Case studies of repurposing FRP wind blades for second-life new infrastructure

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ABSTRACT: This paper presents two case studies of the repurposing projects of decommissioned wind turbine blades in architectural and structural engineering applications conducted under a multinational research project is entitled "Re-Wind" (www.re-wind.info) that was funded by the US-Ireland Tripartite program. The group has worked closely together in the Re-Wind Network over the past five years to conduct research on the topic of repurposing of decommissioned FRP wind turbine blades. Repurposing is defined by the Re-Wind team as the reverse engineering, redesigning and remanufacturing of a wind blade that has reached the end of its life on a turbine and taken out of service and then reused as a load-bearing structural element in a new structure (e.g., bridge, transmission pole, sound barrier, sea-wall, shelter). Further repurposing examples are provided in a publicly available Re-Wind Design Catalog. The Re-Wind Network was the first group to develop practical methods and design procedures to make these new "second-life" structures. The Network has developed design and construction details for two full-size prototype demonstration structures – a pedestrian bridge constructed in Cork, Ireland in January 2022 and a transmission pole to be constructed at the Smoky Hills Wind Farm in Lincoln and Ellsworth Counties, in Kansas, USA in the late 2022. The paper provides details on the planning, design, analysis, testing and construction of these two demonstration projects.

1 INTRODUCTION

With the increase in wind energy over the last few decades, many countries around the world are beginning to divest from traditional nonrenewable energy sources. However, a new issue has arisen in the form of wind turbine blade waste. Turbine blades are made primarily of glass fiber reinforced polymer (GFRP) composite materials which cannot be recycled, and they and are only designed for a service life of 20-25 years. Once the blades have reached their end of life (EOL), they are required to be decommissioned regardless of their condition. The issues associated with decommissioning a wind farm and how to dispose of the blades are complex (Bank et al, 2021). The technologies being considered for blade EOL are reuse, repurposing, recycling, reclamation, co-processing, incineration or landfilling (Gentry et al, 2020). Each of these needs to be evaluated with respect to economic feasibility, environmental impact and social acceptance (Deeney et al, 2021). The scale of EOL blade waste makes it an especially concerning issue, as there will be an estimated cumulative total of 43 million tonnes of blade waste worldwide by 2050 if no blades are disposed of in the interim and are stockpiled, with Europe and the United States processing a combined 41% of this waste (Liu and Barlow 2017).

1.1 *Re-Wind Network*

To address the global issue of wind turbine blade waste, the Re-Wind Network (www.re-wind.info) was founded in 2017 as a partnership between the US, UK, and Republic of Ireland. The main goal of this research team is to investigate the use of decommissioned wind turbine blades in second-life structural applications. The team began the project in 2017 by identifying blades for use in a turbine blade pedestrian bridge demonstration project. In 2018, the team studied the potential to develop a pedestrian bridge using a Vestas V27 blade, determined its mechanical and structural properties, and published the design and analysis results in the first Bladebridge paper in 2019 (Suhail et al. 2019). Work on the BladeBridge continued through a partnership between Georgia Tech (GT), University College Cork (UCC), and Munster Technological University (MTU), and the team constructed its first ever BladeBridge in Cork, Ireland in January 2022 (Nehls, 2022). In addition to the BladeBridge work, the GT team has been investigating the application of decommissioned blades as power transmission poles. Several papers regarding the BladePole have been published (Alshannaq et al. 2021a, Alshannaq et al. 2021b), and a demonstration project is planned for construction in Kansas, USA in late 2022. The Re-Wind Network has proposed a number of additional repurposing solutions which can be found in the Re-Wind 2021 Design Catalogue (McDonald et al. 2021).

1.2 *Windblade Geometry*

Using wind blades in structures creates a number of unique challenges, first of which being the characterization of the blade geometry. A portion of the cross-section of the LM 13.4 wind blade used in the Cork BladeBridge along with the naming convention used for the different airfoil components is shown in Figure 1. The airfoil can be divided into two halves known as the low pressure (LP) side which is convex, and the high pressure (HP) side which is convex-concave. Each side contains a leading edge (LE) component, a spar cap (SC) component, and a trailing edge (TE) component. The airfoil is stiffened by two channel-shaped webs, which are parallel and extend along a majority of the length of the blade. Some non-FRP material is present in the blades, including a thin outer coating on the blade (known as the gel coat), a foam material in the trailing edge, and an adhesive between the different components. For the purposes of testing and analysis, only the blade's FRP material is considered.

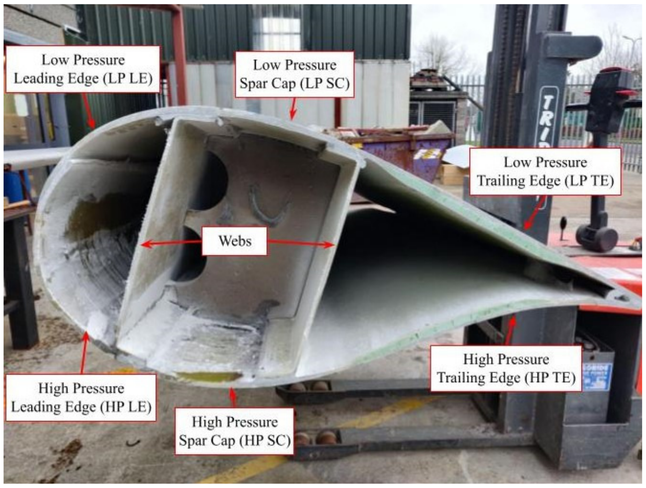

Figure 1. Cross section of LM 13.4 blade at maximum chord.

Not only do airfoils have a complex geometry, but due to fabrication tolerances, the overall wind blade geometry can vary somewhat from blade to blade. Because of this, developing a method for representing a given blade accurately is essential for use in design drawings, engineering analysis, fabrication processes and logistical planning. To address this challenge, the Re-Wind team has created a four-phase computational forensics technology known as the "BladeMachine", which captures the full blade geometry as a 'Digital Twin' with various levels of fidelity and attribute richness (Tasistro-Hart et al. 2019, Kiernicki et al. 2022). Phase 1 of the BladeMachine consists of creating a point cloud model from a LiDAR scan of a wind blade. Then, in Phase 2, the point cloud model is matched to a public airfoil database using a best-fit algorithm. Once the proper airfoils are identified, the software automatically lofts the airfoils into a new 3D "thin" model in Phase 3. Finally, in Phase 4, thickness and material data is input to create a "thick" model which includes the blade's internal structure. The results from both Phase 3 and Phase 4 enable the team to create architectural renderings as well as structural models of any blade repurposing solution.

2 CASE STUDY 1: BLADEBRIDGE

The first case study investigated in this paper is the BladeBridge – a pedestrian bridge constructed in Cork, Ireland which was installed on the Midleton-Youghal Greenway in January 2022. The bridge is approximately 5m long and 3.5m wide and has a skew of 14°. The bridge rests on cast in-place concrete abutments, and the connections, transverse beams, and deck are all galvanized steel.

2.1 *Sourcing, Funding, Planning*

In 2020, the BladeBridge teams at GT and UCC developed a partnership with the structures laboratory at Munster Technological University (MTU). MTU and the local Cork County Council were able to identify a potential BladeBridge site on the Midleton-Youghal Greenway, which was under development by Cork County Council. The greenway was granted Part 8 planning permission in 2019 and is funded under the Irish Government Department of Transport's "Project Ireland 2040" initiative (Cork County Council 2022).

Once the BladeBridge site was confirmed, the team needed to source suitable decommissioned blades, both for testing and for use on the project. Everun Ltd., a Northern-Ireland based company specializing in wind energy asset management, donated eight blades to the team. The blades were manufactured by LM Windpower and were from from Nordex N29 turbines, with each blade measuring at 13.4m. Testing of the blades was conducted at the MTU structures laboratory in collaboration with the GT and UCC teams. The construction of the bridge was completed by local contractors and fabricators, with supervision from MTU and the Cork County Council.

2.2 *Characterization of a Turbine Blade for use as a BladeBridge*

Using wind turbine blades in second-life structural applications raises several structural issues. First, the loads that the blades will experience in these applications differ greatly from those experienced while the blades were in service on a turbine. In addition, the fact that the blades are constructed in multiple pieces and bonded together introduces the possibility of adhesive failure, which is typically not a consideration in traditional civil engineering materials. Lastly, the fact that the blades are EOL products also adds to the challenge of characterizing their structural capabilities, as each individual blade may have developed unique defects over the course of its service life. These challenges make it especially pertinent to develop a methodology for properly characterizing each unique blade.

2.2.1 *Materials Testing*

Resin burnout tests were conducted in accordance with ASTM D2584 in order to determine the laminate properties of the wind blade's FRP material. Tensile and compressive tests, conducted in accordance with ASTM D3039 and ASTM D3410, were also performed on both the spar cap and web material. Further details and results of the material testing can be found in Ruane et al. (2022).

2.2.2 *Structural Testing*

The orientation of the wind blades for use in the BladeBridge (horizontal with the trailing edge oriented above the leading edge) dictates that the blades will primarily experience edgewise bending. The load-deflection behavior of the blade in edgewise bending was determined through a full-scale 4-point bending test of a 4m portion of the blade at the MTU structures laboratory. The blade sustained a maximum total load of 87.2kN with a deflection at the loading points of 18.5mm. It is important to point out that the portion of the blade tested was closer to the tip of the blade and was therefore weaker than the section to be used in the BladeBridge. The testing of the tip section was done due to the limitation of the clearance in the test rig, which did not permit the research team to fit the actual section used in the BladeBridge. Further details regarding the structural testing can be found in Ruane et al. (2022).

2.3 *BladeBridge Design*

The design of the BladeBridge occurred in two phases – initial renderings were created for use in communicating with various stakeholders and to determine aesthetic details, and a final structural design was then completed by the MTU team for use in construction.

2.3.1 *Architectural Renderings*

Using the BladeMachine 3D blade models, the GT team created the initial renderings of the BladeBridge using Rhinoceros 3D and Enscape. Various design iterations were explored, with initial designs having the blades cut to match the span length of the bridge and a guardrail wrapping around the outside face of the blades, as seen in Figure 2a. It was decided by the Cork County Council to maintain the full length of the blades in order for the public to recognize the decommissioned blades more easily. The council also opted for a guardrail that attaches to the top of the blades, which not only conserves material but also allows for unobstructed views of the blades from all angles (Fig 2b).

Figure 2 (a). Cork BladeBridge rendering with cut blades and exterior guardrail. (b). Cork BladeBridge rending with full-length blades and guardrail above blades.

2.3.2 *Structural Design*

The structural design of the BladeBridge involved detail designs of connections between the transverse beams and the blades, as well as the concrete abutments holding the blades at both ends. The wind blades have a majority of their strength in the spar cap, so it was imperative that the connections bolted directly into the spar cap rather than into the leading edge or trailing edge. Bolting into the blade proved to be a challenge due to the fact that it is a closed, curved surface, but the team was able to determine a solution in the form of proprietary blind fasteners. Concrete abutments were custom designed in order to cradle the root and airfoil ends of the blades, with the remainder of the blade tips being embedded into the greenway site. Further details regarding the BladeBridge's structural design can be found in Zhang et al. (2022).

2.4 *Fabrication & Installation*

The bridge was constructed by local fabricators and contractors in Cork, Ireland in late 2021 and was installed on the Midleton-Youghal Greenway site in January 2022 (Fig 3).

Figure 3. Bladebridge during installation on the Midleton-Youghall Greenway.

3 CASE STUDY 2: BLADEPOLE

The second case study investigated is the BladePole – a power transmission pole constructed from an upright wind blade. Further details regarding the BladePole design and mockup fabrication can be found in Al-Haddad et al. (2022).

3.1 *Sourcing, Funding, Planning*

The repurposing of a wind blade as a power transmission pole, called BladePole, was investigated by the Georgia Tech team starting in 2019. The BladePole initiative was initially funded by the National Science Foundation (NSF), and in 2021, the Georgia Tech Re-Wind team received a second NSF grant from the Partnership for Innovation (PFI) program which focuses on commercialization of Re-Wind technology, including the BladePole.
Decommissioned GE37 wind blades parts supplied to the research team by Logistcus Group, which were used for materials testing and fabricating a BladePole prototype. The prototyping and testing were funded by ENEL Green Power and the hardware was provided by Hubbell Power Systems, Inc. The GE37 wind blades were decommissioned from a wind farm in Langford, Texas after 11 years in service. The final BladePole product is planned to be constructed near a wind farm in Kansas in late 2022.

3.2 *Characterization of a Turbine Blade for use as a BladePole*

Detailed analyses have been conducted by the Re-Wind Network to characterize the material and structural properties of a turbine blade for use in a power transmission pole application (Alshannaq et al. 2021a, Alshannaq et al. 2021b). It was found that BladePole in this application, has a safety factor of 6.2 relative to the required service loads of a typical 230 kV tangent pole. This can be attributed to the fact that the blades were originally designed to withstand much greater flexural loads, as the dynamic wind loads on a moving turbine far exceed the loads experienced as a stationary pole. In addition to the structural properties of the blade, the FRP material of the blade is also non-corrosive and non-conductive, making it a durable material choice for use as a tangent pole.

3.3 *BladePole Design*

The BladePole team is focused on the repurposing of blades as vertical tangent poles for 230 kiloVolt (kV) transmission lines, which is the basis for structural analysis and comparisons. A rendering of a BladePole in a double circuit 230 kV transmission line is shown in Figure 4.

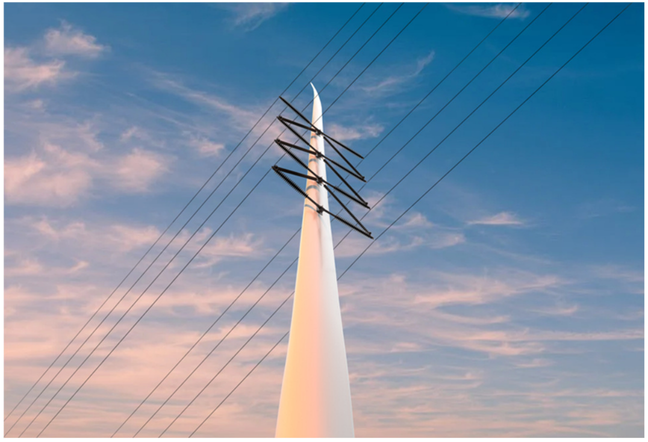

Figure 4. BladePole rendering as a 230 kV tangent pole.

3.3.1 *Pole Design*

Using a 3D model of a GE37 wind blade generated by the BladeMachine, the BladePole team created several design options for the BladePole using Rhinoceros 3D. Figure 5 shows various options for placing the hardware and wire groupings, with the heights dictated by standard power transmission pole design codes. It was decided to attach the root of the blade in a concrete foundation for added stability against wind loads.

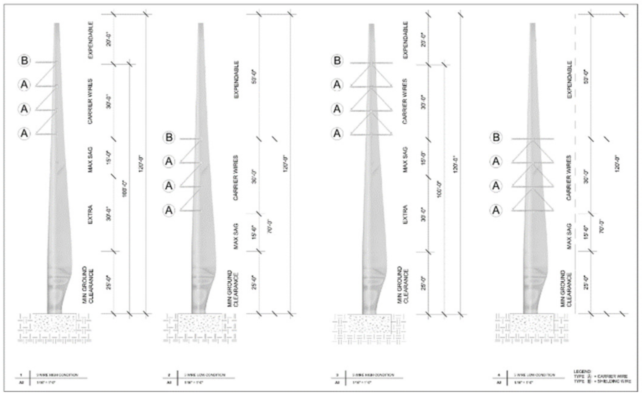

Figure 5. Various configurations of BladePole hardware height (min and max) and wire groupings (1 ft=0.3m).

3.3.2 *Universal Connector*

A significant challenge that arose when designing the BladePole was the issue of connecting the power transmission hardware to the curved outer surface of the blade. The team designed a solution known as the Universal Connector (UC), which is a custom fabricated steel fixture that can transfer the forces from the external hardware into the spar cap of the blade. The UC is composed of five steel plates that are welded together – the base plate which bolts into the blade, the web which bolts into the hardware, two hangers which connect the base plate and web, and the stiffener which is welded on the outer portion of the hanger (Fig 6). The UC is connected to the spar cap of the wind blade using six blind bolt fasteners, which allows for a bolted connection without access to the interior of the blade.

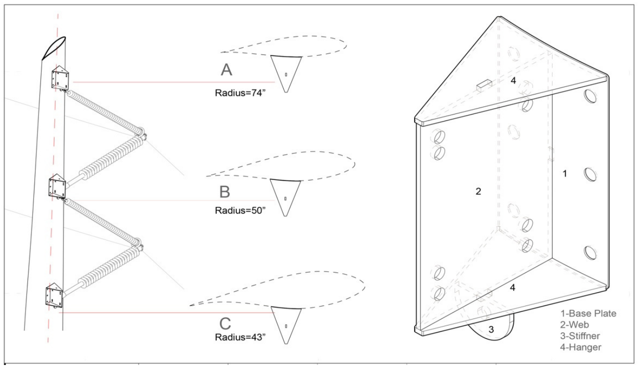

Figure 6. Model of the Universal Connector (UC) which connects the braced line hardware to the wind blade.

3.4 *Prototype Fabrication*

In 2021, a mockup of the BladePole was constructed on a 6m portion of a GE37 wind blade. A centerline was drawn down the spar cap of the blade using a laser level, and holes were drilled using a diamond-tipped hole saw. Four UC's were then attached along the centerline using blind bolt fasteners, and finally the braced line post hardware was installed. Figure 7 shows the mockup demonstration with all of the hardware fully installed. The BladePole team has conducted full-scale structural testing of the mockup and will report results elsewhere.

Figure 7. Completed BladePole prototype.

3.5 *Construction Sequencing*

In addition to completing the structural design of the BladePole, the team has also created a construction sequence for the installation of a series of BladePoles in the field. Figure 8 depicts an eight-step sequence beginning with site excavation and concluding with the transmission wire installation. Further details regarding the BladePole construction sequencing can be found in Henao et al. (2022).

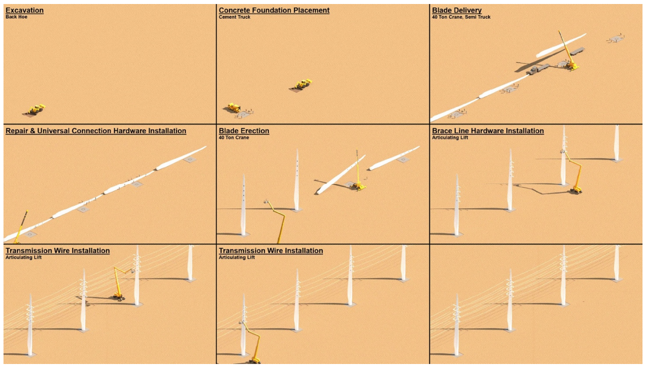

Figure 8. BladePole construction sequence.

4 CONCLUSION

Wind turbine blades have been proven to be strong and durable structural components, even in their second life after decommissioning. They serve as a promising and more sustainable alternative to traditional construction materials such as steel, timber, and concrete. Several challenges in the realms of structural characterization, travel logistics, and commercialization still need investigation before the widespread use of wind blades in structures can be achieved. However, the BladeBridge and BladePole case studies presented in this paper reveal that wind blade structures are becoming increasingly viable in real-life applications around the world.

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