LARGE-SCALE TESTING OF A GFRP POWER TRANSMISSION POLE PROTOTYPE MADE FROM A DECOMMISSIONED GE37 WIND TURBINE BLADE

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ABSTRACT

Millions of tons of GFRP composites are expected to stockpile in the next 20-30 years from decommissioning wind turbine blades, which are made primarily of these materials. Responsible and attractive solutions are currently being studied by several research teams across Europe and the United States. The Re-Wind Network is one of these research teams that focuses on developing strategies and methodologies to transform the decommissioned wind blades into ready-to-use civil infrastructure (e.g., pedestrian bridge girders and power transmission poles). This paper reports on testing of a part of a full-sized power transmission pole prototype, made from a decommissioned GE37 wind turbine blade, and loaded in the gravity direction mimicking expected loads during its “new” lifetime. Full-scale connection testing is summarized and combined with the results of the test on the 5.5 m high full-size section of the prototype to obtain safety factors for various structural components under different expected load cases (these include gravity, wind, and ice loads). Structural Integrity of the various components of the power pole is studied to prove efficacy of the proposed second-life application of the decommissioned wind blade as a power transmission pole. Recommendations to improve the design for the planned future field full-blade prototyping are emphasized.

KEYWORDS

Decommissioned wind turbine blade; repurposing; power transmission pole prototype; connection testing.

INTRODUCTION

Composite materials are widely used for structural applications, especially as construction materials, due to their high strength-to-weight ratio, high stiffness-to-weight ratio, durability, and fatigue resistance (Bank, 2006). In the wind power industry, GFRP materials are the main constituents in manufacturing of wind turbine blades, which allows for lightweight large structures. However, due to uncertainty in their fatigue properties, the life spans of wind turbine blades are limited to 20-25 years of service (Brøndsted et al., 2005). This is expected to result in millions of tonnes of GFRP materials to be disposed of in the coming years (Cooperman et al., 2021). Even though there are various methods of disposing or recycling of GFRP materials, most of these methods are not feasible either from an economical point of view or from strength and stiffness points of view (Jensen & Skelton, 2018; Oliveux et al., 2015; Yazdanbakhsh & Bank, 2014). Thus, research is now focused on developing new strategies and methods to re-use and repurpose these structures in second-life infrastructural applications (e.g., pedestrian bridge girders, called “BladeBridge”, and power transmission poles, called “BladePole”) (Alshannaq et al., 2021; Anmet, 2021; CompositesWorld, 2022; Ruane et al., 2023; Ruane et al., 2022).

Wind turbine blades are long structures (i.e., reaching 100 m in length) connected as cantilever beams to a rotating hub that generates electricity. A wind blade is essentially made of GFRP materials in three main parts; a sandwich-structured aerodynamic (airfoil) shell, thick-solid GFRP bearing spar caps, and sandwich-structured stabilizing webs as shown in Figure 1, except at the root which is a circle (the root is where the wind blade attaches to the rotating hub). Other cross sections along the wind blade or other types of wind blades might have multiple webs. The nature of the spar caps as thick GFRP material (e.g., reaching 50 mm in thickness in GE37 wind turbine blade (Alshannaq et al., 2022)) make them a suitable candidate for attaching (i.e., bolting) other components to the body of the wind blade. These components include the necessary appendages for the proposed second-life applications.

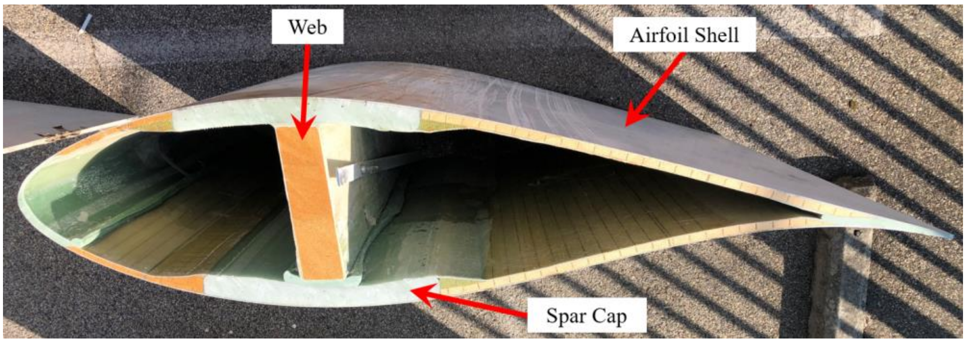


Figure 1: A typical cross section in a GE37 wind blade.

The Re-Wind Network (www.re-wind.info) consists of an international research team (in the United Kingdom, the Republic of Ireland, and the United States) specialized in studying re-using and re-purposing of wind turbine blades in civil infrastructure. Various applications have been studied and presented in their design catalogue (Bank et al., 2018; McDonald et al., 2022). The catalogue contains various applications with different types of wind blades at different scales. In Europe, prototyping of two BladeBridges have been successfully implemented in Draperstown, Northern Ireland, and in Cork, Ireland, which are intended for future proof load testing (CompositesWorld, 2022; Re-Wind, 2022; Ruane et al., 2023). In the United States, the team is focused on prototyping a BladeBridge and a BladePole (according to US design codes and standards). This process is essential for a future full-scale prototyping in the field and for future implementation at the industry level. A power transmission line prototype is planned in the coming 1-2 years in the US.

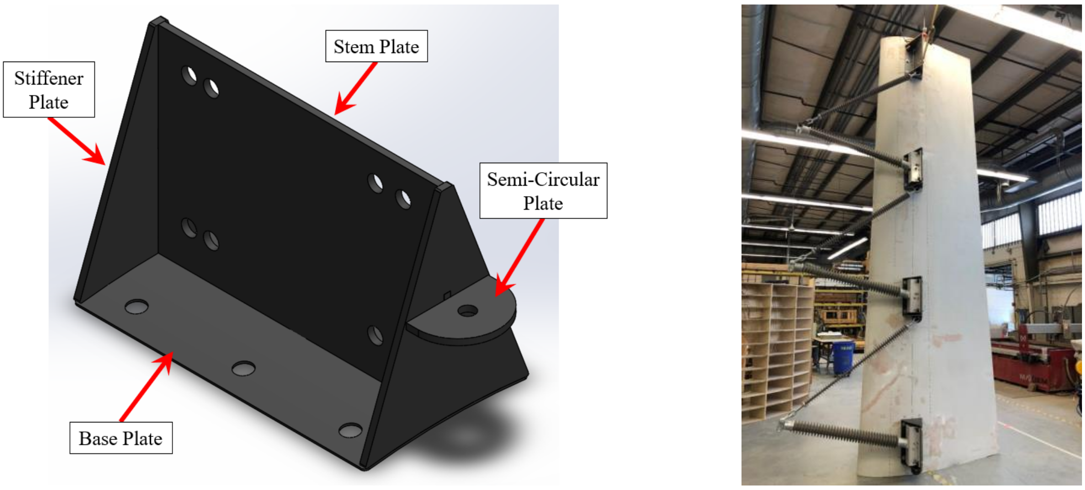
This paper reports on testing of a 5.5-m-high power transmission pole prototype, made from a decommissioned GE37 wind turbine blade, under gravity loading. The results of testing, combined with the results of full-sized connection testing to spar cap blocks, are analyzed to obtain safety factors for various structural components.

FULL-SIZED CONNECTION TESTING

The BladePole prototyping process involves testing of various structural components and connections to the wind blade. These include the conductor-carrying structures (e.g., braced-line posts, and davits), the connections between these structures and the body of the wind blade, the structural capacity and stability of the wind blade itself, and the foundation between the wind blade and the ground. The conductor-carrying structures are tested and rated by the manufacturer with specific safety margins and thus not tested by the research team. The connections between the components and the wind blade have been presented by Alshannaq et al. (2023) and is summarized herein. Essential physical and mechanical properties of the GFRP spar cap, which will be needed for future stability check of the wind blade (e.g., Finite Element Analysis), were presented by Alshannaq et al. (2022). Testing of the sandwich shell and the web materials is also needed and is underway. The foundation analysis and design are still to be addressed in the full-scale field prototyping.

In order to characterize the connections to the spar caps of the wind blade, the research team designed a steel connector, called “Universal connector plate - UC”, which can receive any type of off-the-shelf components, the UC is shown in Figure 2a. It consists of a 3.18-mm-thick base plate that conforms to the curved surface of the wind blade, two 9.53-mm-thick stiffener plates, a 9.53-mm-thick stem plate that receives the braced-line post, and a 9.53-mm-thick semi-circular plate with a hole to receive the tension member of the braced-line post beneath it (see Figure 2b). This UC is designed specifically (with a hole pattern) to receive off-the-shelf braced-line posts supplied to the research team by Hubbell

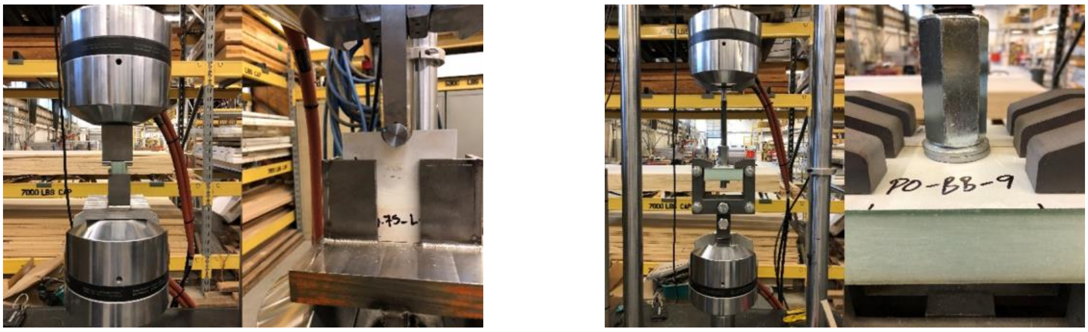
Power Systems (BLP043F12012), which are attached to the spar cap of the wind blade as shown in Figure 2b (Al-Haddad et al., 2022; Alshannaq et al., 2023). Testing of connections was presented by Alshannaq et al. (2023) from the small size of a bolt to the large size of a full-sized connection attached to the spar cap of GE37. Due to the nature of the wind blade's body (i.e., hollow structure with difficulty reaching the inside), a blind bolting technique was used in which the bolt is inserted from the outside of the wind blade, and an inside anchor is deployed and bears on the inside surface of the wind blade (BlindBolt, 2022; RS, 2022). Figure 3a and b show specimens cut from the GE37 spar cap and tested in bolt bearing and pullout, while Figure 3c through Figure 3e show the UC connected to spar cap blocks to characterize the full-sized connection capacity in strong-axis bending, in weak-axis bending, and in pullout, respectively.



a) details of the Universal Connector b) the 5.5-m-high BladePole prototype

Figure 2: A braced-line post connected to the BladePole prototype through the Universal Connector.

The pin-bearing and pullout testing results are summarized in Table 1. The thin material is intended to cover spar cap thicknesses ranging from 25.4 mm to 35.6 mm at stations 29 m to 32 m from the root of the GE37, and the thick material is intended to cover spar cap thicknesses ranging from 40.6 mm to 55.0 mm at stations in the root-transition region of the GE37. The results of full-sized connections tested in strong-axis bending, weak-axis bending, and pullout are summarized in Table 2.



a) specimen tested in pin-bearing b) specimen tested in pullout

c) full-scale connection tested in strong-axis bending d) full-scale connection tested in weak-axis bending e) full-scale connection tested in pullout

Figure 3: Coupon-scale and full-scale connection testing.

Table 1: Results of pullout and pin-bearing testing

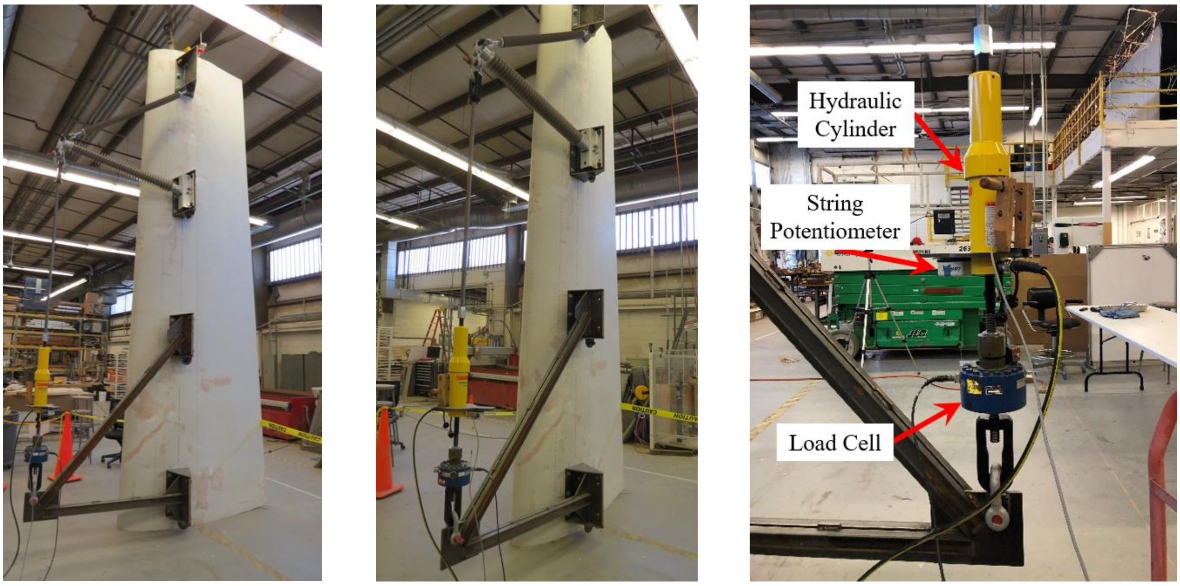
Pullout Testing				
	BlindBolt		RS BlindNut	
	Thick spar cap	Thin spar cap	Thick spar cap	Thin spar cap
Sample Size (*n*)	10	10	10	10
Mean (kN)	84.5	65.6	131.5	130.4
COV (%)	3.1	9.9	4.5	5.0
Pin-Bearing Testing				
	19.1-mm pin		25.4-mm pin	
	Longitudinal	Transverse	Longitudinal	Transverse
Sample Size (*n*)	10	10	10	10
Mean (MPa)	302	212	296	246
COV (%)	5.8	4.5	11	4.2

Table 2: Results of full-sized connection tests

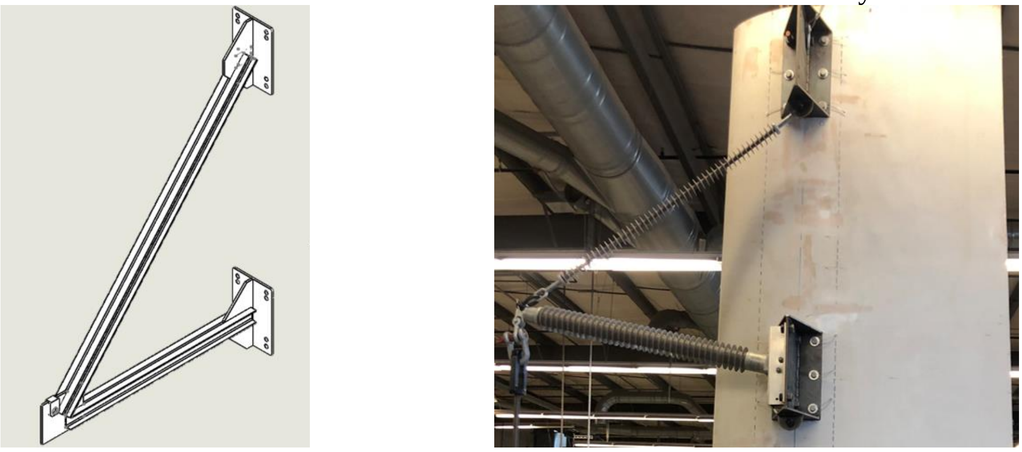
Property	RS BlindNut (kN)	BlindBolt (kN)
Strong-axis	227	260
Weak-axis	99.9	101
Pull-out	190	206

POWER TRANSMISSION POLE PROTOTYPE TESTING

Load cases expected during the lifetime of a power transmission pole include; extreme wind along different orientations, concurrent wind and ice, extreme ice, differential ice on the conductors, a broken conductor, or a broken shield wire. The testing of the 5.5-m-high power transmission pole prototype shown in Figure 2b is intended to cover one of these load cases which is the gravity loading (from the weight of conductors and ice). The prototype was constructed at the Digital Fabrication Laboratory at Georgia Institute of Technology between stations 19.0 m to 24.5 m from the root of a decommissioned GE37 wind turbine blade. The prototype consisted of four UC's spaced at 1.57 m vertically and braced-line posts extended horizontally to 1.42 m from the UC's. The test setup is shown in Figure 4a through Figure 4c, which includes the use of 222-kN load cell and a 250-mm string potentiometer connected to a NI cDAQ-9178 data acquisition system for simultaneous load and deflection logging. The load cell was connected to a 270-kN, 150-mm-stroke hydraulic cylinder. To apply the gravity loading, a triangular fixture was manufactured from double C-section (back-to-back) made from Grade-50 steel and connected through 12.7 mm gusset plates at the intersection of the two members and at the bases (see Figure 4d). This fixture was designed to be stronger than the rating of the braced-line post to force the failure either in the braced-line post (shown in Figure 4e) or at the UC-wind blade connection.



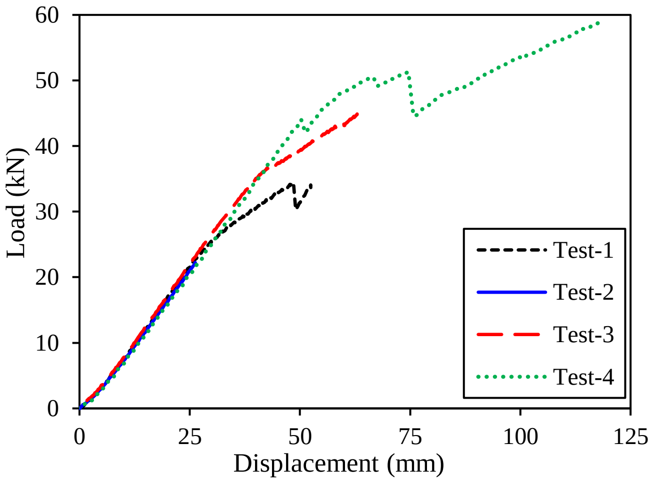
a) details of the test setup b) details of the test setup c) instruments and load application assembly



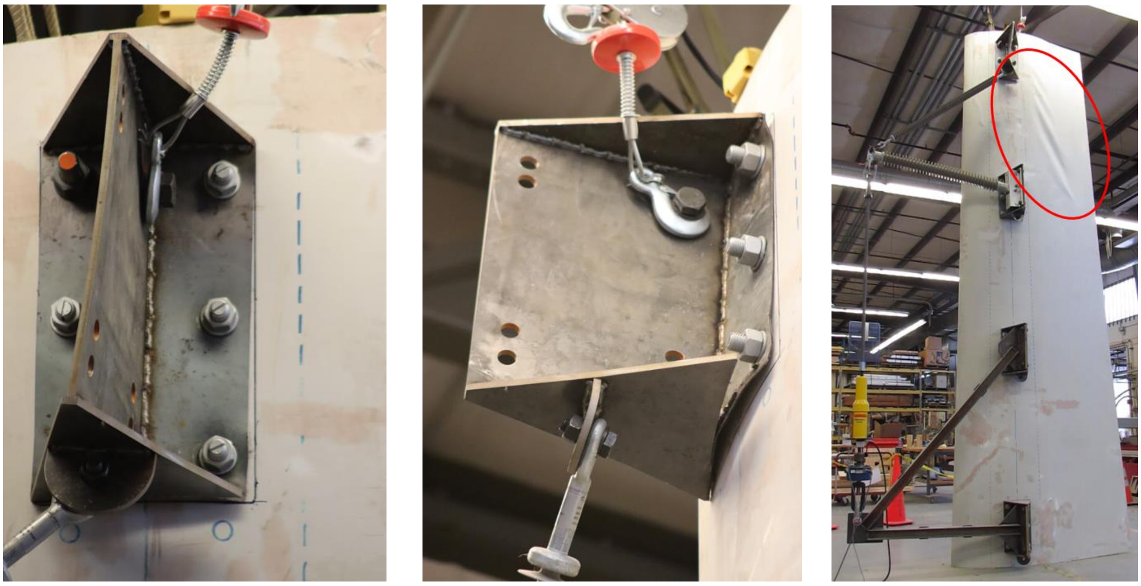
d) triangular steel fixture used for load application e) braced-line post assembly tested

Figure 4: Test setup for the 5.5-m BladePole prototype.

Figure 5a shows the load-deflection curves of the tests done on the prototype. Different tests were performed at different load levels to observe the deflection and failure after each load level. Test-1 was loaded to 33.4 kN, Test-2 was loaded to 22.2 kN, Test-3 was loaded to 44.5 kN, and Test-4 was loaded to 57.8 kN. After Test-1, the UC rotated from its original location due to the RS BlindNut being oversized for the holes used, thus the upper UC's bolts were changed to the larger BlindBolts (refer to Figure 4e and Figure 5b and c for comparison of the bolt type for the top UC) (BlindBolt, 2022; RS, 2022). The final test (i.e., Test-4) reached a failure load of 57.8 kN and a deflection of 118 mm. This ultimate load was accompanied by buckling of the wind blade shell as seen in Figure 5d (due to the horizontal couple generated between the upper UC and the one beneath it) and failure of the upper UC (which connects the tension member of the braced-line post) as seen in Figure 5b and Figure 5c. Rotation of the upper UC was observed for both types of blind bolts used (i.e., the RS BlindNut and the BlindBolt), however, the rotation occurred while using BlindBolts was less and thus used for the final tests (refer to Figure 5b for visualization of the rotation amount).



a) load-deflection curves of the tested prototype



b) UC rotation and bending under loading

c) UC welding fracture under loading

d) buckling of the wind blade shell under loading

Figure 5: Results of the 5.5-m BladePole prototype testing.

RESULTS AND DISCUSSION

The results obtained from the full-sized connections and the 5.5-m prototype give important data related to the safety of the field full-scale proof testing and implementation. If the demand is calculated from structural analysis of the BladePole with a vertical (i.e., gravity) load of 22.2 kN at the location where the conductors attach to the braced-line posts, the safety factor against strong-axis loading will be 10 for the case of RS BlindNut and 12 for the case of BlindBolt, while against weak-axis loading will be

4.3 for both blind bolt types. A combined case of strong-axis and weak-axis loading occurred in the testing of the 5.5-m prototype and resulted in an overall safety factor of 2.6. Even though this value is relatively low for such critical structure, the results suggest using stronger UC's or stronger wind blade sections (i.e., near the root-transition region) to attain the required strength and safety levels. The buckling of the UC's base plate and the welding fracture suggest using welding on both sides of the stem and stiffener plates and using a thicker base plate to accommodate the increase in welding, with attention to be made by using a base plate that is bendable. These recommendations are intended to be applied in the field full-scale power transmission line.

CONCLUSIONS

This paper describes testing of a 5.5-m-high power transmission pole prototype, and its parts, made from a decommissioned GE37 wind turbine blade, under gravity loading. The following conclusions are obtained:

- Full-sized connections to the GE37 wind blade's spar cap are structurally safe with a minimum safety factor of 4.3 against bending of the UC and welding fracture. These modes of failure in the steel UC are preferred over sudden failure in the composite materials. Increasing the thickness of the steel plates and the welding thickness, might improve these safety factors. These recommendations will be implemented in the planned field full-scale power transmission line.
- The connections are made to the spar cap of the GE37 wind blade due to the central location of the spar cap with respect to the wind blade's cross section (reducing unnecessary eccentricity) and to the nature of the spar cap material being solid GFRP. Connections to the shell and the webs are not advised due to the sandwich nature of these parts which make them susceptible to crushing under bearing action of the blind bolts on the inside surface.
- The testing of the 5.5-m BladePole prototype revealed additional limit states that should be taken into account in the design of repurposed wind blade as power transmission pole. Shell shear-buckling was observed near the top UC due to the horizontal couple generated between the upper UC and the one beneath it.
- Finite Element Analysis (FEA) is being conducted to predict the expected modes of failure in the BladePole model before field implementation. These modes of failure will vary depending on the load case being studied and its force-resultant on the wind blade's body.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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