Structural Re-Use of De-Commissioned Wind Turbine Blades in Civil Engineering Applications

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ABSTRACT

The production of wind energy worldwide has increased 20-fold since 2001. Composite material wind turbine blades, typically designed for a 20-year fatigue life, are beginning to come out of service in large numbers. In general, these de-commission blades, composed primarily of glass fibers in a thermoset matrix, are demolished and landfilled. There is little motivation for recycling the composite materials, as the processes for reclaiming the fibers (solvolysis, pyrolysis) have not been proven to be economically viable. This research seeks to establish structural re-use applications for wind turbine blades in civil engineering infrastructure, hypothesizing that advanced composite materials may be an attractive alternative to conventional infrastructure materials (e.g. steel, reinforced concrete). This paper presents an analysis and materials characterization of a 47 meter Clipper C96 wind blade. The primarily numerical analysis is accompanied by materials characterization taken from an un-used Clipper blade donated to the project from the Wind Turbine Testing Center (WTTC). The paper presents a brief background on wind turbine blade adaptive re-use, proposing a hypothetical load bearing application of the Clipper wind blade as an electrical transmission tower structure carrying axial compression, along with flapwise and edgewise bending forces. The paper summarizes the composite laminates and cross-section geometries of the blade and establishes the axial and flexural stiffnesses of the blade at multiple sections along the blade length. From a first-order estimation of applied loads for the tower application, the resulting stresses in the composite materials are estimated and compared to the design material properties for the wind blade as originally constructed.

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INTRODUCTION

Fiber-reinforced polymer composites are attractive construction materials due to their light weight, high strength-to-weight and stiffness-to-weight ratios, fatigue strength, and durability [1]. One major structural use for modern composite materials is in the fabrication of wind turbine blades, in which relatively thick laminates are bonded to lightweight sandwich shells in the shape of airfoils. The composite construction allows for highly complex geometries, lightweight construction and substantial fatigue resistance. However, due to the uncertainty in terms of fatigue loading, the service lives of wind blades are typically limited to 20 years [2]. The relative short service lives of these structures in their intended role as wind blades may allow for viable structural reuse, defined here as use of the entire wind blade or major sections cut from the wind blade, in load-bearing applications. The focus of the present work is on civil infrastructure applications, as these applications often involve large structures at relatively low stresses, deployed in environments where durability is often a prime concern.

Many researchers have studied end-of-service options for composite wind turbine blades including disposal, recycling, and reconfiguration/reuse. Disposal is typically accomplished through incineration or landfilling; however, this is an environmentally harmful option that has many drawbacks with little positive societal impact. Recycling can be accomplished using mechanical, thermal and chemical processing, with the extracted materials used as replacements for virgin constituents in new composites [3-4] or in cementitious mortars and concretes [5]. However, the feasibility of useful, economical extraction and the resulting mechanical property variations in composites fabricated with recycled fibers are significant issues. For the most part, FRP composites have reduced properties when manufactured with recycled fibers [6-7]. The research team believes that reuse may be the most promising option, and is working to develop, analyze, and prototype applications where large parts of the wind blades are utilized in new or retrofitted civil infrastructure [8-9].

When considering reuse options for these elements, the specific geometry and internal structure of the wind blades must be identified. A wind blade structure is typically composed of three major parts: the aerodynamic shell, the spar cap, and the shear webs. The spar cap and shear webs form a tapered box beam structure that cantilevers from the root of the wind turbine. Determination of the outer airfoil geometry, the internal skeletal structure and the material/laminated structure of these parts can be challenging due to proprietary construction techniques and the lack of information from wind blade manufacturers. This has resulted in several studies focusing on the digital "reconstruction" of wind blades. The current research program on the reconstruction process has led to a methodology, based on point-cloud acquisition and evolutionary solvers that predict the internal structure and geometry of any wind blade [10].

The present work focuses on the parametrization of the geometry and internal structure of a C96 Clipper blade. The Clipper blades (models C89 to C100) range from 43.2 to 48.2 meters long and are used to drive the 2.5 MW Liberty horizontal axis wind turbine. The research team was provided summary specifications detailing the internal structure of the blades. These parameters were used to calculate the engineering strength and stiffness properties at 10 stations along the C96 blade. With this information, an adaptive reuse application is proposed, where a section of the wind blade, taken from the tip, is used as an electrical transmission tower, with design loads and stresses identified for the structure.

WIND BLADE GEOMETRY

Wind blade geometry typically consists of a circular root which is connected to the hub around which the wind blades rotate, a relatively short transition zone, and an aerodynamic airfoil shape for the rest of the element. The aerodynamic shape (often called the shell) gives the wind blade the propeller shape that allows it to move effectively in the wind. The two spar caps (i.e., the flanges of the internal beam) are the primary load-bearing elements of the blade in the wind loading direction. The shear webs give the wind blade the ability to resist shear and torsional loading and provide stability for the overall shape. Section details for the wind blade used are given in Figure 1. A total of 10 stations were identified along the length of the wind blade and were used to determine the mechanical properties along the length (Figure 2).

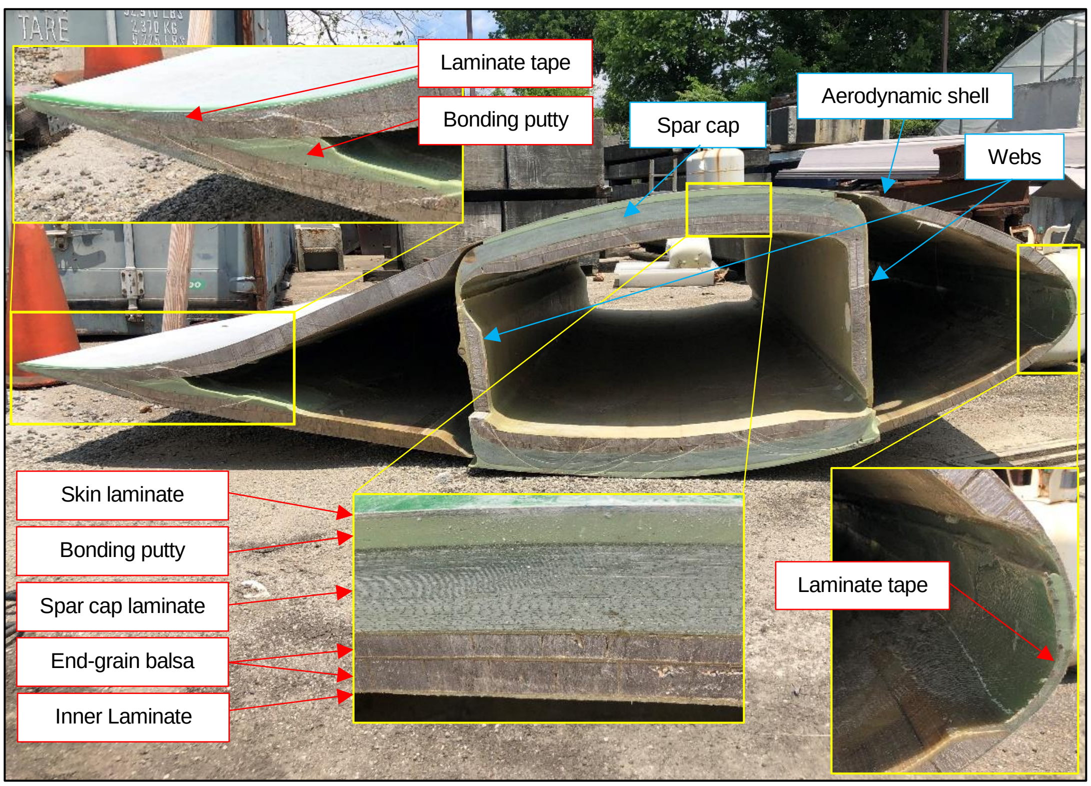
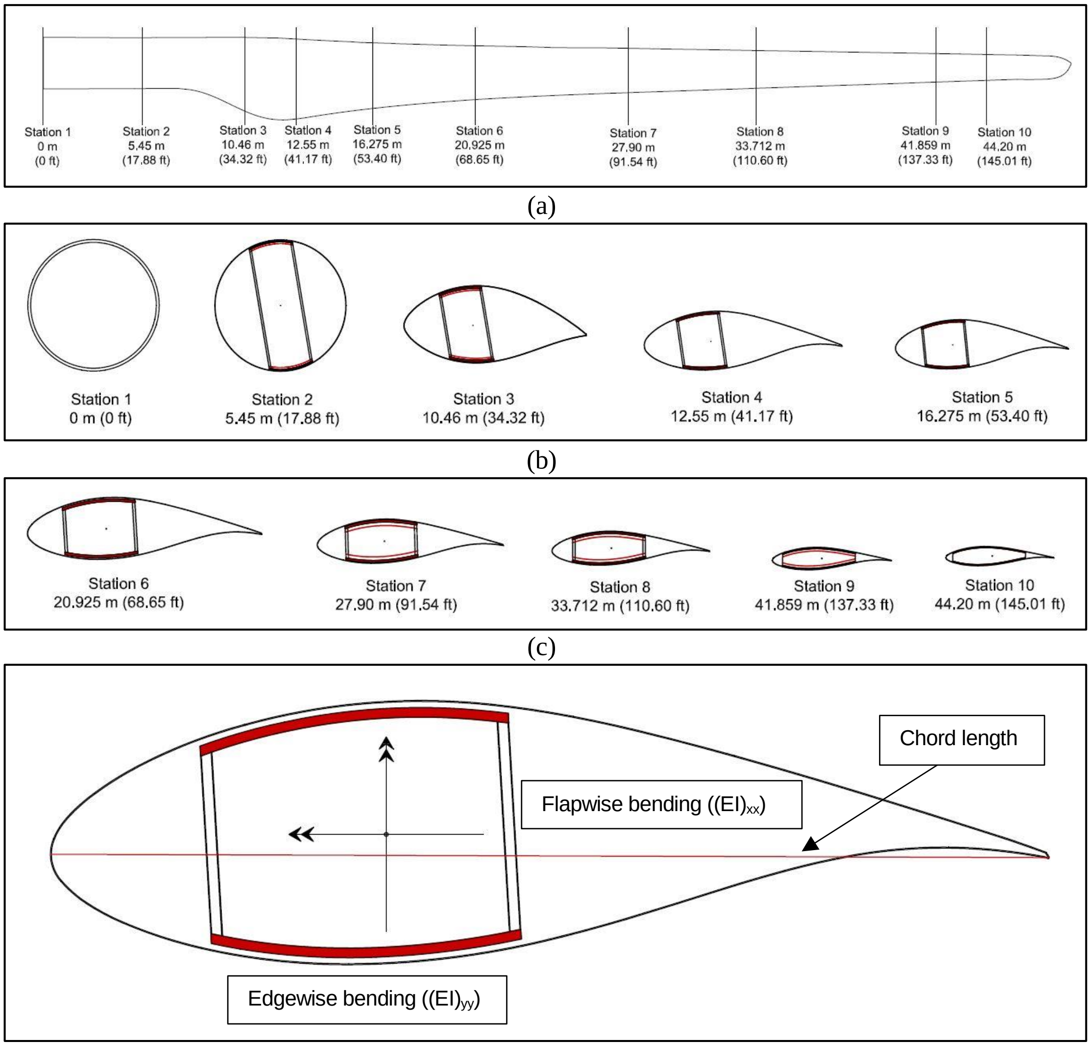


Figure 1. Internal geometry of the Clipper C96 wind blade
(photograph taken near Station 7, see Figure 2).



(d)

Figure 2. (a) Stations along the wind blade selected for mechanical characterization; (b) and (c) cross sections at the specified stations; and (d) edgewise and flapwise bending.

AXIAL AND FLEXURAL SECTION PROPERTY DETERMINATION

The cross-section stiffness at each of the wind blade stations is determined based on the stiffness of the laminates and the position of the various laminates in the cross-sections. AutoCad was used to determine the area, centroids, and inertial properties for the spar cap, the web and the airfoil shell. For these calculations, the presence of sandwich core materials (end-grain balsa) was ignored. At each section the laminate configuration was taken from the Clipper blade specifications. The stiffness and first-ply failure strength were determined for the spar cap, the webs and the aerodynamic shell using Autodesk Helius Composite software [11]. The laminate strength and stiffness values were used with the areal and inertial properties to establish composite beam section properties.

The Clipper blade specification shows ply-drops in the spar cap laminate, depicted as a function of blade length in Figure 3. The overall thickness of the spar cap varies from 72 mm at the root of the blade to 5.6 mm at near the tip of the blade where the spar cap ends. Note that at the root end an additional 69 layers of uni- and bi-axial fabrics (not shown in Figure 3) merge with the spar cap laminate to form the root laminate. The root laminate tapers quickly and all root laminate layers are dropped at a distance of 2.5 m from the root.

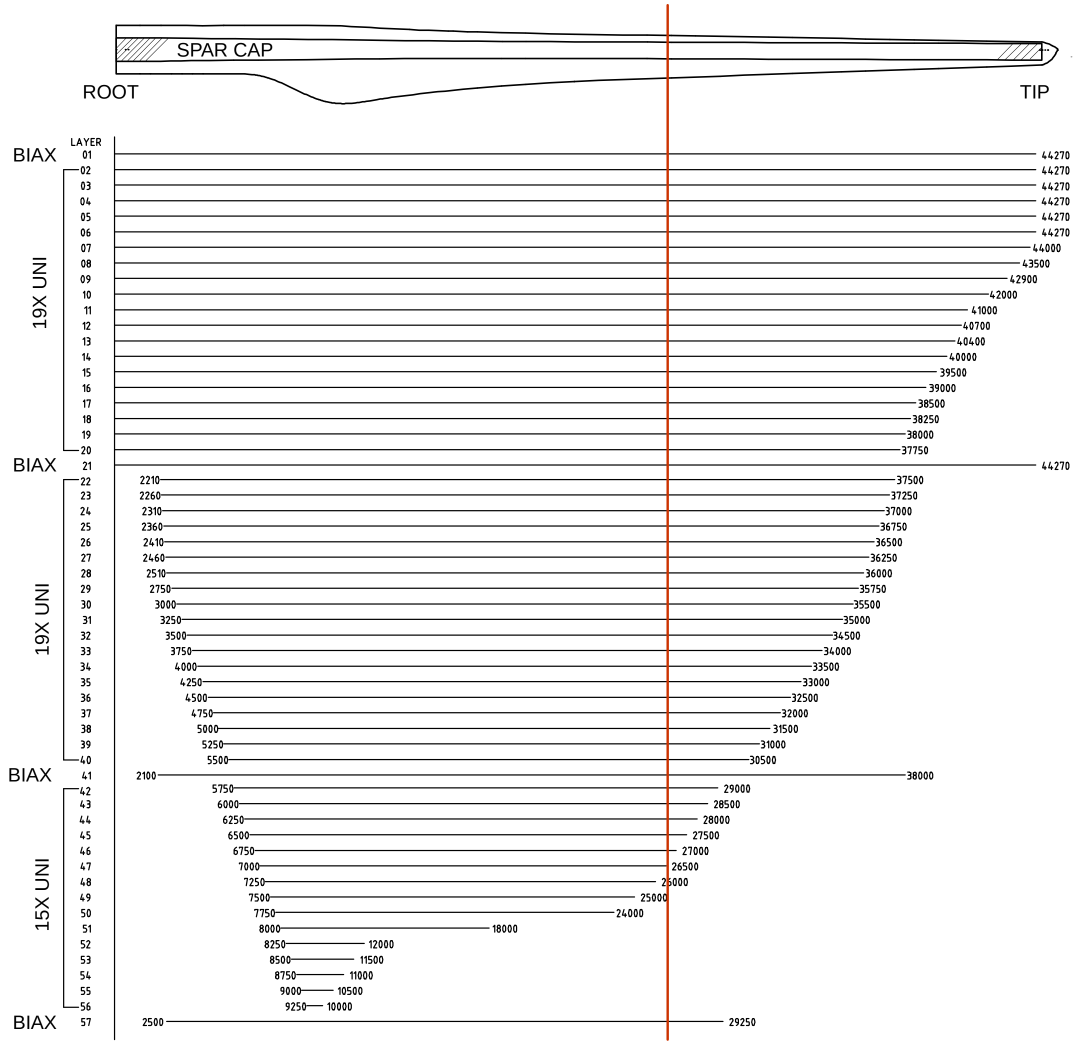


Figure 3. Spar cap laminate layup as a function of blade length.
Red line indicates location of burnout test, see Figures 4 and 5.

Selected fiber layups for each location were verified using burnout tests per ASTM D2584 [12] as shown in Figure 4. Figure 5 shows the individual lamina in the spar cap laminate, a sample taken 26.5 meters from the root of the blade. The observed laminate structure was as follows: [Mat / 90 / 0 / 90 / 0_{23} / ±45 / 0_{16} / ±45]. According to the Clipper specifications, the biaxial layers are 989 g/m^2 stitched mats and the uni-directional layers weigh 950 g/m^2. Figure 5 clearly shows the modest amount of glass weft that was stitched to the unidirectional fibers. The weights of the individual layers confirm the information provided in the specification.

The volume fraction from the spar cap laminate is calculated from the burn out test to be 50.0%. This is slightly lower than the reference value of 54% observed by Nijssen in the Optimat wind blade material program [13-14]. The presence of the mat layers in the spar cap sample for the present work reduces the overall volume fraction observed during the burnout test.

(a) (b)

Figure 4. ASTM D2584 burnout samples taken at different locations of the wind blade section; (a) shell and web and (b) spar cap.

Figure 5. Fiber layout verified from ASTM D2584 burnout test of a spar cap sample from Station 7.

The distribution of bending and axial stiffness values along the wind blade are shown in Figure 6. As shown in Figure 6(a), the edgewise bending stiffness $(EI)_{yy}$ is generally higher than the flapwise bending stiffness $(EI)_{xx}$ except at the transition zone (defined as the location along the blade where the shape of the blade transitions from a circle, near the root, to the airfoil sections).

Calculations show the contribution from each part of the section and are highlighted in Figure 7(a), (b) and (c). At the root (length = zero), the structure consists of a solid composite ring (no webs, no spar cap, no sandwich panel). Moving away from the root, the major contributor to bending stiffness in the edgewise direction is the shell, while the spar cap is the major contributor to bending stiffness in the flapwise direction as well as the axial rigidity EA.

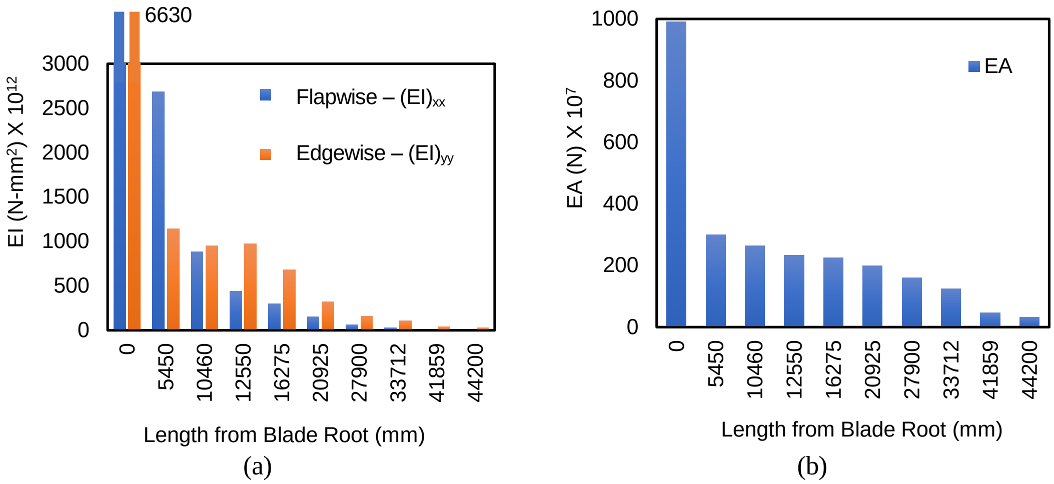


Figure 6. (a) Bending stiffness distribution in flapwise and edgewise directions and (b) axial stiffness distribution.

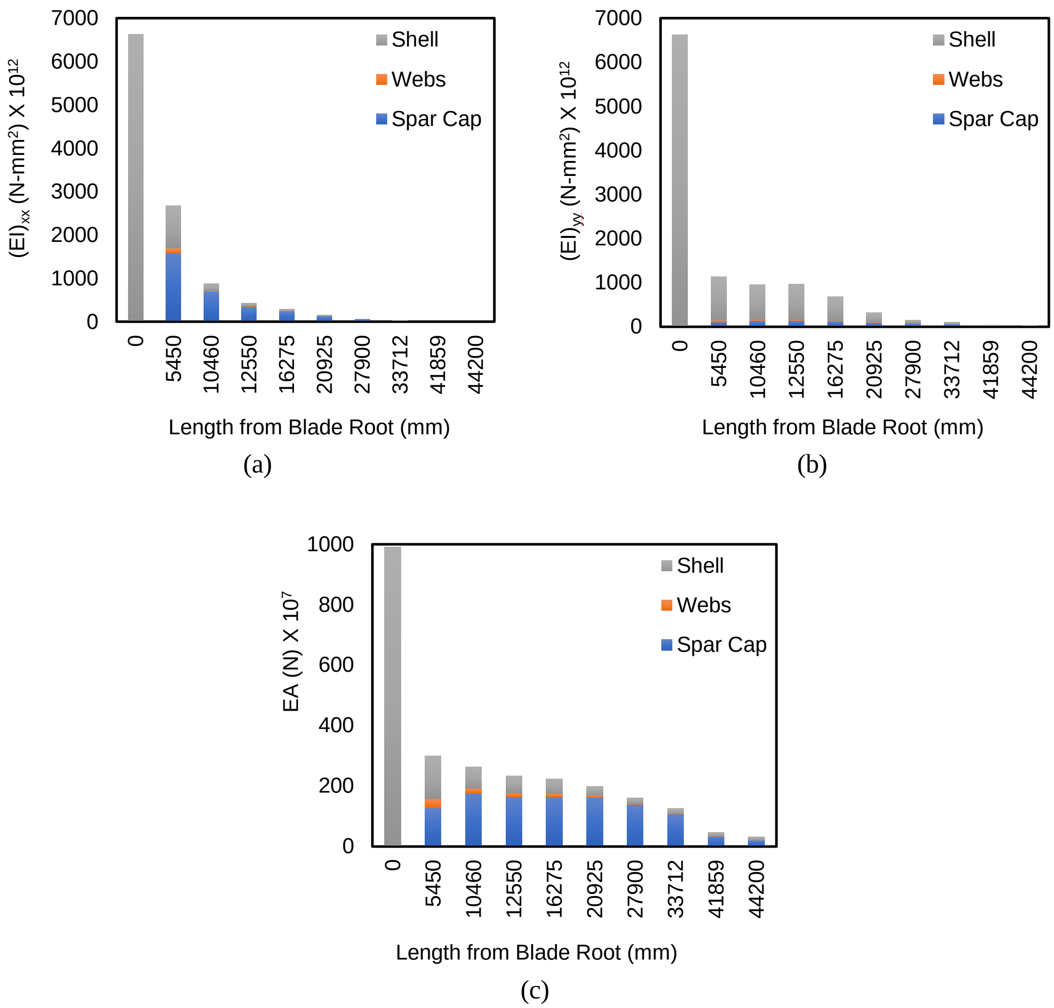
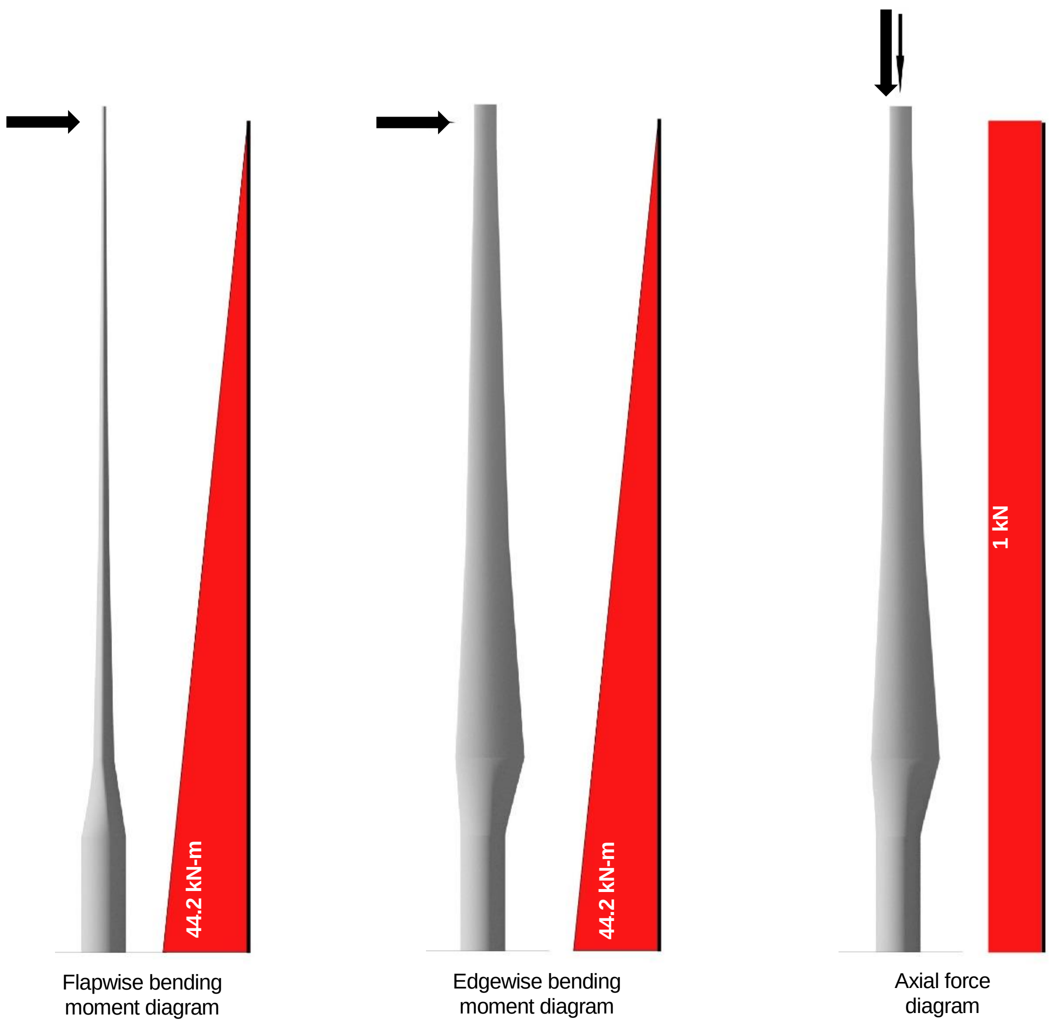


Figure 7. Stiffness distribution in the three primary sub-structures: spar cap, webs, and shell: (a) flapwise bending, (b) edgewise bending, and (c) axial.

STRESSES IN THE BLADE DUE TO BENDING AND AXIAL LOADS

To illustrate the unique behavior of wind blades under the applied static loads, the Clipper blade is fixed at the "zero" point (cantilever) and is subjected to a unit load (1 kN) in the flapwise direction (edgewise bending), in the edgewise direction (flapwise bending), and in the axial direction. These unit loads are applied separately at Station 10, where the spar cap ends, near the tip, and produce the bending moments and axial forces shown in Figure 8(a). The resulting maximum stresses in different components composing the cross-section of the wind blade are shown in Figures 8(b) and 8(c). The flapwise bending stresses are primarily carried in the spar cap, while the edgewise bending stresses are carried by the aerodynamic shell. The relative axial stiffness of the different parts of the cross section are shown in Figure 8(d), with the spar cap being the stiffest and the webs being the least stiff part. At the root end there are no separate parts as the webs, spar cap and shell merge.



(a)

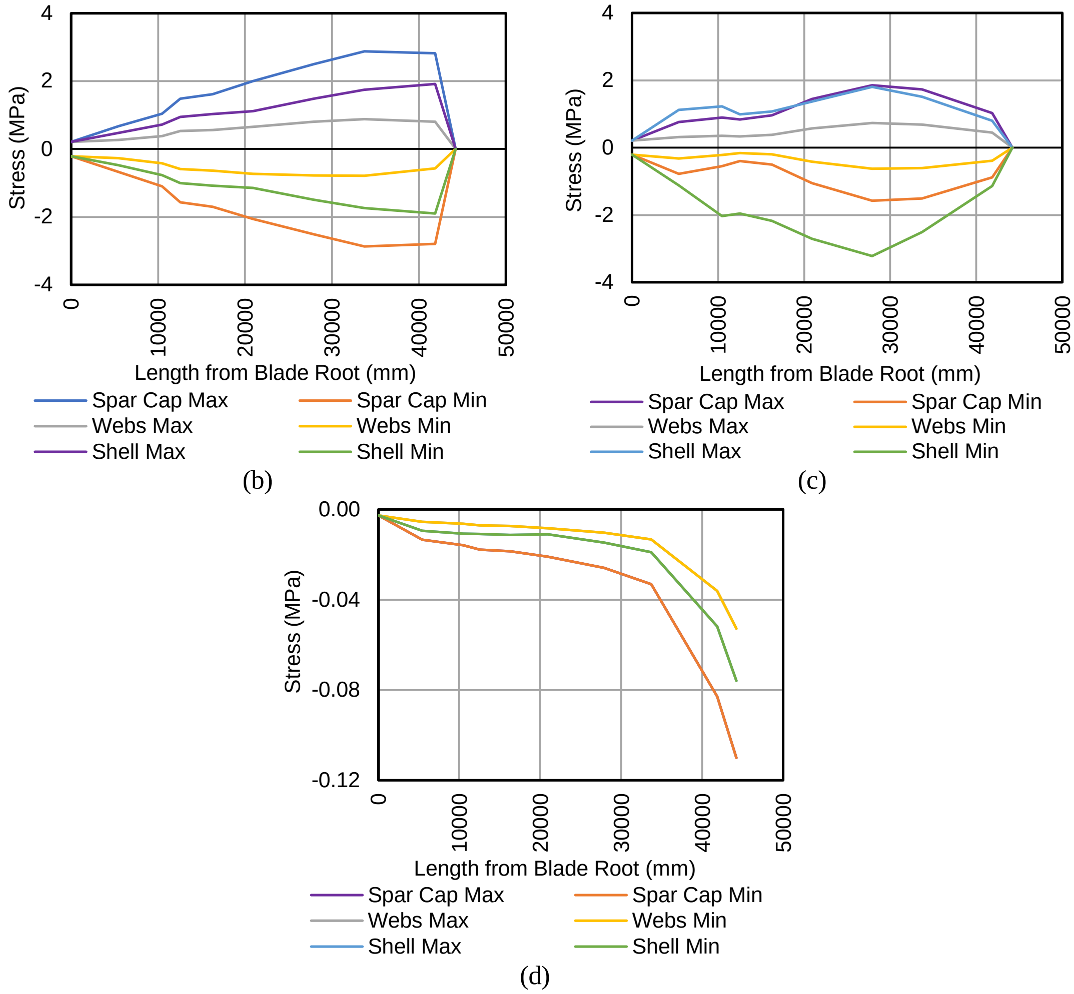


Figure 8. (a) Bending moment and axial force diagrams due to unit loads in the edgewise, flapwise, and axial directions, (b) Bending stresses due to flapwise bending, (c) bending stresses due to edgewise bending, and (d) axial compressive stresses.

Figure 8 reveals crucial findings that outlines the path forward for the structural analysis and re-design of wind blades. The results presented in Figure 8(b) demonstrate that the spar cap is the main contributor to the flapwise stiffness; those presented in Figure 8(c) indicate that the shell is the major contributor to edgewise stiffness. However, though the shell is stiff, it is not sufficiently strong based on first-ply failure. When such criteria are considered, the shell will likely be the limiting case for design – that is, elements in the shell, near the leading and trailing edge of the wind blade, will reach their limiting stresses first. But failure in the controlling ply in the shell does not constitute complete failure of the structure; once the first ply failure occurs, the spar cap will provide increasing strength in the edgewise direction – albeit with some stiffness reduction. A more complete consideration of the controlling failure modes will be the focus of future work. The results presented in Figure 8(c) demonstrate that axial stiffness decreases along the length of the wind blade, with higher stresses carried by the different components closer to the tip.

In addition, Figures 8(b) and (c) reveal sudden changes in the stresses between stations 3 and 5. The cause for these changes is reflected in Figure 2, which shows a transition of the airfoil from a circular section to an airfoil section between these stations. Thereafter the chord length (as defined in Figure 2) decreases linearly along the wind blade towards the tip and the stress transitions are smoother.

MATERIALS PROPERTIES OF WIND BLADE COMPOSITES

Laminates in wind blades can be characterized as either (*i*) primarily uni-directional; (*ii*) tri-axial $[\pm 45/0]_N$ with significant strength in the longitudinal direction and improved transverse and shear properties; or (*iii*) bi-axial laminates, $[0/90]_N$. The specific materials and fiber geometry used in commercial wind blades are proprietary. Manufacturers do not publish layups, material strengths or design allowable stresses. There are, however, national and international efforts to develop datasets of static and fatigue properties of reference wind blade materials. In the U.S., Sandia National Laboratory, Montana State University, and the National Renewable Energy Lab publish material property data for a range of wind blade materials using multiple resin and fiber suppliers [15]. In Europe, the OPTIMAT research program has created a similar database of reference materials that generally match those used in production wind blades in Europe.

Key material properties from the three OPTIMAT laminates are provided in Table I as taken from Nijssen et al. [14]. The significant figures in the table are exactly as taken from the reference and represent mean property data extracted from the OPTIDAT database.

PROPOSED ADAPTIVE RE-USE APPLICATION

The proposed adaptive re-use application is a three-phase electrical transmission tower for 60 to 130 kV sub-transmission lines (Figure 9). These poles are taller than the typical distribution poles in cities and suburbs, but are smaller than the cross-country towers used for the transmission of electricity directly from power plants. The proposal is to use approximately 21 meters of the tapering section of the blade with a supplemental frame for the three “phases” (the cables that carry the alternating current). Approximately two meters of the blade will be underground, with the portion of the blade underground encased in Portland cement concrete. The blade cavity in the underground section will be filled with concrete as well.

TABLE I. REPRESENTATIVE MATERIAL PROPERTIES
FROM THE OPTIDAT DATABASE [14].

Material	E_{11} MPa	E_{22} MPa	G_{12} MPa	ν_{12}	ρ kg/m^3	F_t^0 MPa	F_c^0 MPa
Uni-axial	38,887	9,000	3,600	0.249	1,869	810	507
Tri-Axial	24,800	11,500	4,861	0.416	1,826	436	349
Bi-Axial	11,700	11,700	9,770	0.501	1,782	180	144

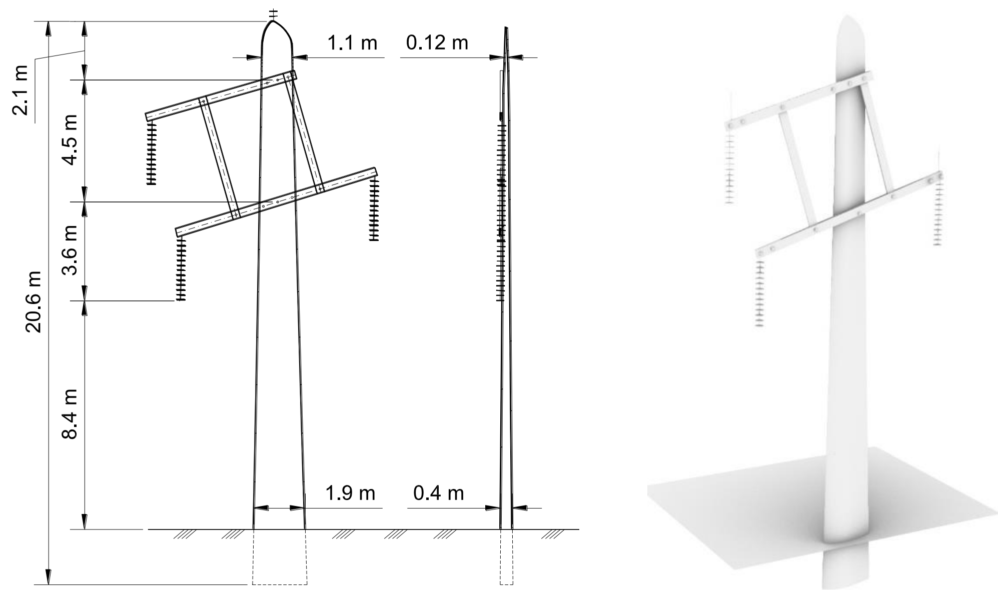


Figure 9. Conceptual prototype of the wind blade tip as a pole in a power transmission line.

ESTIMATED LOADS ON THE POLES

The loads on the utility towers are both axial and flexural, and the pole behaves as a cantilever, much like the blade in its original application on a wind turbine. The tip of the blade experiences some level of restraint from the steel shielding cables that run along the blade tip between adjacent towers.

There are well-established standards for the analysis of electrical transmission towers, with ASCE 74 [16] being the primary resource used in the United States. Individual loads that must be considered include self-weight of the tower and the supported electrical cables, the weight of ice collecting on the cables, the potential for non-concentric loading due to either unbalanced ice loading or broken conductors, and wind. The individual loads are applied in 16 combinations using load multipliers found in ASCE 74. A complete discussion of all load cases is beyond the scope of this paper. Rather, a discussion of two critical and controlling load cases is presented briefly.

The governing axial load combination of ice and wind leads to an axial force on the blade of 107.7 kN and a lateral load of 0.5 kN (distributed along the blade). The governing transverse wind loading combination (wind moving transverse to the direction of the electrical wires) leads to an axial force on the blade of 40.9 kN with a lateral wind load of 4.9 kN (distributed along the blade). For this initial screening assessment, the stresses can be computed as multipliers of the unit loads applied to the wind blade as depicted in Figure 8. The first load combination (ice and wind) will result in a maximum compressive stress of approximately 120 MPa in the wind blade. For reference, the compressive strength of a primarily uniaxial Glass-FRP is approximately 500 MPa (see Table I). The second load combination (transverse wind) results in a maximum compressive stress of 50 MPa which is also far less than the typical Glass-FRP strength.

From this first-order analysis, it is clear that the tower application has merit, and the strengths of the composite materials are likely to be sufficient to resist the global forces applied to the wind blade. Additional work will be needed to address issues of local and global structural stability, deflections due to wind and unbalanced gravity loads, and most importantly, the establishment of end-of-first-life material properties for second-life structural design.

SUMMARY AND CONCLUSIONS

This paper examines the feasibility of an adaptive reuse application of composite wind blades as primary support structures for electrical transmission towers. The results indicate that adaptive reuse of wind blades is feasible as an environmentally-preferable alternative to disposal of these advanced structures. Section stiffness values were determined at multiple stations along a C96 Clipper blade, and the contributions of each component part to the overall section stiffness at each station were highlighted. A simplified static analysis of critical load cases taken from governing ASCE Standards indicated that the blade structure could easily resist the expected loading for this application. The present work is aimed at developing reliable and rigorous analysis and design procedures for these novel structural elements, to allow for their re-use in civil infrastructure applications, instead of being disposed of. Future work in this area will focus on the experimental validation of critical material and section mechanical properties, as well as full-scale physical tests for each potential reuse application.

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