WindAid 1.7 Wind Turbine Blade

Comparative Mechanical Testing Methods

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Abstract

As part of the blade manufacturing process improvement cycle undertaken at WindAid in the summer of 2026, a research and testing campaign into the blade's material composition and mechanical properties was requested. WindAid requested a study of known or suspected failure modes of WindAid 1.7 blades deployed in Northern Peru and the construction of a test plan which can quantify the effects of design and material changes on these blades. To satisfy the requirements for the study, a Failure Modes and Effects Analysis (FMEA) was completed, and, for failure modes where the blade material was considered to be a contributing or mitigating factor, testing is suggested, along with desired results and communication.

Background

Failure Modes and Effects Analysis

Daniel Infantes and Jonathan Behrens compiled an initial FMEA for the WindAid 1.7 blade, following input from Sr Abel. Primary sources for the analysis were recovered parts, which were discovered to have failed or be failing after being installed, and an assessment of the labour and manufacturing capabilities available to WindAid. High RPN failure modes (defined as an RPN above 100) were blade breakup from a strike/impact, fatigue wear forming stress cracks in the blade, and a bearing failure leading to contact between the rotor and stator. This last failure mode may be exacerbated by manufacturing defects in the blade, but also has many other contributing factors; thus, the primary scope of mechanical testing is to be defined as assessing the material's susceptibility to impact, continuous bending loads, and cyclic bending fatigue. Specific causes for these failure classes and the methods to quantify sensitivity are detailed for each failure class below, as well as means of documenting and comparing the results of various designs subjected to this testing.

Pugh Matrix

An industry standard for comparative testing, a Pugh Matrix is a simple calculation for the efficacy of design changes along a variety of performance metrics. The proposed matrix composed throughout this report measures the mechanical metrics necessary for this evaluation, but expanding the tool to cover economic, material, complexity, or other important characteristics of the design is recommended to generate a fuller picture of the design's efficiency.

The Pugh matrix consists of a chart with rows comprised of criteria critical to the design. Each criterion is then given a weight from one to five. This expresses the importance of this criterion relative to others. The third column of the chart is the baseline, or the current design. This is given a zero in all categories. Lastly, the further columns of the chart each measure whether a design improves (+1), has no impact (0) or worsens (-1) the blade's performance in the criteria. The final row of the table then contains the sum of each design, multiplying each 1, 0 or -1 by the criterion's weight to achieve a positive or negative "score" for the design. Table 1 Demonstrates the empty Pugh Matrix set forth by this report. The "Example" reference demonstrates how even a design which fails the most significant category can be considered an improvement to the design if it is superior in many other criteria.

Table 1: Testing Pugh Matrix with a sample improvement

Criterion	*Description*	*Weight*	*Current*	*Example*
Impact Resistance	Blade does not fracture during impact loading	5	0	-1
Freewheeling	Strength in tension	2	0	1
Bending Strength	Correlation of structural and material strength	4	0	1
Mechanical Fatigue	Cycle life estimated from UTS	1	0	0
Total			***0***	***1***

Throughout the report, the weights and methods for determining each criterion's score will be discussed.

Impact Loading

Impact Testing Rationale

A primary concern of WindAid is the potential for injury caused by an event (such as a bird strike) leading to the separation of the blade into parts. Several strikes have been reported in the history of deployments, although none have led to injuries. As such, constructing an accurate simulation of an impact scenario is key to confirming the blade's longevity. Traditional Izod or Charpy testing rigs, utilising a falling hammer, are not compatible with the composite structure of a WindAid 1.7; thus, this method aims to gather required data without the creation of a bespoke testing rig and the purchase of expensive measuring equipment.

Data Collection and Output

Required Output

The minimum information required to certify a blade is a simulated bird strike where no pieces of the material large enough to cause harm separate from the blade. The mass of a projectile which can be used to simulate a bird is defined under ASTM F330-21, which utilises three classes of birds (small, medium, and large) as 2 lbs (0.91 kg), 4 lbs (1.81 kg), and 8 lbs (3.63 kg). This is the extent to which this standard applies to the required testing setup, as it governs aerospace transparencies but is the nearest available standard and assists in problem definition. Specifying the impact velocity desired is based on the operational conditions of the WindAid 1.7, as found in data analysed from two installations in the Salpo community of La Libertad, Peru. From both installations, the maximum 10-minute average wind speeds recorded approached 7.5 m/s, assuming that both the speed of the bird is negligible compared to the turbine's speed, and that the turbine is operating at its optimal tip-speed ratio of 7, the speed of the blade tip will be 52.5 m/s, and the speed at the midspan 26.25 m/s. These numbers provide reasonable estimates for worst-case bird strikes. The impact energy for each of these is shown on Table 2.

Table 2: Impact energy for bird size and impact location

	Blade Tip	*Midspan*
Small Bird (.91 kg)	1.254 kJ	313 J
Medium Bird (1.81 kg)	2.494 kJ	623 J
Large Bird (3.63 kg)	5.002 kJ	1.251 kJ

Testing Criteria

Simply, the impact test must consist of a 5 kJ (calculated worst case) impact at the blade tip and a 1.25 kJ impact at the midspan. The impact should be conducted either directly on the leading edge, or if possible, trigonometric calculations should be conducted to determine the angle of impact. Success in this test will be defined as:

1. The blade shedding no pieces greater than 1 cm^2 during either impact, and
2. No cracks on any blade surface resulting from either impact.

This may be considered a 0 (No Improvement) on the Pugh Matrix; any design which fails to meet this threshold shall be considered a -1 (Worsened). Further comparative testing shall consist of a means of generating a point impact load at one or more predetermined locations on the planform and measuring the energy absorbed by the blade during that impact by measuring excess energy in the loading device. An immediate failure of this test would still be determined by the above criteria, but a well-designed testing machine would generate a numeric output from this test, thus enabling -1, 0, and 1 results to be issued by comparing the absorbed energy to the baseline (current WindAid 1.7 design).

Freewheeling and Fatigue Failure Modes

Tensile Testing Rationale

Under normal conditions, the blade's survivability and operating parameters will be governed by its bending strength. When the blade undergoes freewheeling, or spinning without load, or in fatigue, these parameters can be approximated by tensile capacity. The shear loads, which are borne by the blade as large tensile or compressive loads in the outer carbon fibres of the blade, especially in fatigue combinations, create large strains at the blade root.

The uniaxial tensile test directly measures the in-plane tensile strength, tensile modulus, and failure strain of the composite laminate. These are fundamental material properties that underpin all structural analysis of the blade. Since WindAid sources materials from multiple vendors, the tensile modulus and strength are the most direct indicators of fibre volume fraction, fibre alignment quality, and laminate consolidation achieved during manufacture. Changes in any of these manufacturing variables will produce measurable changes in tensile properties. The test is conducted per ASTM D3039/D3039M, the governing standard for uniaxial tensile testing of continuous-fibre polymer matrix composites.

Data Collection and Output

Specimen Preparation

Flat rectangular coupons are cut from various predetermined locations in the blade. The standard specimen is 250 mm long and 25 mm wide with a constant rectangular cross-section; no waisting is required for fibre-reinforced composites as in metallic tensile specimens. The thickness of the section should be 2 mm, since the 2x2 weave of fibre used may be considered a multidirectional laminate. If end tabs are required, the gauge length between tabs is to be a minimum of 100 mm. A minimum of five specimens is required, taken from different sides and surfaces of the blade.

Tensile Testing Criteria

The primary output of the tensile test is a stress-strain curve for the blade, standardised from the five samples. This curve provides the ultimate tensile strength, yield strength, failure strength, and Young's (elastic) Modulus. Compared to the stress-strain curve of the current WindAid 1.7 design, a 1 (Improved) score may be achieved by a design with an increased tensile strength and yield strength, or a greater

toughness (area under the stress-strain curve). Likewise, a -1 is issued where either of these criteria is decreased.

Fatigue Calculation Criteria

The uniaxial tensile test serves as the foundation for a broader fatigue characterisation. The static test is run as written on five coupons, yielding ultimate tensile strength σ_u, tensile modulus E, and failure strain ε_f. These values anchor the S-N curve, which describes how the material's strength degrades with cyclic loading through the power-law relation:

$$\sigma_{max} = \sigma_u \cdot N^{(-1/k)}$$

Where N is cycles to failure and k is the fatigue exponent (a material constant, typically 10 for glass-fibre/epoxy and 20 for carbon-fibre/epoxy). Because the blade experiences a non-zero mean stress from centrifugal loading rather than fully reversed cycling, the S-N curve is corrected using the modified Goodman relation:

$$\sigma_a = \sigma_e \cdot (1 - \frac{\sigma_m}{\sigma_u})$$

Which reduces the allowable cyclic amplitude σ_a in proportion to the mean stress σ_m, with σ_e taken from the S-N curve at the target design life cycle count (10^7 to 10^8 cycles for a small wind turbine). Estimated service lifetimes are to be compared with those of the other designs, with a substantial factor of safety to account for variable loadings. A 1 is given to a design with an improved cycle life, and a -1 for a decreased cycle life. If Miner's equations or other correction factors for random loadings are used, every design must be reevaluated against this same standard.

Bending Failure Modes

Bending Testing Rationale

During operation, the wind turbine blade may be treated as fixed in the centre (hub) and free at its ends. The lift forces which cause the blade to spin also contribute to a distributed shear load along the planform, which is highest at the blade tip. This produces a predominantly bending load, which is the typical load condition for the blade. Thus, quantifying the elasticity and bending properties of the blade is key to understanding its operation.

Data Collection and Output

A force-displacement plot of the blade, detailing the response of the full span of the blade for masses from 100 g until failure. The precision of these measurements is not critical but must be consistent throughout tests. The force-displacement plot should indicate clearly a region of elastic deformation, wherein the linear fit is approximately the elasticity (in pascals) of the blade.

In ideal circumstances, this elasticity should be very similar to the Young's Modulus determined in the tensile testing of the resin/carbon fibre composite. If differences in these values (and the greater shape of the plot) exist, this is an indicator of undesirable failure mechanisms under bending. These could include anisotropic buckling within the composite shell, delamination of the shell from the core material, or failures within the matrix due to the geometric loading of the bending test. Thus, designs exhibiting notably different (especially weaker) bending responses to the tensile test should be considered a failure to improve (-1). Strong correlation between bending and tension typically will indicate a higher level of manufacturing quality, and demonstrates that the blade is operating in a manner which accords with its design, carrying

almost all load in the stronger shell material. If a design change has a stronger correlation to the tensile data, it may be given a 1 for having improved the blade's structural capacity relative to its material strength. Similar correlation to the current design is, therefore, a score of 0.

Conclusion

These testing methods establish a systematic design for the evaluation of modifications to the WindAid 1.7 wind turbine blade. The mechanical testing proposed establishes clear baselines and qualitative comparisons for these modifications, quickening and standardising communication and implementation. Utilising the Pugh Matrix improves design transparency and allows shareholders a clear, objective lens for evaluating the decisions being made when changes are suggested, without requiring elaborate testing schemes or field installation of unproven hardware.

Beyond mechanical certification, the Pugh Matrix suggests the consultation of a broader host of factors governing the implementation of improvements to WindAid's blades. Material availability, cost, time and ease of manufacturing may all be easily considered within the methodology proposed. Furthermore, when circumstances require or allow so, additional criteria based on environmental testing, thermal properties, or generator efficiency may all be assessed by a standard rubric which strictly compares the designs by numeric methods.

This document is meant to provide a foundation for mechanical testing, validation, and broader transparency within the blade design process for the WindAid Institute. From the requirements illustrated, the implementation of these tests may proceed in a repeatable fashion that supports clear decision-making on relevant objectives.