

Wind Turbine Blade Trailing Edge Structural Design

Sambamurthy Saravakota¹

¹Mechanical Engineering, Renewable Energy, India.

Abstract - Wind turbine blades are the critical components of wind turbines, converting wind's kinetic energy into mechanical energy, which is then transformed into electricity. The efficiency of this process largely depends on the blades' structural design. Among the various structural elements, the blade trailing edge is crucial for blade performance as it is subjected to edge driven loads, which are due to blade own weight. In addition, Trailing edge is more critical for aero performance and noise reduction. This paper describes the potential standard design methods implemented in existing blade designs and associated challenges. In addition, this paper describes the design enhancements of trailing edge to cope up with the latest blade design requirements.

Key Words: Wind turbine, wind blades, trailing edge, structural design, aero performance.

1.INTRODUCTION

Wind energy has emerged as a cornerstone in the global shift toward renewable energy sources. As nations and communities strive to reduce their reliance on fossil fuels, wind turbines have become increasingly prevalent. With the growing adoption of wind power, there is an urgent need to maximize the performance of wind turbines while simultaneously minimizing costs and environmental impacts.

As the demand for higher energy output from wind turbines grows, manufacturers have responded by increasing the length of turbine blades. Longer blades allow turbines to sweep a larger area and capture more wind energy, thereby boosting power generation. However, this increase in blade length leads to a corresponding rise in both aerodynamic and gravitational loads acting on the blade structure. Aerodynamic loads refer to the forces exerted by the wind on the blades as they rotate. Longer blades experience higher wind forces because the area exposed to the wind increases. These forces can cause greater bending and twisting stresses, which the blade must be designed to withstand throughout its operational life. Gravitational loads are the forces due to the weight of the blade itself. As blade length increases, so does its mass, resulting in higher gravitational stresses, especially when the blade is in a horizontal position. These stresses contribute to the overall fatigue experienced by the blade material over time.

To meet these demands, a more robust approach is necessary during the blade design, operation, and maintenance phases, which include advanced materials, better structural design and rigorous testing validation etc.

2. Trailing Edge design and loading

Typically, trailing edge constitutes adhesive joint to connect both pressure side and suction side shells of aerofoil configured wind blades, which could result in failures including trailing edge adhesive joint debonding and cracking and buckling. The curved trailing edge panels are more vulnerable to breathing due to a torsional load caused by the Brazier effect. The repeated inward and outward bending of the trailing edge panels increases the peel stresses on the adhesive at the edges of the trailing edge. In addition, the out-of-plane deformation of the trailing edge can alter the blade's desired airfoil geometry leads to significant aerodynamic issues like flow separation, wake dynamics and there by variable aero performance. The breathing effect could influence the altering the flow and leads to acoustic noise emissions.

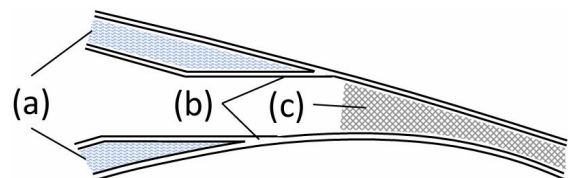


Fig -1: Trailing edge components: (a) Foam/balsa core; (b) composite laminate; (c) adhesive [1]

Trailing edge failures have also been reported by several researchers in the past as described in [2-6]. The specific failure mode attributed to either extreme or fatigue loading conditions. In addition to extreme and fatigue loading, the trailing edge of a wind turbine blade may subject to complex loads from various environmental and operational factors. Environmental factors like impact from foreign objects, rain erosion, ice accumulations, lightening strikes and temperature variations etc. On the other hand, operational factors could be manufacturing process defects and transportation damages etc. However, the scope of the present paper is dwell into failure modes occurring from extreme and fatigue loading conditions only.

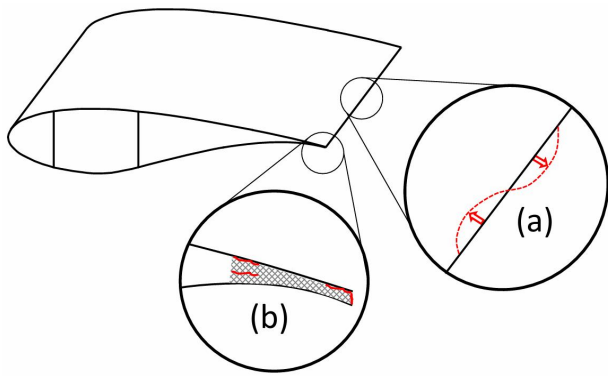


Figure 1. Trailing edge failures: (a) buckling; (b) debond [1]

2.1 Failure modes due to extreme loading conditions

Buckling could be one of the more prominent failure modes expected in trailing edge under extreme loading conditions. In general, buckling failure mode can be assessed in full blade testing as global failure mode while blade is subjected to extreme loading. Ghasemnejad et al. [7] tested coupons of wind turbine trailing edge composite material to failure to examine the structural response during post-buckling.

2.2 Failure modes due to fatigue loading conditions

In general, bond line cracks appear during fatigue loading of the trailing edge bond line joint as the glue material is weaker in fatigue performance compared to trailing edge laminate. This failure mode is more evident while the blade is tested under single axis fatigue loading in edge direction, which is IEC requirement for blade certification [8]. During a fatigue certification test of an 81.6 m blade, Rosemeir et al. [9] reported trailing edge transverse and longitudinal cracks initiation at both the inner and outer adhesive edges.

Considering these more common trailing edge failure modes, one should focus more rigorously on future design of trailing edge region mainly to address these issues to avoid the turbine down time. In additional research, Haselbach et al. [10] examined methods to improve trailing edge design using foam inserts, resulting in increased buckling resistance.

3. Trailing Edge design insight from current blades

During operational conditions, the trailing edge can experience buckling and cracking failure modes.

3.1 Buckling failure mode

The buckling failure mode appears with the thinner/weaker core materials & face laminates in sandwich panels. While the blade is subjected to repair, the skin laminate and/or core can be exposed to excessive grinding and leads to thinner materials than the design intent. This undesirable grinding operation leads the trailing edge becomes structurally unstable. When the blade chord length increases, the trailing edge panels become wider and may experience buckling under operational loads due to being unsupported.

3.2 Trailing edge bond line cracks

The multiple cracks can originate and progress either in the laminate or through the trailing edge joint until final failure where the joint can no longer take further loading. Cracks within the laminate can be correlated with the standard failure theories like Hashin failure criteria, Tsai-Hill and Tsai-Wu criteria etc. On the other hand, cracks can propagate through the interface of the composite laminate and adhesive material. This type of interface failure modes is in general assessing through fracture mechanics principles like Mode 1 (opening), Mode 2 (sliding) & Mode 3 (tearing). These modes often appear in combination, causing cracks in the adhesive bond line that can propagate to the composite laminate and foam core.

For the trailing edge, Mode1 failure is in general caused by the opening of trailing edge panels. Mode1 causes delamination or interface cracking between laminate and adhesive. Manufacturing defects like bond line voids or thicker bond lines can create high internal stresses, which lead to micro-cracks that propagate in Mode1. Even after local skin buckling, mode 1 tensile loading can cause further debonding and delamination in the trailing edge sandwich structure.

Edge wise fatigue loads can cause high shear stresses in the laminate and adhesive and lead to mode2 sliding failure at interface. This sliding Mode2 crack can occur in combination with Mode 1 as well and influence crack growth direction.

Mode 3 i.e. tearing mode results due to out-of-plane shearing motion, where the crack surfaces slide relative to one another parallel to the crack front. In general combine loads contribute to mode 3 fracture. Buckling-induced failure mode generally triggers mode3 failure mode and can lead to catastrophic failure.

3.3 Resin system in blades

The choice of resin system has a significant impact on the sensitivity of the TE to different crack modes, primarily due to differences in fatigue performance and fracture toughness. In general, epoxy resin systems are more resilient than Polyester resin systems to all crack modes due to their higher fatigue resistance and fracture toughness. So, the Trailing edge bond line in polyester blades is a high-risk area for fatigue damage and hence needs more stringent manufacturing control and more frequent blade inspection.

Table -1: Sensitivity to epoxy vs. polyester resin systems

Characteristic	Epoxy	Polyester	Implication for TE
Fatigue performance	High	Low	Polyester is weak under the cyclic tensile loads (Mode I) from the TE breathing effect
Fracture toughness	High	Low	Epoxy is more resistant to TE crack propagation

3.4 Trailing Edge adhesion

The trailing edge joint has another critical design variable is bond line dimensions such as bond width. Thickness and percentage of adhesive filling etc. Investigation into bond line thickness effects demonstrated that fracture toughness decreases with thickness [11]. Thinner bond line makes the joint flexible and yield more fracture toughness. Tomblin et al. [12] tested different adhesives with varying thicknesses and observed decreased shear strength with the thicker bond line. Thick bond lines weaken joint loads and increase the likelihood of void content in the joint. Rafiee and Hashemi-Tahero [13] conducted a finite element analysis on the trailing edge joint with various bond line widths and reported a change in failure mode from cohesive for short bond line widths to adherent delamination in large bond line widths.

3.5 Trailing edge Design simulations

Although it is difficult to precisely capture bond line dimensions in the trailing edge joint, the finite element formulation significantly affects joint behavior. Based on several studies, trailing edge panels with shell elements and bond lines with solid elements is recommended [14-15]. Detailed sub-modelling can aid complex trailing edge finite element simulations but is often computationally costly.

3.6 Trailing edge Testing limitations

In contemporary blade design procedures, buckling assessment of the trailing edge often necessitates costly testing since it can result in blade failure. Consequently, there are restricted opportunities to validate the buckling failure mode of the trailing edge. Validation of adhesion cracks remains incomplete because current tests cannot load critical trailing edge areas without exceeding safe limits elsewhere, which causes other failure modes to dominate.

4. Design improvements in trailing edge

The prior section outlined current design issues with trailing edge joints in wind blades. This section outlines possible ways to address the above design challenges.

4.1 Design for buckling

The structural stability of the trailing edge can be improved by strengthening the sandwich panels with thicker core materials surrounded by thick face sheets. Adding stiffeners to trailing edge can also enhance structural stability.

General stiffener types are:

- Foam inserts in buckling-prone regions
- Composite stiffener strips integrate with the skin laminate
- Web based stiffeners which distribute shear loads effectively.

4.2 Design for bond line cracks in trailing edge

To design against bond line cracks in trailing edge, focus on using tougher and fatigue-resistant adhesives, consider adding biaxial interfacial layers between unidirectional layers to prevent crack propagation.

4.3 Trailing edge design modeling improvements

The proper modeling of the trailing edge including adhesive distribution helps in estimating the more accurate stress flow and can be addressed by adding more reinforcements. It is necessary to account for shell to solid element connections because their varying degrees of freedom may affect load distribution.

4.4 Trailing Edge Testing Improvements

Single-axis loading in the edge direction may not produce the desired damage if non-orthogonal load cases drive the critical failure mode. Testing in the critical design load direction validates the failure mode more effectively within a limited testing scope.

5. CONCLUSIONS

The trailing edge joint is challenging to reinforce due to limited access for adding materials, especially as blade length increases and edge-driven loads become more significant. Design improvements such as stiffeners, enhanced material choices, and revised architectures may offer more effective solutions.

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