or floods, before they arrive. As a result of these provisions, the shelters must have a flexible interior space for multiple or mixed uses.[120] A tensile system with a primary structural system has the ability to span large distances without interior columns or interruptions. This uninterrupted structural system is perfect for the allowance of flexible and mixed use interior spaces.

Phase 2: Command Center

Priorities

The second phase for the interior of the cable net shelter sets its priority on creating a disaster relief command center to base recovery and relief operations out of. Current FEMA practices, dictated by their current strategic plan, use a hub and spoke plan of action. This strategic plan, as illustrated

Figure 52: FEMA Hub and Spoke

Source: FEMA, 2018

[119] United States. Federal Emergency Management Agency. *FEMA Strategic Plan 2018-2022*. By FEMA. Washington, DC: Federal Emergency Management Agency, 2018.

[120] Abdulrahman Bashawri, Stephen Garrity, and Krisen Moodley. "An Overview of the Design of Disaster Relief Shelters." *Procedia Economics and Finance* 18 (2014): 924-31. doi:10.1016/s2212-5671(14)01019-3.

in figure 52, centers the operation out of a single location, bringing every worker, volunteer, and victim to a single location. From this single location, each person is given a role and location to further their assistance. These roles can see each person stay at the command center, or be allocated to another location for further assistance. The large scale and uninterrupted floor plan of the CFRP cable net shelter makes it the perfect location for this command center.

Programmatic Space

While in use as a command center, the shelter will still be used primarily as environmental protection and sleeping arrangements. However, as people and personnel are allocated to their proper locations, the number of displaced persons on site will slowly dwindle over the weeks. As the cots and sleeping arrangements begin to thin, more space will open up for the other required programs. While spaces for restrooms, garbage, and storage will remain in place for obvious reasons, organizations such as the Red Cross, Salvation Army, and Mental Health Clinics can begin to infuse into the space. Bringing these organizations under the same roof will directly bring help to in need, instead of waiting for them to go and get help.

The addition of a temporary, metal mezzanine deck along the central corridor of the 25’ structure will create the extra space required for the command center. This command center will be the hub that all of the FEMA

and rescue operations stem out of.[121] Creating a central, organized location helps to give order to the chaos that occurs post disaster. Additionally, disasters of this scale require more than just a single shelter location. Cities and counties effected by a single disaster could spread out for miles. Therefore, FEMA does not set up just a single disaster relief location. Having a single, large span command center helps to organize these multiple locations to work together cohesively. This command center phase takes charge of victim safety, rescue operations, cleanup procedures, and personnel placement. Additionally, the central mezzanine level give the added benefit of an extra layer of safety. While FEMA does its best to organize post-disaster situations, there is a lot of chaos involved when thousands of people are displaced. Unfortunately, FEMA has recognized that there are some individuals who take advantage of the chaos and attempt to steal personal items.[122] A private, second story command center doubles as an observation deck for the security personnel to operate out of. This command center phase will begin as within the first two weeks and continue until all rescue and cleanup operations are complete. This phase could last up to an entire year depending on the scale of disaster involved.[123]

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[121] United States. Congress. Senate. *Disaster Recovery Reform Act of 2018: Report of the Committee on Homeland Security and Governmental Affairs, United States Senate, to Accompany S. 3041, to Amend the Robert T. Stafford Disaster Relief and Emergency Assistance Act to Provide for Disaster Recovery Reforms, and for Other Purposes*.

[122] United States. Federal Emergency Management Agency. *FEMA Strategic Plan 2018-2022*. By FEMA. Washington, DC: Federal Emergency Management Agency, 2018.

[123] Adham Hany Abulnour, "The Post-disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." *HBRC Journal*10, no. 1 (2014): 10-24. doi:10.1016/j.hbrcj.2013.06.001.

Phase 3: Temporary Housing

Priorities

The final phase involved in the programmatic setup for this structure begins three months after the disaster event. At this time, FEMA begins to expand their scope to state administered housing assistance. This program helps families that are most effected by the disaster events to get them back on their feet.[124] After Hurricane Katrina, the government spent hundreds of millions of dollars to help families in need for up to three years. FEMA temporary housing trailers saw at least 114,000 households come and go within that time.[125] The priorities for these housing units are both privacy and comfort for the individual family units.

Figure 53: Interior Render

Source: Author

[124] United States. Congress. Senate. *Disaster Recovery Reform Act of 2018: Report of the Committee on Homeland Security and Governmental Affairs, United States Senate, to Accompany S. 3041, to Amend the Robert T. Stafford Disaster Relief and Emergency Assistance Act to Provide for Disaster Recovery Reforms, and for Other Purposes*.

[125] Allison Plyer, "Facts for Features: Katrina Impact." *The Data Center*. Accessed January 28, 2019. https://www.datacenterresearch.org/data-resources/katrina/facts-for-impact/.

Programmatic Space

Within the cable net space, the command center and housing phases may overlap for a series of months. As people are reconnected with their families or allocated to additional shelters, the double bunked cot sleeping arrangement will start to dwindle. As space opens up, acoustic dampening partitions and proper bedding can be brought in and arranged within the space. Following FEMA's Katrina home model, each family is given 400 sq. ft. of private space for them to settle as they look for new homes and jobs. While housing 20 families will not solve the entire disaster crisis, it will help to alleviate the heavy load, as well as cost of housing thousands of people across the area. The layout of this space should prioritize visual and acoustic privacy, as well as basic comforts such as couches, refrigerators, dining tables, and even televisions.

Dismantling and Reuse

Following the interior programming phase 3 and the reallocation of the final displaced residents, the dismantling and reuse of the structure can begin. This process runs in the reverse order as the construction, and may even take more time, as the number of volunteers and laborers is sure to decrease months and years after the disaster. Following the inverse of the construction, the nonstructural, prefabricated SIP walls and aluminum frame must be dismantled and removed first. Next, the tension cables reverse roles and become the guy cables, guiding the steel truss arch downwards with the

help of the reattached gin pole. Once the primary structure arches are lowered, the silicone coated fiberglass membrane can be detached and rolled back into seven separate bundles. Checking and marking and locations of ware, such as ripped fabric, can be noted during this phase and repaired before the next erection of the structure.

When the membrane is loaded, the cable to cable overlap conditions should be removed, along with the cable anchors from the steel frame. The cables can then be re-spooled and stored for transport. Before the next reuse of the shelter, the permanent cold pour resin CFRP anchors should be individually stress tested to ensure proper strength and structural integrity. The final step is the dismantling of the steel truss frame into its 6 original prefabricated components.

Conclusions

The use of CFRP cables in place of traditional steel cables has the opportunity to revolutionize long span tensile structures. These cables can perform the same structural abilities with less weight, fewer anchors, lower sag, longer life span, and much higher strength. As I have shown, the financial investment is not only worth it over the life cycle of the cable, but even right away when considering the efficient material usage. Additionally, currently active physical and modeled anchoring systems have shown to perform as expected over their still-active 30 year life, despite worries over lack of sheer strength. A CFRP cable net, like the one in the emergency

shelter design, lowers the cable weight by over 10 times on account of its lighter and stronger material properties. Not only does this lower the dead load considerably, it also allows for much longer span possibilities before cable breaking strength becomes an issue.

Within the design for a temporary long span cable net emergency shelter, the CFRP cable net shows how this weight savings can make a huge difference in the force required during erection process. Additionally, the superior properties of CFRP cables allow for fewer cables, anchors, and cable overlaps. This, along with the weight savings, will help to cut costs on both material usage, as well as labor times. The weight savings and smaller diameters of CFRP cables also allow for an increase ease of transportation

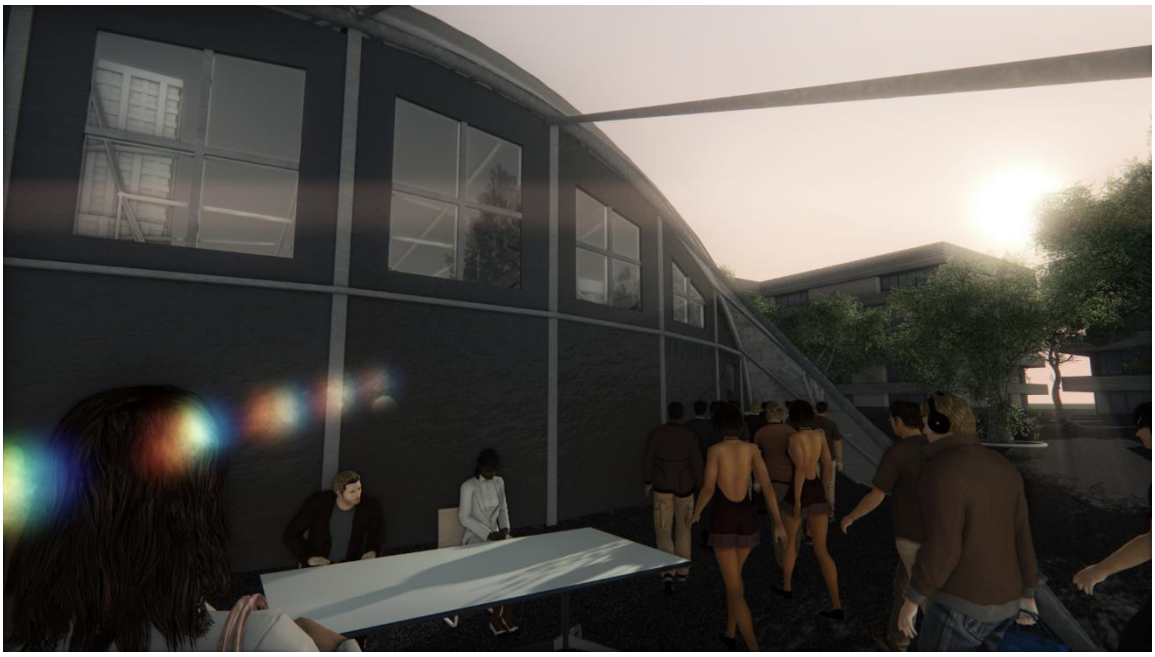

Figure 54: Check-In Render

Source: Author

and handling during the construction process. CFRP cables, with smaller diameters and lighter weights, directly translate to savings in material cost, labor time, and equipment size.

While my design for a temporary long span CFRP cable net structure shows the possibilities and strengths of CFRP cables, a cable net is just one use for these structural cables. Cables similar to the ones described are currently being used as tendons for ground anchors, posttensioning tensile support for concrete slabs, seafloor cable tethers for oil rigs, and even as cable stays for suspension bridges. There is even the possibility of use as X-bracing for sheer stabilization in skyscrapers and large buildings. These cables can create longer bridges, larger domes, and taller buildings than currently possible with steel cables.

Sample Construction Schedule

	Task Name	Start	Hours	Assigned To	Predecessors
1	**Foundations**	03/04/19	3		
2	Unload and Prepare (mix) Concrete	03/04/19	2	Volunteer	
3	Drill for Rebar for 4 Concrete Dead Man Anchors	03/04/19	3	Skilled	
4	Pour Concrete into Moulds	03/04/19	2	Skilled	3, 2
5	Cure Time	03/04/19	24		4
6	Drill Transverse Cable Net Anchors	03/04/19	8	Skilled	
7	Drill Longitudinal Cable Net Anchors	03/05/19	8	Skilled	6
8	Foundations Finished	03/07/19	0		5
9					
10	**Steel Truss**	03/04/19	2d		
11	Unload Trusses	03/04/19	2	Volunteer	
12	Move into Foundation Position	03/04/19	3	Volunteer	11
13	Bolt and Tack Weld Frames	03/04/19	6	Skilled	12
14	Secure Frames to Foundation	03/07/19	3	Skilled	8
15	Truss Finished	03/08/19	0		14
16					
17					
18					
19	**Cable Net**	03/05/19	4d		
20	Connect Slack Longitudinal Cable Anchors to Frame	03/05/19	4	Skilled	13
21	Connect Slack Transverse Cable to Ground Anchors	03/05/19	4	Skilled	20
22	Attach Clips at Overlapping Nodes	03/06/19	8	Volunteer	21
23	Cable Net Finished	03/07/19			22
24	**Fabric**	03/07/19		Volunteer	
25	Unroll Two Lowest Fabric Sections	03/07/19		Skilled	22
26	Connect Belt Straps to Structure	03/07/19		Volunteer	25
27	Unroll Two Middle Fabric Sections	03/07/19		Volunteer	25
28	Connect Belt Straps to Structure	03/08/19		Skilled	26
29	Mechanically Clamp Two Fabric Sections across 5m overlap	03/08/19		Skilled	26
30	Unroll Central Fabric Section	03/08/19		Volunteer	27
31	Connect Belt Straps to Structure	03/08/19		Skilled	30
32	Mechanically Clamp Fabric Sections across 5m overlap	03/08/19		Skilled	30
33	Unroll Two Arch Covering Fabric Sections	03/08/19		Volunteer	30
34	Connect Belt Straps	03/08/19		Skilled	33
35	Mechanically Clamp Fabric to Fabric Overlaps	03/08/19		Skilled	33
36	Fabric Finished	03/09/19			35
37	**Erection**	03/08/19			
38	Layout Gin Poles on Ground	03/08/19		Volunteer	15
39	Attach Erection Cables to Guy Poles	03/08/19		Skilled	38
40	Mount and Attach Cables to Pneumatic Jack	03/08/19		Skilled	39
41	Raise Gin Poles into Position	03/09/19		Skilled	40
42	Attach Guy Cables	03/09/19		Skilled	41
43	Raise Structure into Position	03/09/19		Skilled	42, 36, 23, 15, 8

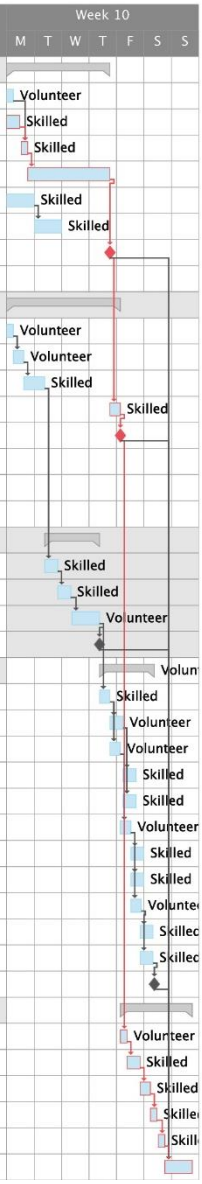

Figure 55: Sample Construction Schedule

Source: Author

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