Strategies for Redesigning High Performance FRP Wind Blades as Future Electrical Infrastructure

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ABSTRACT: Wind capture is one of the best forms of renewable energy generation and is growing both on and offshore at a staggering pace world-wide. One of the major challenges however is what to do with the Fiber Reinforced Composite blades that drive the turbines at the end of service life which is typically only 20 years. Working with colleagues at Queen's University Belfast (Northern Ireland) and University College Cork (Republic of Ireland), **The Re-Wind Team** at Georgia Tech has developed a patented re-use application for deploying the end-of-life blades as the vertical tower structures in future high voltage electrical transmission lines thus contributing to the circular economy. The US electrical grid will undergo trillions of dollars' worth of expansion and improvements over the next two decades. By reusing the blades to replace virgin materials such as steel and concrete within the electrical grid, this design will not only avoid landfilling millions of tons of composite material it will also reduce the overall carbon footprint of future grid construction.

KEYWORDS: Global Sustainability, Mitigation and Adaptation, Materials and Advanced Digital Fabrication, Circular Economies, Future Electric Grid, Power Transmission, Resilient Infrastructure, Economic Sustainability

INTRODUCTION

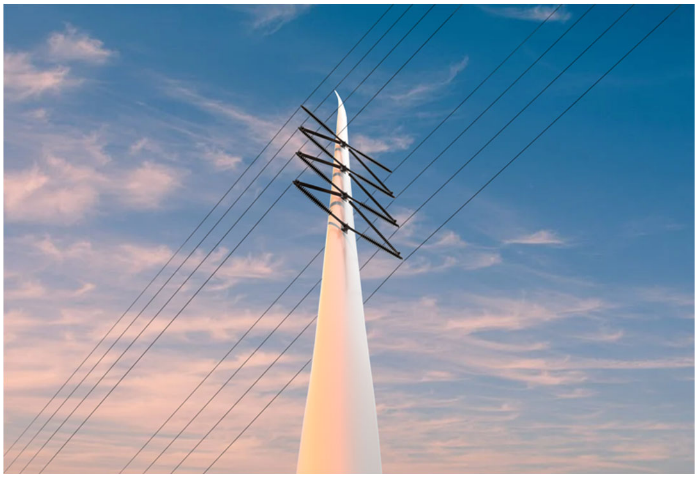

Figure 1: Detail of BladePole with Braced Line Post Hardware

From humble beginnings turning mills and pumps in the lowlands of Northern Europe wind power has become one of the highest output forms of renewable energy in the world with an estimated 192 GW of installed capacity in 2020 and an estimated 15-18% of global electricity production projected by 2050 (Lui et al 2017). While this energy is clean and renewable it does have at least one major hurdle to overcome which is what to do with the end-of-life (EoL) fiber reinforced polymer blades that harvest the wind and turn the turbines to generate electricity. The Re-Wind network is a group of engineers, architects, geographers and policy researchers in the USA, Ireland, and Northern Ireland that have been developing multiple technologies and applications for second life reuse of these high value blades within a circular economy paradigm. In addition to the primary application discussed in this paper, The BladePole (Figures 1 & 2), the team has developed a suite of reuse applications as a *Design Atlas* to guide the community as we tackle this issue for decades to come. The applications include pedestrian bridges, seawall barriers, and affordable housing to name a few.

1.0 PROBLEM: End-of-Life (EoL) Wind Blade Waste is A Looming Disaster

1.1 Context

The wind energy system follows a linear economy where raw materials are extracted to manufacture wind turbines, these are used and maintained for approximately 20-25 years and finally deemed for decommissioning or repowering (WindEurope 2020). Wind power is considered a renewable energy source because it uses the wind to generate energy and therefore it does not emit greenhouse gas emissions during its use phase. Additionally, the wind industry continues to focus its efforts to improve the manufacturing process of wind turbine production and all of the components. Unfortunately, the wind energy industry currently does not fully implement a circular economy model where 100% of the components are recirculated at end-of-life, a so-called cradle to cradle approach.

When a wind turbine is deemed for repowering or decommissioning, 85%-90% of the total mass of the turbine can be recycled like the foundation, tower, gearbox, and generator mainly because these are composed of steel and concrete materials that are traditionally used and have standard recycling processes in place (WindEurope 2020). However, wind turbine blades are composites made of carbon or glass fiber, a polymer matrix, balsa wood or foams, structural adhesives, and coatings that make it very difficult and energy intensive to separate (Jensen and Skelton 2018). Therefore, when wind turbines come out of service, blades are typically landfilled or incinerated (Bloomberg 2020).

1.2 Decommissioning and Repowering

In the United States, the terms decommissioning and repowering are distinguishable in wind energy. When a wind turbine is deemed for repowering, it is understood that everything but the tower is replaced to improve the wind turbine efficiency with new technology (Bank et al. 2021). This happens when new and improved technology in wind energy is available, and the benefits outweigh keeping the old turbine in place. Additionally, tax benefits could potentially expedite the decision to repower much earlier than the original projected decommissioning date of the system, sometimes even when the system has not been used for half of its expected life span. On the other hand, decommissioning efforts focus on removing the entire wind turbine from the foundation up. The methods used for removing the elements vary from taking them down with care for potential resale opportunities, to taking the wind turbine down from the base then cutting it in place and shipping to landfill, incineration, or recycling facilities. However, most of the blades are abandoned in placed, especially the ones from the first generation of wind farms, or decommissioning contractors are stockpiling them for prospective future use in cost-effective recycling processes (Bank et al. 2021). Currently, when it comes to wind energy, the major concern is the next step with what to do with the stockpiling of blades.

1.3. Blade Waste

Very recently, blades are starting to be designed with recycled capabilities (Siemens Gamesa 2021), and these have been developed for offshore applications. This could be a potential solution when these blades reach their end-of-life. However, current blade waste is being accumulated on site which are the blades coming out of service from the first wind farms installed in the late 1990s and early 2000s. At least 20,000,000 tons (44,000,000,000 pounds) is expected to be the accumulated decommissioned blade waste in the world by 2050 (Liu and Barlow 2017) with the United States contributing 2,200,000 tons of this blade waste by 2050 as well (Cooperman 2021).

1.4. Current End-of-Life Processes

Current end-of-life procedures involve sending the cut sections of wind blade for landfilling (Bloomberg 2020), incineration for energy recovery (EPRI 2018), and recycling practices. The recycling practices have been implemented as end-of-life mechanisms to recover part of the raw materials in the composite wind blade through mechanical, chemical, or thermal recycling. These recycling practices begin by mechanically crushing, grinding, and shredding the blades (EPRI 2018); consequently, they involve processes like pyrolysis to recover fiber, char, and gasses for energy (EPRI 2020), solvolysis to recover high-quality glass and carbon fibers, cement kiln co-processing to recover cement raw materials, and mechanical processing to convert into pellets, needles, fine filler, and fiber retention (Bennet et al. 2021). However, these processes typically reduce the value of the material and miss the potential economic advantage of repurposing the blade as a whole or with minimal modifications.

Additional end-of-life applications include repurposing by resizing and reshaping the element which will result in high value end products (Jensen and Skelton 2018). However, it is still difficult to provide a standardized procedure to the new end product in contrast with the conventional product that it is trying to replace. In other words, for the repurposed second life product to compete with conventional ones, clear standards and documentation are required for universal application. Previous research has investigated wind turbine blade geometry and internal structure and developed a workflow to identify and optimize airfoil curves from a point-cloud model of a blade (Tasistro-Hart et al. 2019). Based on the blade's cross section and the multiple potential segment cuts possible, previous literature presents repurposing solutions to use decommissioned wind turbine blades as foundations, doors, window covers and even roof frames (Bank et al. 2018). For larger element sizes, conceptual research has focused on repurposing blades as horizontal support beams for bridges (Andre et al. 2020). Additionally, a deeper structural analysis has been performed for blades used as vertical cantilever structures used for energy transmission (Alshannaq et al. 2021). Therefore, this paper aims to provide clear documentation on how blades repurposed as energy transmission poles can increase resiliency both in the waste stream and in the energy transmission sector, especially in coastal cities.

2.0 NEED: The Future Electrical Grid Must Be Built

2.1 Power Transmission Networks in 2050

According to the American Society of Civil Engineers (ASCE) *Infrastructure Report Card 2021* the United States received a 'C-' on its last evaluation. The US power transmission and distribution system, T&D, has been neglected for decades, has not kept up with demand, and has become exponentially more vulnerable to weather related outages due to the extreme weather events caused by climate change. In 2011 The Electrical Power Research Institute, EPRI, estimated that the grid was in need of approximately $400 billion with of upgrades in order to return more than $1.2 trillion worth of societal benefits.

The future grid must be designed for a planet that is undergoing extreme shifts due to climate change. *High Intensity Low Frequency* (HILF) events will dictate structural requirements in many regions, especially on the coast. The design service loads of all the primary and secondary load carrying structures will need to be significantly increased to resist the increased loads that are projected from these HILF's. According to Professor Massoud Amin at the University of Minnesota the total number of grid outages more than doubled in a decade from 107 outages between 1991-1995 to 232 outages between 2001-2005 (Amin 2008). The majority of these outages were caused by weather events.

Additionally, the demand on the grid continues to increase year over year due to causes such as increased remote work scenarios, population growth, and increased distributed power generation through renewable technologies such as wind power and solar (Graham et al. 2017). All of these issues are well known yet still have not been properly addressed. The looming explosion of demand on the grid that is coming with the electric vehicle revolution will exacerbate the problem even further (Bowermaster 2018).

3.0 SOLUTION: Wind Blade Reuse as Future Electrical Infrastructure

Figure 2: BladePole as a series of straight run *Tangent Poles* in a double circuit 230 KV transmission line

3.1 BladePole Concept and Affordances: Cheaper, Faster, Better

One of the most promising second life blade applications is the *BladePole* Concept (Patent Filing: WO2021/026198A1) which takes EoL blades and uses them as the vertical structure in electrical transmission grids replacing costly and high embodied energy structures. After being decommissioned by the wind farm owner the blades become a significant reclaimed material resource for infrastructural construction projects, we think of it as *The New Forest*. For the purposes of this applied research project the team is focused on reuse of the blades as the vertical tangent poles for 230 KiloVolt (KV) transmission lines and we use the loading requirements and costs for these systems as the basis for analysis and comparison.

3.2 The Three E's of BladePole: Ecology, Economics, and Engineering

The BladePole affordances can be classified by their ecological, economic, and engineering potential. From an ecological perspective the reuse of wind turbine blades as high-performance utility poles provides a significant avoided carbon cost by eliminating the use of virgin materials such as steel lattice towers, heavy gauge steel monopoles and rotomolded ferro-cement poles as the tower component of the structure. Future research may even allow for direct burial foundations, in which case all virgin materials would be avoided in the structure as there would be no need for a concrete foundation. If all decommissioned blades were repurposed as BladePoles, or other second life applications, the United States would reduce its total landfill usage by more than one percent by volume (Cooperman 2021) which is an enormous amount of waste that would be kept out of Earth's fragile crust.

As promising as the ecological affordances are, material conservation and landfill constraints alone are not enough to motivate blade reuse at scale. There must also be an economic motivator to truly solve this problem (Cooperman 2021). The highest and best reuse value of wind blades resides in reusing the whole blade as a large, high-cost structure rather than reprocessing it for smaller sections or even worse, shredding or burning the blade for silica recapture and small amounts of fuel (Bank et al. 2021). According to the transmission and distribution non-profit MISO (Midcontinent Independent System Operator) the average cost of a 230KV steel monopole for double circuit tangent poles was approximately $40,000 per pole in 2019. The average number of poles per mile of transmission line is five. Therefore, simply based on an apples-to-apples comparison of a 200-mile transmission line the BladePole approach would save utility companies and their customers, $40,000,000 on a single project alone (MISO MTEP19). Those savings could be reinvested in additional renewable energy assets to reduce the carbon offset of BladePole even further. Therefore, BladePole creates a strong sustainable business model for decades of reuse projects as the grid is rebuilt and expanded.

Lastly, due to the fact that the blades were originally designed for incredibly high dynamic loading in flexure, similar to an airplane wing, these FRP structures have many times greater load carrying capacity than is required by the design service loads of a typical 230KV tangent pole. As compared to a single circuit transmission line with steel monopoles at a 1,000-foot spacing the BladePole has a safety factor 6.2 times greater than the design service load that is required (Alshannaq et al. 2021a). This, along with the fact that the blades are non-corrosive and non-conductive, makes them incredibly durable and resilient when deployed in high population coastal areas that have historically experienced HILF weather events and that are also subject to accelerated corrosion due to airborne sea salts. This level of improved performance would normally increase capital costs but in this case, it is a cost savings.

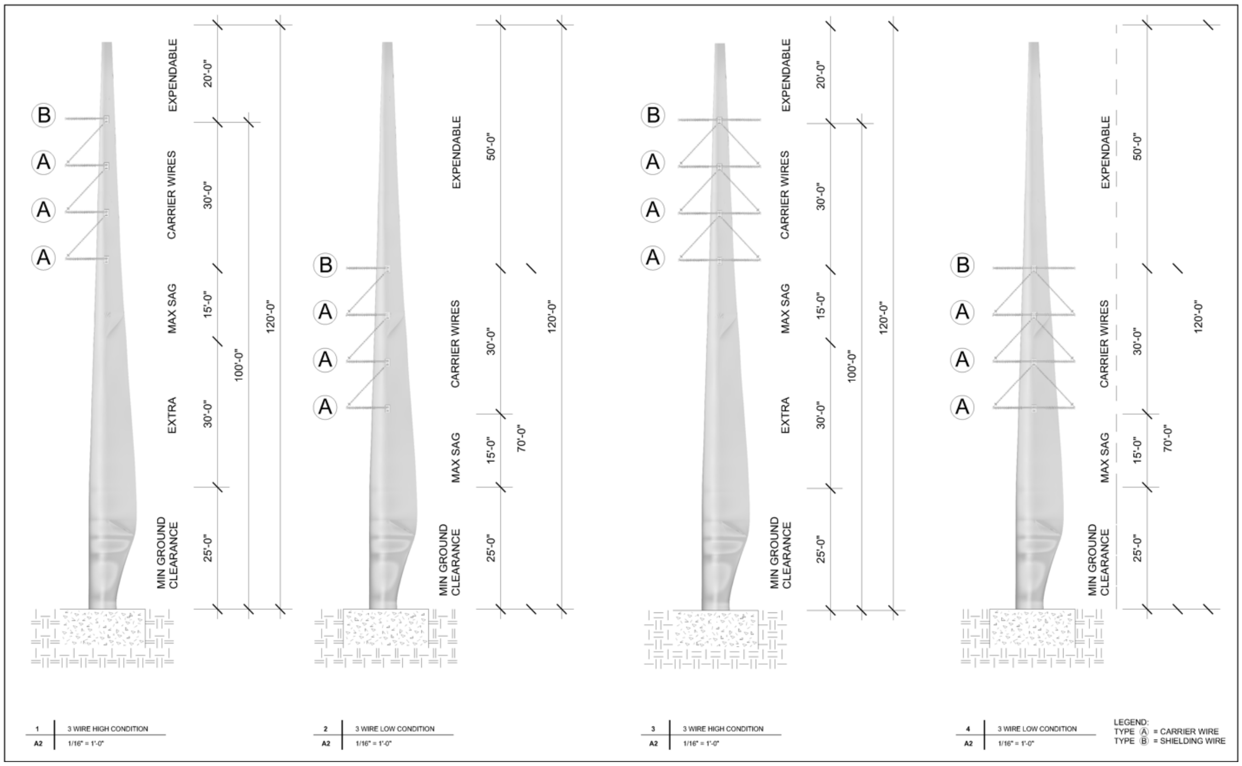

Figure 3: BladePole showing various configurations of hardware height (min and max) and wire groupings

3.3 Blade Machine: Computational Forensics

For architects and engineers to design for second life applications we must have a method of representing the blades accurately for use in design drawings, engineering analysis, fabrication processes and logistical planning. The Re-Wind team has developed a four-part computational forensics technology for capturing blade geometry as a 'Digital Twin' with various levels of fidelity and attribute richness (Tasistro-Hart et al. 2019, Kiernicki et al. 2021). This technology is referred to as the 'Blade Machine' and it produces a data rich digital model for each blade type. First the existing blade is laser scanned which yields a point cloud model. This point cloud model is than 'reprocessed' through a best fit algorithm by comparing the results of the scan to a public airfoil database (Figure 4). After the search algorithm has identified the best fit airfoils, the system automatically constructs a new surface geometry model using a visual programming environment (Figure 5). From there, the 'thin' surface geometry can be 'thickened' to represent the internal composition and materiality of the blade. The Blade Machine is an enabling technology for the BladePole application.

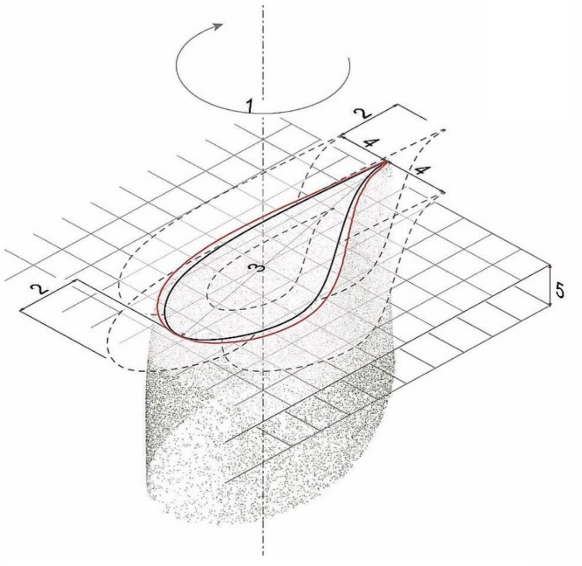

Figure 4: Blade Machine analyzing point cloud scan looking for best fit airfoils from database. Author: Tasistro-Hart 2019

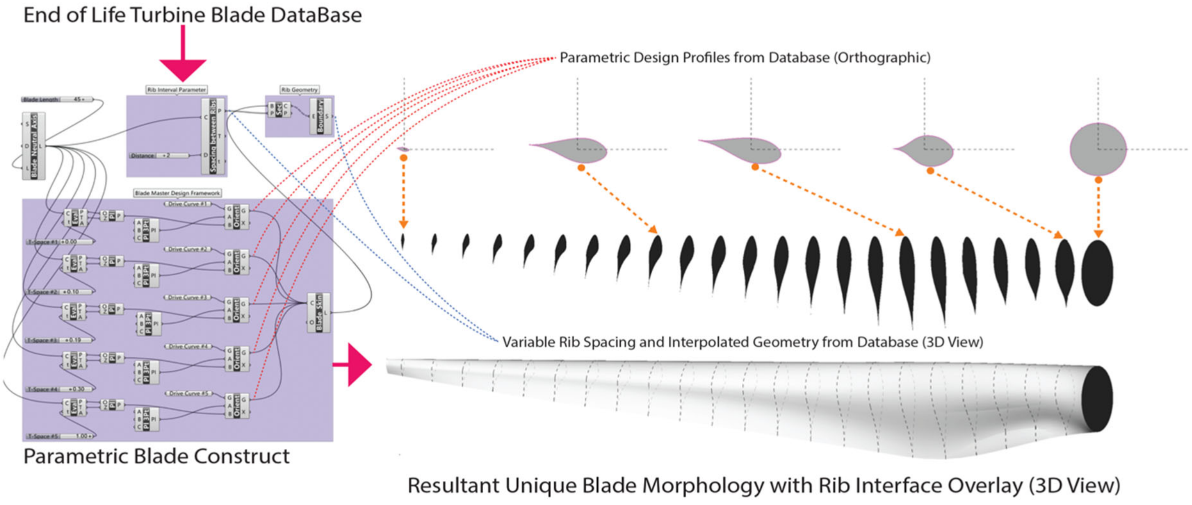

Figure 5: Blade Machine constructing a new model of the blade's *Digital Twin* as a NURBS surface

3.4 Universal Connector and Parametric Adaptation

One of the most challenging aspects of any FRP blade reuse project is developing methods to connect other non-blade components to the blade structure. The BladePole team has developed the *Universal Connector* (UC) and a method of installation which allows for the attachment and structural transfer of forces into the spar cap of the blade through a custom steel fixture (Figure 6). The spar cap is the main load carrying component of a wind blade and is composed of solid FRP (Alshannaq et al. 2021b). Having this UC allows for the usage of standard transmission line hardware such as braced line posts or davits for wire carrying functions. The UC is composed of five steel pieces of various gauges that have been waterjet cut and welded together. More specifically, the UC pieces consist of a Base Plate, Web, Hanger, and two Stiffeners. Each UC is attached to the BladePole by 6 blind bolts that connect the UC Base Plate directly to the face of the spar cap, see Section 4. The blind bolt attachment method is paramount since access to the interior of the blade is impractical. Aligned along the centerline of the spar cap, the UC ensures maximum rigidity as it carries the loads of the braced line hardware and transmission lines. By utilizing parametric adaptations, the UC can accurately mate to the curvature of any processed Blade Machine geometry. Subsequently, the curvature of the UC Base Plate is automatically adjusted by the Blade Machine to the geometry of the blade and the stiffeners will adapt by remaining perpendicular to the centerline of the spar cap. Parametric adaptation also allows the location and diameter of receiving holes in the UC Web to be adjusted to match various hole patterns for different hardware types. Collectively these functions can automatically create machining files from the parametric model for fabrication tasks.

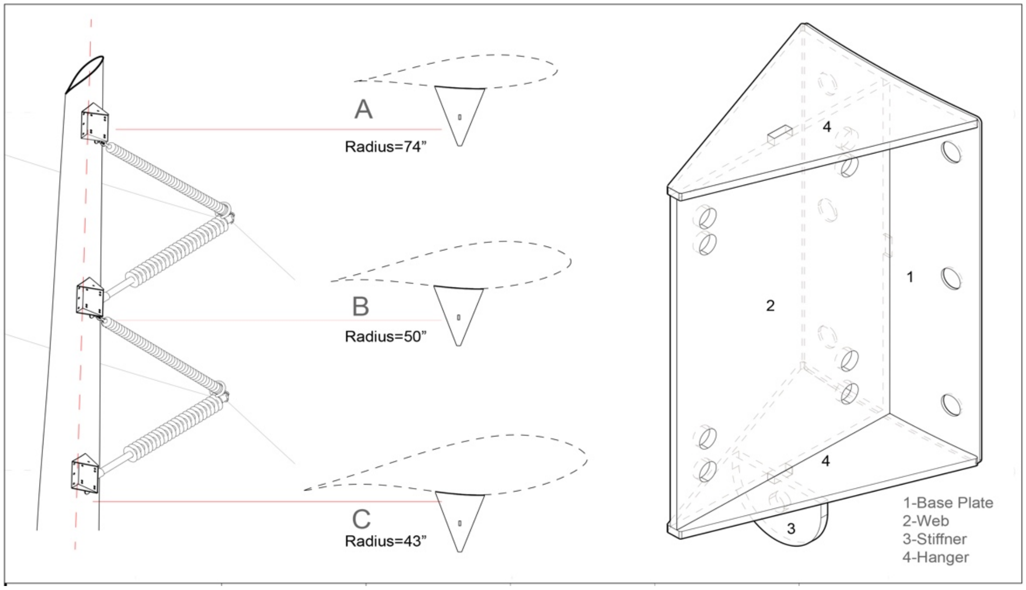

Figure 6: The Universal Connector (UC) is a steel fixture that allows attachment points to the FRP spar cap for various structural functions and automatically adjusts to the blade's local curvature in the Blade Machine model

3.5 Construction Logistics

The onsite construction sequence of the BladePole consists of eight primary steps (Figure 7). Step number one requires excavation of the site with a backhoe. These will be where the concrete mat foundations will be poured. Once the foundations have cured the blades are delivered by flatbed trucks and laid out onsite by a small crane. Next any damage to the blade is assessed, manually repaired and then the blade is painted. The UC hardware is also installed during this step. The blade is then erected by a crane and lifted onto the concrete foundation. Next the braced line post hardware is installed on each blade with the use of an articulating lift. Finally, the transmission wires are installed across each blade, in some cases as a single circuit on one side only and in other cases as a double circuit with transmission lines running on both sides of the blade as seen in Figure 7.

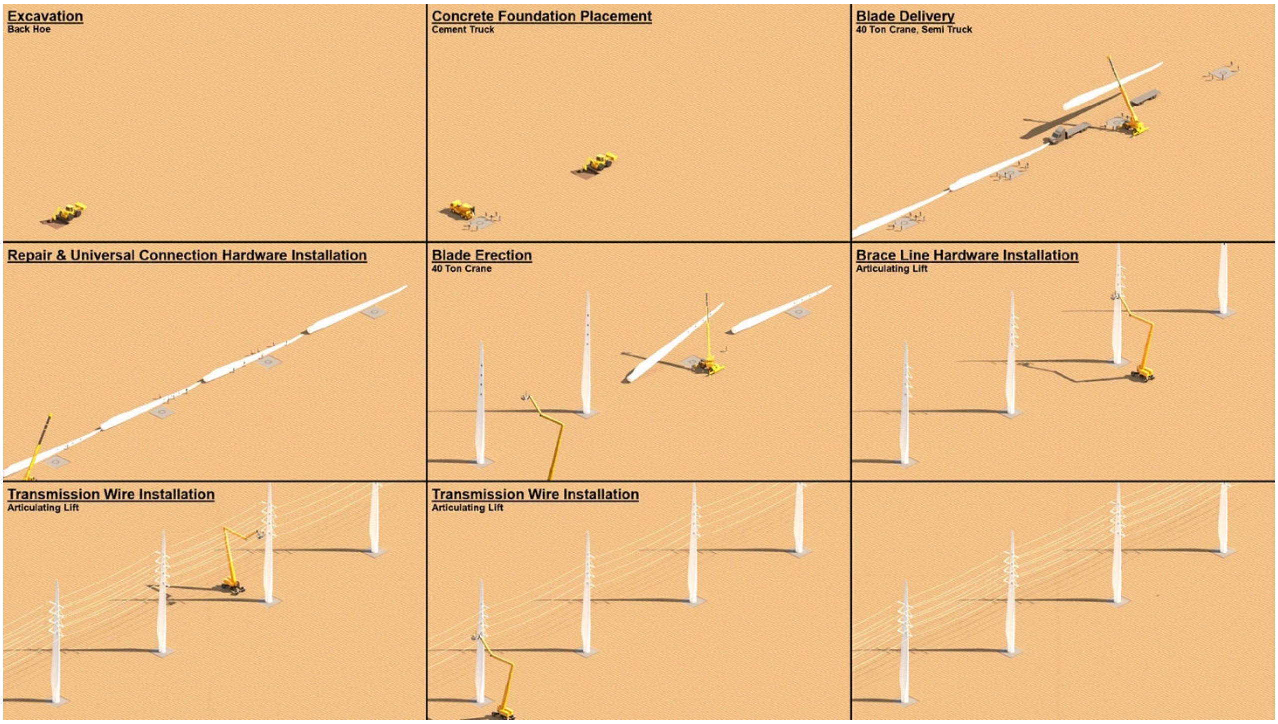

Figure 7: BladePole construction sequence in the field: 1) Excavation of site, 2) Concrete foundations are placed, 3) Blades are delivered, 4) Blade repairs are made and UC's are installed, 5) Blade erection with small crane, 6) Braced Line Post Hardware is installed, 7) Transmission wires are installed on first side, 8) Transmission wires are installed opposite side

4.0 VALIDATION: Experimental Proof of Concept

4.1. Making, Mocking, and Breaking in the Digital Fabrication Laboratory

Figure 8: Decommissioned blades delivered to the lab

Figure 9: Large sections are cut into smaller test specimen

To test the feasibility of the BladePole the team has constructed a full-scale demonstration in the Digital Fabrication Laboratory at the Georgia Tech School of Architecture (Figures 8-15). After design and engineering work was completed, a decommissioned blade was delivered by flatbed truck and cut into sections. As the blade was being sectioned, the Universal Connector (UC) was fabricated from the parametric model using a CNC waterjet. The UC is constructed from 5 pieces of mild steel (11ga and 3/8") that are welded together to form the final UC component. The side that bolts to the BladePole itself is bump formed along precut guides to fit the radius to ensure proper load transfer from the UC to the spar cap. Approximately 12 of the UC's were fabricated, some for the final mockup and others for engineering testing. On the 20 foot tall section of blade used for the mockup, centerlines were drawn down the spar cap and holes were laid out with a template. These holes are where the UC connectors will finally be mounted with blind bolt hardware.

In orded to account for the taper of the blade and put the centerline of the leading edge on the horizontal, the blade was rested on wooden shims. The line was marked with masking tape and cut flat. The blind bolt holes are cut using a diamond tipped hole saw and a handheld drill. Once the layout and hole drilling work was complete the UC hardware and braced line post hardware was installed and the blade was erected vertically using a forklift and boom.

Figure 10: Steel is formed to fit blade curvature

Figure 11: Steel plates are CNC waterjet cut and MIG welded to create the final UC

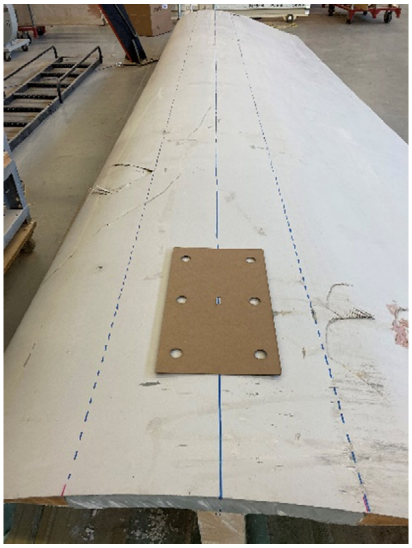

Figure 12: Hole layout and prep for drilling

Figure 13: Drilling of hardware holes with diamond saw

Figure 14: UC and Braced Line Post hardware is completely installed and blade is erected in the lab awaiting a full-scale structural test

Figure 15: UC and Braced Line Post hardware is completely installed and blade is erected in the lab awaiting a full-scale structural test

CONCLUSION

By identifying high value practical infrastructure needs and mapping the affordances of the existing stock of FRP wind blades we will be able to develop sustainable, ie resilient, design and development models to support second life circular economies for the reuse of wind blades. Future work for this project will include full-scale structural load tests of the BladePole and a full-scale demonstration project in 2022.

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