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# BladeBridge: Design and construction of a pedestrian bridge using decommissioned wind turbine blades

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ABSTRACT: The purpose of this study was to develop a replicable methodology for testing the capabilities and characteristics of a wind turbine blade in a structural re-use application with the specific goal of creating and demonstrating an efficient and commercially viable wind blade pedestrian bridge design. Wind energy experienced a dramatic increase in popularity following the turn of the century and it is now a common source of renewable energy around the world. However, while wind turbines are able to produce clean energy while in service, turbine blades are designed for a fatigue life of only about 20 years. With the difficulty and costs associated with recycling the composite material blades used on the turbines, wind power companies choose to dispose of decommissioned blades in landfills instead. The Re-Wind BladeBridge project aims to promote a more sustainable life cycle for wind power by demonstrating that decommissioned wind turbine blades have the capability to be repurposed as structural elements in bridges. This paper presents an analysis and characterization of a LM 13.4 wind blade from a Nordex N29 turbine, along with a design for a pedestrian bridge using two LM 13.4 wind blades to create a 5-meter span bridge. Software developed by the Re-Wind team called "BladeMachine" was used to generate the engineering properties of the blade at multiple sections along the blade length. Resin burnout tests and mechanical testing in tension and compression were performed to determine the material and mechanical properties of the composite materials in the blade. Additionally, a four-point edge-wise bending test was performed on a 4-meter section of the wind blade to evaluate its load-carrying behavior. The results of these tests revealed that the LM 13.4 blades are suitable to be re-utilized as girders for a short-span pedestrian bridge. An overview of the design of the BladeBridge currently under construction in County Cork, Ireland is presented, including details on the architectural and structural design processes.

## 1 INTRODUCTION

Wind energy has become an essential source of power around the world over the last few decades, allowing many countries to divest from traditional nonrenewable energy sources. However, a new issue is beginning to arise in the form of wind turbine blade waste. Turbine blades are made of fiber reinforced polymer (FRP) composite materials and only designed for a service life of 20–25 years, after which they are then considered to be at their end of life (EOL) and are required to be decommissioned regardless of their condition. Waste management for the FRP is difficult, as they are not biodegradable and are very difficult to recycle. The scale of EOL blade waste makes it an

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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 & Barlow 2017). With typical blade lengths ranging from 40 to 60 meters, the volume and mass of blade waste will increase dramatically as wind energy producers decommission and repower wind farms in the coming few years.

The ReWind Network (www.re-wind.info) was founded in 2017 to address the growing issue of wind turbine blade waste. It consists of researchers and industry professionals in the US, UK, and Ireland and focuses on repurposing FRP wind turbine blades in structural applications. In the last few years, the differences between repurposing, reusing, recycling and disposal have been discussed in numerous publications. A clear definition of these differences in terms of environmental impact now exist, and they are not used interchangeably (Gentry et al 2021; NCC 2021; WindEurope 2021). The network has created a "Design Catalogue" which showcases renderings of various potential repurposing solutions (McDonald et al. 2021). Of these solutions, the network is in the process of designing and constructing full-scale demonstrations for two solutions: a wind blade power pole (BladePole) in Kansas, USA, (Alshannaq et al. 2021) and a wind blade pedestrian bridge (BladeBridge) in Cork, Ireland.

This paper discusses the experimental testing, computational modelling, and design work involved in creating the Cork BladeBridge currently being installed (November 2021). The bridge uses repurposed LM 13.4 blades originally from Nordex N29 turbines as its main girders and has a span of approximately 5 meters. Figure 1 shows a rendering created by the Georgia Tech (GT) team of the prototype bridge in situ. While the site parameters called for a short span pedestrian bridge, the GT team has also created design concepts for BladeBridges of longer spans, see Figure 2 from the ReWind Design Catalog (McDonald et al. 2021).

Figure 1. 3D rendering of the Cork BladeBridge on the Midleton-Youghal Greenway site.

Figure 2. Additional BladeBridge concepts from the ReWind Design Catalog.

## 2 SOURCING, FUNDING, AND PLANNING

The structures laboratory in Munster Technological University has expertise in bridge design and long-standing relationships with consulting engineering companies and clients such as local authorities (city and county councils). MTU identified an opportunity to build a blade bridge on a long-distance pedestrian and cycle route, 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 2020).

The Re-Wind team sourced decommissioned Nordex N29 turbine blades from Everun Ltd., a Northern-Ireland based company specializing in wind energy asset management. The blades are 13.4 m long, making them suitable for short span pedestrian or greenway bridges. Everun donated the blades to the project, and a flatbed truck was hired to transport the blades 430 km to Cork. Three blades, one for testing and two for the BladeBridge fabrication, were delivered to the MTU structures laboratory, while five more blades placed temporarily in storage.

Experimental testing and structural design for the BladeBridge began in Fall 2020 and was conducted in collaboration between GT, MTU, and UCC. The MTU team has collaborated with Cork County Council along with local fabricators and suppliers to construct the BladeBridge, which is set to be completed in late 2021.

## 3 EXPERIMENTAL TESTING: MATERIAL AND SECTION PROPERTIES

Using wind blades in structures generates a number of unique challenges. The loads that the blades will experience in these applications differ greatly from those experienced while the blades were in service on a turbine. The unique geometry of the blades calls for complex modelling techniques and testing setups. 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. In addition to all of these parameters, 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. Because of this, it was essential for the team to conduct extensive testing in order to ensure that the blades have the proper strength and stiffness values to be safely used as bridge girders.

A typical wind blade airfoil section along with the naming convention used for the different airfoil components is shown in Figure 3. The airfoil can be divided into a "top" and "bottom," known as the high pressure (HP) side and the low pressure (LP) side respectively. Each side contains a leading edge (LE) section, a spar cap (SC) section, and a trailing edge (TE) section. The airfoil is held together and stiffened by the webs, which are two parallel FRP pieces that extend along 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 shell), 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.

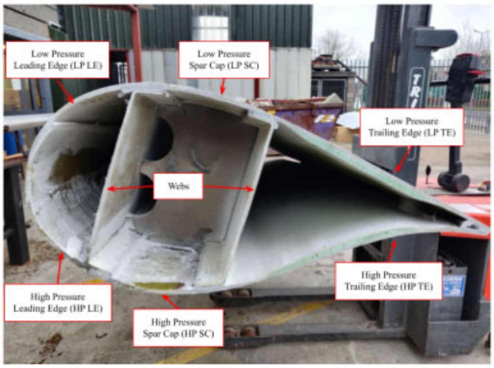


Figure 3. Cross section of LM 13.4 blade at maximum chord (2.51 m from root end), with naming convention labels.

A diagram of the full LM 13.4 blade can be seen in Figure 4a. As shown in the figure, the tip of the blade was removed before arriving in the lab, so the full specimen measures at 11.0 m. The naming convention for airfoil locations along the blade is shown in Figure 4b. It can be seen that station numbers correspond with the cross-section's distance from the root end of the blade – for example, station 2 (S2) is 2.0 m from the root end.

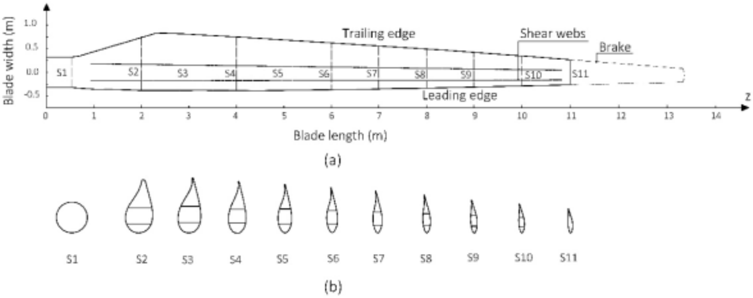


Figure 4. a) Elevation view of a LM 13.4-meter wind blade. b) Station sections along the blade.

The ReWind teams at MTU and QUB conducted extensive materials and mechanical testing to characterize the FRP material of the LM 13.4 blades. Resin burnout tests, conducted in accordance with ASTM D2584 (ASTM 2011), were performed on the spar cap and webs at multiple stations by both the MTU and QUB teams in order to determine how the material properties varied along the length of the blade. Samples were burned in a furnace to remove the matrix epoxy and isolate the glass fiber material, which allowed the team to calculate the fiber weight and volume fractions of each sample in accordance with ASTM D3171 (ASTM 2015), and to separate the fiber layers and study the material's fiber architecture. Tension and compression testing on coupons of the LM 13.4 blades, conducted in accordance with ASTM D3039 (ASTM 2017) and ASTM D3410 (ASTM 2016), were completed by the QUB team to determine the blade's mechanical properties. Further details on the procedures, results, and analyses of these tests can be found in (Ruane et al. 2022).

The centers of gravity, composite centroids, axial and flexural stiffnesses at multiple locations along the length of the wind blade were calculated using algorithms embedded in a proprietary "BladeMachine", a set of custom software scripts embedded in a NURBS modeling software used to generate a digital twin of the wind blade to facilitate design and engineering tasks (Kiernicki et al. 2022). The edgewise flexural stiffnesses, which equate to strong axis bending for the airfoil shaped cross-sections, are depicted in Figure 5 below.

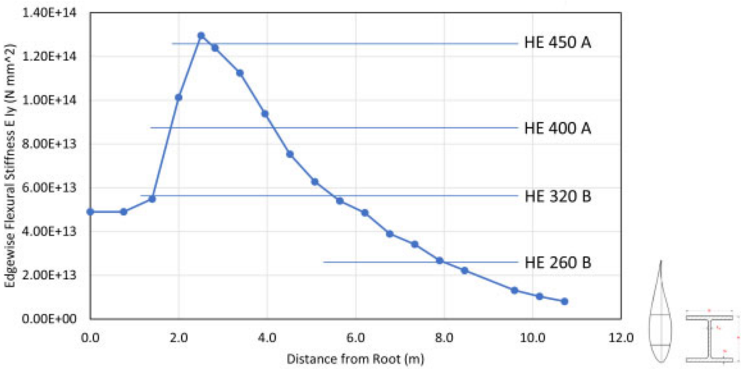


Figure 5. Edgewise bending stiffness of the LM13.4 wind turbine blade and four equivalent European steel wide flange shapes for comparison.

The figure depicts the flexural stiffness of the wind blade (EI) as a function of its length measured from the root end. Because of the variable geometry of the wind blade, it is stiffest at the first full airfoil section at 2.5 m from the root end. As the wind blade contains a number of different composite laminates with varying elastic moduli, it is not possible to separate the material stiffness (E) from the geometric stiffness (I). The figure also compares the flexural stiffness of the wind blade with those of four typical European wide flange steel sections, which proves that the LM 13.4 blades are suitable to be used in place of traditional wide flange steel beams in structural applications.

For the Cork County bridge, the first 5 m of the blade, measured from the root end, carries load from the deck. The remaining tip of the blade is embedded in the landscape and is not load bearing. In Figure 6 below, the flexural and shear stresses in the loaded section are depicted. The girder is subjected to a 50 kN midspan load – while the self-weight of the wind blade and the bridge deck is neglected. The 50 kN load was selected based on a notional load applied by the rear axle of an emergency vehicle. The purpose of this simplified analysis is to determine the rough order of magnitude of the stresses and gage the suitability of the wind blade for carrying the applied loads.

The neutral axis of section is not at the mid-height of the wind blade, and therefore the flexural tensile and compressive stresses do not have the same magnitude. According to the analysis, a maximum stress of around 10 MPa is anticipated in the trailing edge of the wind blade (in compression). By comparing this to a compressive strength of 415 MPa observed in compression testing of the wind blade materials (Ruane et al. 2022), a strength utilization ratio of around 0.025 is obtained. The composite materials are minimally stressed when carrying these flexural stresses and that neither buckling nor material failure are likely to occur due to flexural loading. A maximum shear stress of 1.5 MPa is predicted for the mid-span load. This stress could be reasonably expected to double to 3 MPa if the load moved from mid-span towards the support. The shear strength of the composite materials in the LM 13.4 blade has not been established at this time, but shear strengths of similar wind blade materials have been established to be around 32 MPa (Alshannaq et al. 2022; Sayer et al. 2013). This equates to a strength utilization ratio of around 0.095.

From this simplified analysis it can be concluded that the wind blade materials should be able to carry the imposed loads, with a high safety factor. Given the short span of the bridge, it is not surprising that the shear stress ratios are higher than the flexural stress ratios.

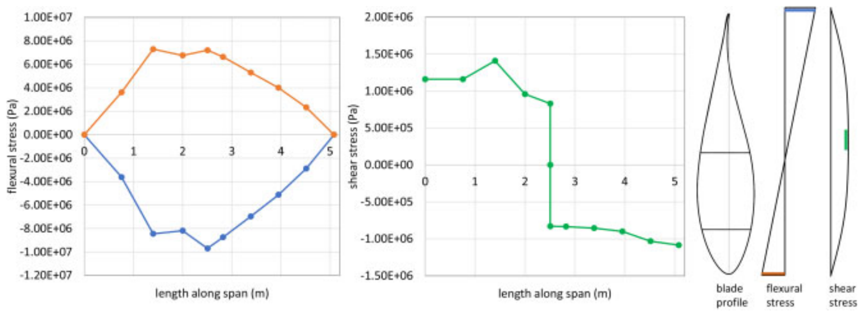


Figure 6. Flexural and shear stresses in the LM 13.4 blade due to a 50 kN concentrated load applied at midspan.

## 4 DESIGN PROCESS

Preliminary designs for the BladeBridge raised several architectural design questions in addition to the structural design requirements. An important consideration was the configuration of the blades – the team considered several different orientations and placements of the wind blades (below deck, cable-stayed, etc.) before deciding on the current edgewise girder orientation on the Cork bridge. Even after the overall orientation was selected, several more iterations were needed before finding a proper x-plane alignment, y-plane alignment, and pitch angle that would ensure that the bolted connections can connect to the spar cap along the length of the bridge. Using the team's BladeMachine software, a 3D model of the LM 13.4 blade was generated using LiDAR scans of the exterior of the blade along with manual measurements taken of the internal sections once the blade was cut. This blade model could then be used in Rhinoceros 3D to create the 3D BladeBridge models and renderings.

Connecting the transverse beams and deck to the blades was another challenge in the design process, as the wind blade is a closed section with a curved outer surface. A number of connection types were load-tested in the Structures Laboratory at MTU, including high tensile threaded rods and proprietary fasteners. The issue of bolting into the closed wind blade section was solved in the form of proprietary blind fasteners, which are designed to be installed from only one side of a drilled hole. The blind fasteners allowed the connection of a steel gusset plate, fabricated to suit the curvature of the turbine blade, directly to the turbine blade at the location of the spar cap. The bridge deck itself consists of steel I-section transverse beams, end panel bracing, and a steel deck plate with the I-beams connected to the gusset plates using typical bolted connection details. In terms of design loading, the BladeBridge is designed for LM4 loading (5kN/$m^2$) and for the accidental vehicle load case in accordance with (Eurocode 2009).

Additional aesthetic details were important for the team to consider as well, including the guardrail design, deck height, blade length, and construction materials. The design of the guardrail underwent several iterations, with different versions connecting to the transverse members, the outer portion of the blades, and the top of the blades. Additionally, the BladeBridge was modeled with the LM 13.4 blade cut at various lengths, and it was ultimately decided that the full LM 13.4 blades would be used. The extra blade length extending into the ground past the bridge is not structural – rather, the Cork County Council wanted to retain the full blades for aesthetic purposes and allow the public to recognize the wind blade shape more easily. In order to render these various BladeBridge models for internal and external circulation, the GT team used Rhinoceros 3D to generate 3D models of the bridge, and then finalized the images by adding surroundings and scale figures in Enscape.

The BladeBridge's abutment design was dictated and funded by Cork County Council. The existing abutments were 750mm wide masonry walls built for the original railway bridge deck, which were found to be in good condition and assessed as suitable for reuse. A reinforced concrete bearing shelf will be provided to the abutments, with a bespoke steel plate cradle cast into the bearing shelf at each corner to receive each blade. Once the blade is lowered on to the cradle system and held in place with threaded bar, the cradles will be cast in concrete to anchor the bridge deck to the abutments and to provide upstands at each corner of the bridge deck. All steelwork is galvanized, and the deck plate is finished with an epoxy resin waterproofing and anti-skid surfacing material. Figure 7 shows an image of the BladeBridge installed on site on the Midleton-Youghal Greenway.

Figure 7. Middleton Greenway BladeBridge installed on site, January 2022.

## 5 DISCUSSION

The ReWind team's investigation revealed that the LM 13.4 blades were in fact suitable to be used as bridge girders. Through extensive cutting and testing of the blades, the team found the FRP blades in general to be in excellent condition despite being EOL products. Resin burnout tests allowed the team to determine in great detail the fiber architecture of the wind blade FRP material including stacking sequence and fiber volume fraction of the spar cap and web flanges at different locations of the blade. Full scale load testing of the blade provided important information that contributed to the bridge design, as the blade specimen's behavior under load and its failure modes could be extrapolated to predict the behavior of the section used in the BladeBridge. Calculations from the BladeMachine provided further predictions of the section properties along the full length of the blade.

Testing results dictated a number of different aspects of the BladeBridge's design. Material studies revealed that the blade material is in fact thickest and strongest at the spar cap, confirming that the location of the bolted connections must always be at the blade's spar cap. Further design decisions were made in accordance with the team's design judgement, the greenway site restrictions, and input from Cork County Council.

## 6 CONCLUSION

BladeBridge has the potential to expand much further beyond just one short-span prototype. A promising avenue for growth is through Ireland's greenway network, which has experienced a surge in popularity in recent years. The country announced in 2020 that it will invest an unprecedented €63.6m of funding exclusively for greenway projects (Kelly 2020). The Department of Tourism, Transport, and Sport also published a Strategy for the Future Development of National and Regional Greenways in 2018, which details a plan to ensure that greenways in Ireland are built to increase tourism, improve local communities, and promote sustainability (Department of Transport, Tourism, and Sport 2018). The BladeBridge falls in line with all of these ideals, as its novelty will make it a centerpiece on any greenway, its construction calls for collaboration between local researchers, suppliers, and fabricators, and the nature of its design invites conversations about material reuse, end of life, and circular economy for renewable energy.

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