Structural Re-use of FRP Composite Wind Turbine Blades as Power-Line Utility Poles and Towers

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Abstract. The production of wind energy worldwide has increased 20-fold since 2001. Composite material wind turbine blades are beginning to come out of service in large numbers. In general, these de-commissioned structures, composed primarily of glass fibers in a thermoset matrix and generally between 13 and 80 m long, are demolished and either landfilled or incinerated. This research seeks to establish structural re-use applications for wind turbine blades in civil engineering infrastructure. This paper presents design concepts along with materials and engineering analysis for high voltage electricity transmission structures made from re-used wind turbine blades. This re-use application targets wind blades in the 25 to 50-m overall length range, with single blades considered for use as cantilevered poles, and multiple blades used as replacements for waist-type truss or guyed towers. Strengths of the composite materials are established from coupons cut from de-commissioned wind blades – and section properties are established from blade geometries acquired using LiDAR scanning, through proprietary algorithms developed as part of the research effort. The section analysis is based on two common commercially available blades in the European and U.S. markets: the Vestas V52 and the Clipper C96. The paper reports on preliminary strength design allowables for the typical wind blade laminates and uses these as the basis for design under gravity, wind, and ice loading. Preliminary design of connections and physical mockup testing of these connections are presented.

Keywords: Wind turbine blades · Recycling of composites · Adaptive re-use · Compression testing

1 Introduction

Fiber reinforced polymer (FRP) composites are attractive structural materials due to their high strength-to-weight and stiffness-to-weight ratios, durability, and fatigue resistance (Bank 2006). In addition, due to FRP's ability to be molded into complex shapes, the great majority of the world's wind turbine blades are constructed from FRP materials. These wind blades are produced primarily from glass and carbon composites using

A. Ilki et al. (Eds.): CICE 2021, LNCE 198, pp. 121–130, 2022.
https://doi.org/10.1007/978-3-030-88166-5_10

thermoset resins, and often include balsa and foam sandwich cores in some areas of the blade assembly. These materials give the wind blade better resistance to sustained static and fatigue loading (Brøndsted et al. 2005).

After 20 years in service, wind turbine blades are de-commissioned and replaced, due either to the perceived end of their fatigue life or to accommodate changes in turbine and blade technology (Hayman et al. 2008). This relatively short-life span combined with a dramatic increase in wind energy production poses a threat to the environment and a challenge to the "clean energy" reputation that wind energy seeks. There are no proven economical means to recycle thermoset FRP composites, and these materials are disposed of using incineration or landfilling. Ongoing research has identified methods such as mechanical, thermal, and chemical separation techniques to extract the constituent materials and allow for their re-use in new composite materials. However, these options have drawbacks such as significant strength reductions (Yazdanbakhsh and Bank 2014, Beauson et al. 2014, Oliveux et al. 2015, Beauson et al. 2016, Chen et al. 2019). Recently, a promising initiative has been undertaken to re-use these materials in civil engineering infrastructure as a whole or as cut parts (Gentry et al. 2018, Bank et al. 2018, Alshannaq et al. 2019).

This paper presents a re-use proposal of de-commissioned wind turbine blades typical of those currently being removed from service in North America. Examples of these include the GE 77, 1.5 MW (megawatt) turbine with 37 m blades and the Clipper Liberty 2.5 MW turbine with 43 to 48 m blades. The current work focuses on the Clipper C96, 46.7 m long blade type as the research team has access to details of the geometry, specifications and materials from this wind blade type. The paper is organized as follows: first, the design proposal and its detailing are described. Then the key parts of the wind blade cross section (i.e. parts that will carry the majority of the load) are described, after which the structural analysis of the proposed configuration is carried out under the critical load cases. Finally, the results are compared to compression-tested coupons from the wind blade in which structural factors of safety and strength utilization ratios are investigated to determine if they comply with reliability design guidelines.

2 Power Transmission Pole Concept

The research team has developed a wide range of concepts for transmission and distribution electrical structures, which are typically 20 to 45 m tall, all with de-commissioned wind blades as the primary load-carrying members. The power transmission application is considered promising for wind blade re-use for the following reasons: (1) power transmission structures cantilever from the ground, matching the cantilevered nature of the wind blades, (2) power transmission structures are relatively lightly loaded compared to the first-life loads carried by the wind blades on the turbines – sustained loads are small, and (3) the environmental durability of the wind turbine blades should ensure that the blade poles will have long second-lives in the expected service environment of power transmission poles.

The pole in Fig. 1 is the most basic of the design concepts developed. In this concept, a 20 to 30 m single wind blade carries three-phase electrical power at either 69 kV or 138 kV. Denoted "tangent" poles, they are placed in the ground at approximately 300

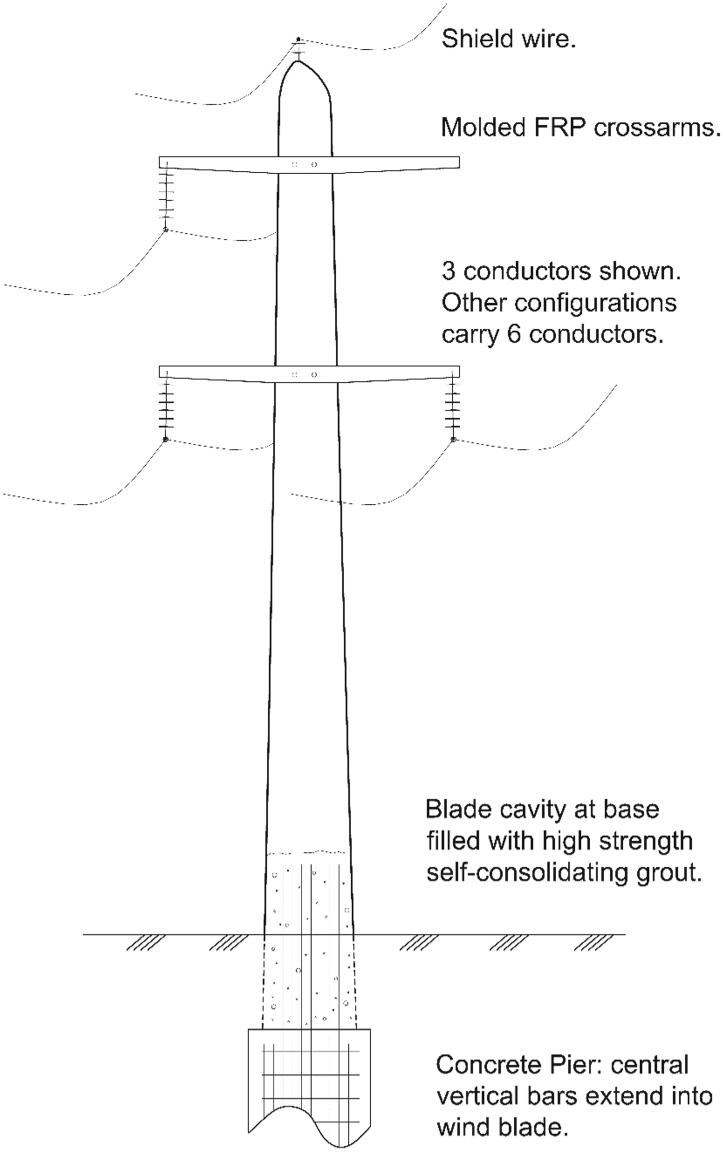

Fig. 1. Power pole concept shown with 3 conductors.

to 500 m spacing, with no appreciable change in direction of the electrical grid at the pole, and thus no requirement for cabling of the structure to the ground. Tangent poles represent about 80% of the total poles used in a transmission installation.

The wind blade is connected to a conventional reinforced concrete pier foundation. The central longitudinal reinforcing bars from the pier extend above the top of the pier and into the hollow section of the wind blade. After the wind blade is plumbed, the lower section of the blade is infilled with a self-consolidating cementitious grout, securing the wind blade to the foundation. Molded FRP cross-arms match the outer geometry of the wind blades, are made in two parts and clamshell mount onto the wind blades. The cross-arms are bolted through the spar cap of the wind blade for security, but the primary load transfer is through bearing of the cross-arm clamshell on the outer surface of the blade. The present work focuses on the design of the primary wind blade spar; the design and testing of the foundation and cross arm connections will be the subject of future work.

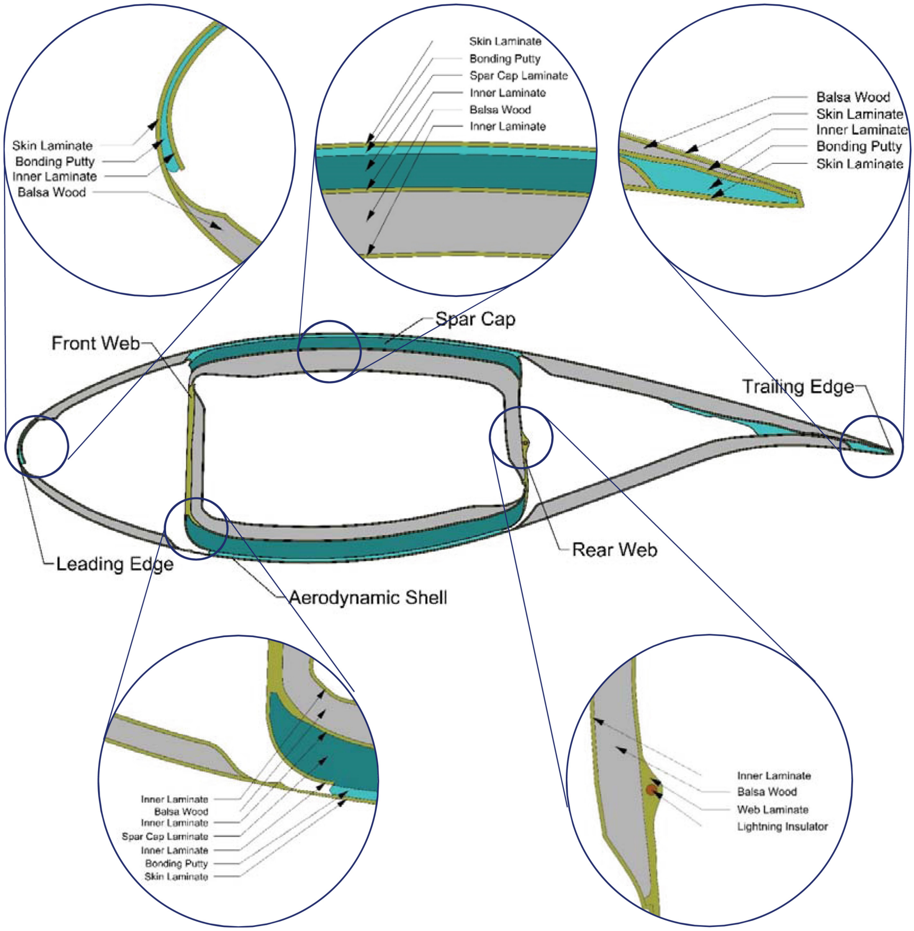

Fig. 2. Internal geometry of the Clipper C96 wind blade

3 Wind Blade Internal Geometry

Any cross section of the wind blade (except the root which is a circular shell) contains three major parts; the aerodynamic shell, the load-bearing spar cap, and the shear-bearing webs. Through visual inspection of the actual cross section illustrated in Fig. 2, the thickest and stiffest part of the cross section is the spar cap -it serves as the primary load-bearing "member" of the overall cross section. The webs are for shear-bearing as well as structural stability of the airfoil shape. The aerodynamic shell is the shape that gives the blade its ability to move with the wind in an efficient manner as well as giving additional resistance to shear and torsional loads. Figure 2 shows some detailing on the layup of the different segments forming the cross section.

4 Structural Analysis of the Proposed Power Pole

ASCE 74 (2009) designates the standards for the structural analysis of any power line project. The loading identifies cases at which one or more of the following situations may occur; extreme wind, extreme ice, combination of both wind and ice, differential ice, and broken conductors and/or shields (i.e. differential loading). When combined, these result in 16 load combinations. After analysing all the combinations, two were found to control the design. These give the highest stresses and strains in the proposed power pole, as shown in Fig. 3. The two load cases were: "Concurrent ice and wind right" (load case 1), and "extreme wind left" (load case 2). Figures 4a and 4b show the expected axial loads and edgewise bending moments (i.e., moment about the vertical axis that passes through the centroid of the cross section in Fig. 2) due to these two load cases, respectively.

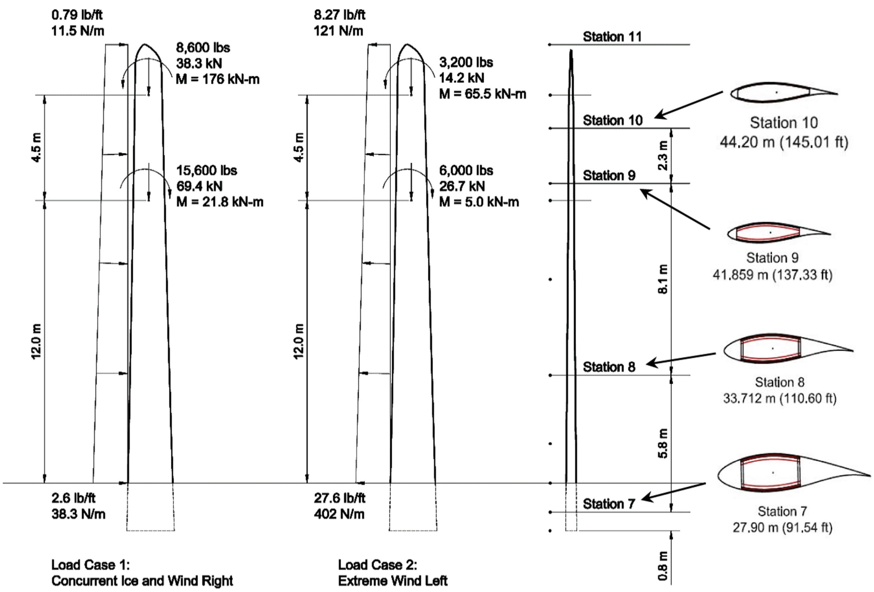

Fig. 3. Load cases 1 and 2 for the proposed power pole

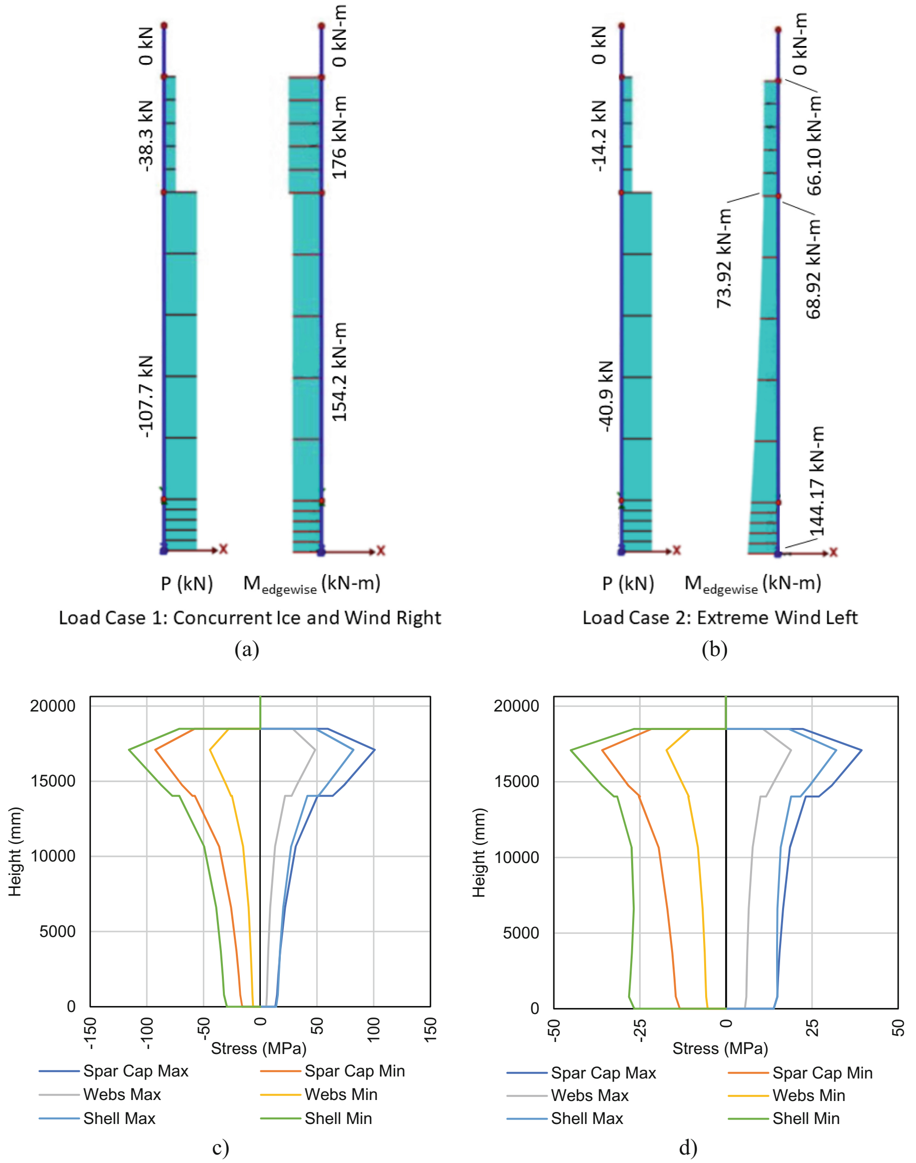

Fig. 4. Structural analysis of the power pole application, a) Axial load and edgewise bending moment from load cases 1, b) Axial load and edgewise bending moment from load cases 2, c) and d) Stress distribution along the used wind blade part due to load case 1 and 2, respectively

Figures 4c and 4d show the resulting stresses across the different parts composing the wind blade due to the two load cases, respectively. Note that the two locations where stresses drop suddenly occur at the attachment points of the crossarms on the power pole structure. As shown in Fig. 4, load case 1 is the critical case resulting in maximum tensile stresses of 100.99 MPa and 82.2 MPa in the spar cap and the shell, respectively. The maximum compressive stresses on the spar cap and shell are 92.6 MPa and 115.9 MPa, respectively. In order to get an insight into the factor of safety and the strength utilization ratio of the composite materials forming the wind blade, coupon testing of samples taken from critical locations (i.e. shell, spar cap, and web) were carried out.

Figures 5a and 5b show the strain and stress distributions at the critical Section (44,200 mm from the root and 18,490 mm from base of blade part used) for load case 1. Figures 5c and 5d show these distributions for load case 2. As can be seen in the figures, even though the distance from the centroid is higher for the shell (due to the nature of the airfoil shape), the tensile stresses are higher in the spar cap due to its higher stiffness (i.e., stiffer parts attract higher loads). However, this is not the case for the compressive stresses.

The first-life design of wind blades requires the aerodynamic shell to be able to adequately move with the wind without structural failure. In contrast, the power pole configuration aims at exploiting the high strength and stiffness of the load-bearing spar

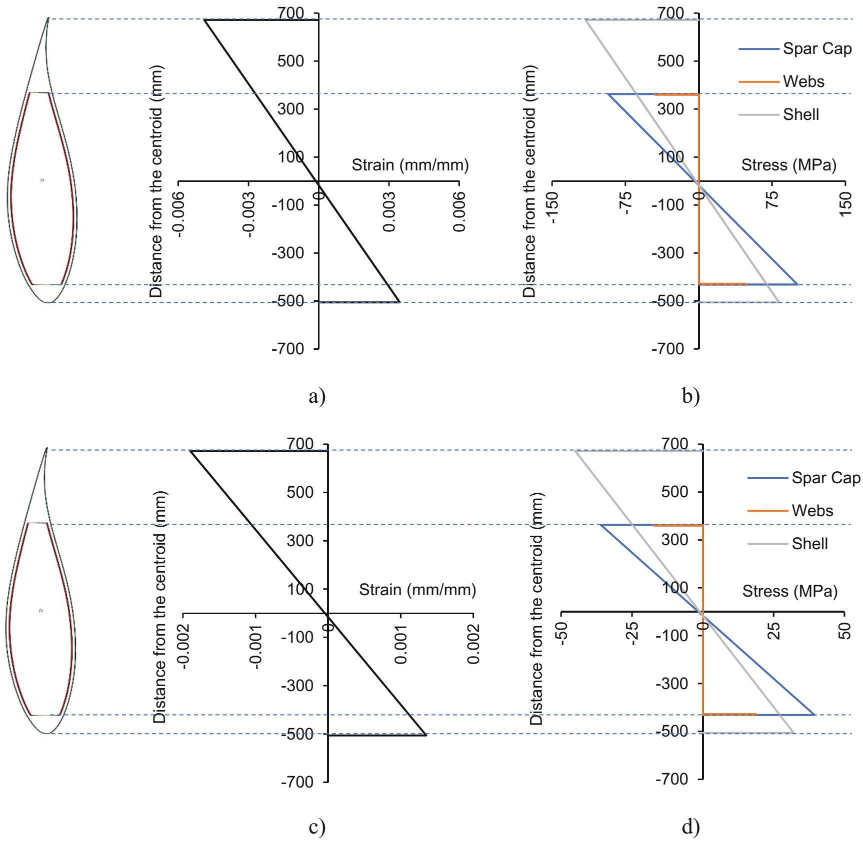

Fig. 5. Critical section results, a) and b) strains and stresses at the critical section due to load case 1, respectively, c) and d) strains and stresses at the critical section due to load case 2

cap. This makes the spar cap the focus of the testing and safety checks for the configuration (i.e., it is assumed that even if the shell fails either in tension or compression, this will not compromise the safety of the power pole).

5 Material Properties and Safety Factors

For the proposed re-use configuration to be viable, measured strength values for the material need to be checked against expected critical stresses on the power pole structure. Samples were taken from the spar cap of the wind blade to measure the longitudinal strength and stiffness of the material. However, there is some ambiguity in the ASTM standards (ASTM-D695 2015, ASTM-D3410 2016, ASTM-D6641 2016) for compressive testing of FRP samples in terms of; thick samples (higher than 2 mm), gripping pressure, and load introduction technique (D695-end bearing, D3410-shear loading, D6641-shear and end bearing). As such, an initial series of experiments were performed to identify proper gripping pressure and testing fixture to be used in the actual testing program for the wind blade samples. No tabs were used in the testing program. Figure 6 shows test set-up.

Fig. 6. Compression test set-up for spar cap material

The average compressive strength of eight tested samples was 347 MPa with a coefficient of variation (COV) of 17.5%. The COV is relatively high which can be attributed to the variability in testing (i.e., different gripping pressures and different end conditions). The longitudinal modulus of elasticity was calculated from the measured stress-strain curves between 1000 $\mu\varepsilon$ and 3000 $\mu\varepsilon$ and found to be 36.1 GPa.

The strength values from the mechanical tests can be compared with the expected critical stresses to obtain first-approximations of factors of safety and strength utilization ratios. Using the average compressive strength of 347 MPa results in a factor of safety (F.S) of 3.75 or a strength utilization ratio of 0.27 for the power pole configuration under the critical load case. These values are considered within the acceptable range for civil engineering infrastructure. Since test results for the laminate in the shell were not conducted, Helius Composites software (Autodesk 2016) was used to predict the theoretical compressive strength of a specimen taken from the shell at the critical stress location (18,490 mm from base of blade part used). The compressive strength of the shell was found to be 202 MPa and the corresponding factor of safety (F.S) was 1.75.

6 Conclusions

The present paper lays the foundation for the potential re-use application of wind turbine blades as utility power poles. Structural analysis of the proposed configuration as well as mechanical testing on the material indicates that the re-use configuration is feasible. While much more thorough mechanical characterization of the materials must be undertaken along with more sophisticated analysis, the preliminary results from the present work are promising in terms of factor of safety. The adaptive re-use of wind turbine blades in the power transmission industry may be an environmentally preferable solution to proposed reduction of the blades to their constituent materials, or landfilling.

Acknowledgements. Support for this research was provided by the National Science Foundation (NSF) under grants 1701413, 1701694 and 1949818; by InvestNI/Department for the Economy (DfE) under grant 16/US/3334 (Jian Fei Chen (QUB) PI) and by Science Foundation Ireland (SFI) (Paul Leahy (UCC) PI) under grant USI-116 as part of the US-Ireland Tripartite research program. Rahul Yarala, Executive Director, Wind Technology Testing Center (WTTC) and the Massachusetts Clean Energy Center (MassCEC) provided wind blade materials to the research team. Dr. Nathan Post of Windesco is acknowledged for his advice and support.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

References

Alshannaq, A, Scott D, Bank L, Bermek M, Gentry R (2019) Structural re-use of de-commissioned wind turbine blades in civil engineering applications. In: Proceedings of the American Society for Composites—Thirty-fourth Technical Conference

American Society of Civil Engineers, ASCE (2009) Guidelines for Electrical Transmission Line Structural Loading. Third Edition ed, Guidelines for Electrical Transmission Line Structural Loading: ASCE Manuals and Reports on Engineering Practice No. 74, New York

ASTM-D695 (2015) Standard Test Method for Compressive Properties of Rigid Plastics. West Conshohocken, PA

ASTM-D3410 (2016) Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading. West Conshohocken, PA

ASTM-D6641 (2016) Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture. West Conshohocken, PA

Autodesk Helius Composite 2016. https://www.autodesk.com/. Accessed 1 1 2020

Bank LC (2006) Composites for Construction: Structural Design with FRP Materials. John Wiley & Sons, Hoboken

Bank LC et al (2018) Concepts for reusing composite materials from decommissioned wind turbine blades in affordable housing. Recycling 3(1):11

Beauson J, Lilholt H, Brøndsted P (2014) Recycling solid residues recovered from glass fibre-reinforced composites – a review applied to wind turbine blade materials. J Reinf Plast Compos 33(16):1542–1556

Beauson J, Madsen B, Toncelli C, Brøndsted P, Bech JI (2016) Recycling of shredded composites from wind turbine blades in new thermoset polymer composites. Compos A Appl Sci Manuf 90:390–399

Brøndsted P, Lilholt H, Lystrup A (2005) Composite materials for wind power turbine blades. Annu Rev Mater Res 35(1):505–538

Chen J, Wang J, Ni A (2019) Recycling and reuse of composite materials for wind turbine blades: an overview. J Reinforced Plastics Compos 38(12):567–577. https://doi.org/10.1007/978-981-13-3717-8_1

Gentry R, Bank LC, Chen JF, Arias F, Al-Haddad T (2018) Adaptive reuse of FRP composite wind turbine blades for civil infrastructure construction, July 17–19, 2018. In: 9th International Conference on Fiber Reinforced Polymer Composites in Civil Engineering (CICE 2018), Paris, France

Hayman B, Wedel-Heinen J, Brøndsted P (2008) Materials challenges in present and future wind energy. MRS Bull 33(4):343–353. https://doi.org/10.1557/mrs2008.70

Oliveux G, Dandy LO, Leeke GA (2015) Current Status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties. Prog Mater Sci 72:61–99

Yazdanbakhsh A, Bank LC (2014) A critical review of research on reuse of mechanically recycled FRP production and end-of-life waste for construction. Polymers 6(6):1810–1826