

Modal-Feature-Based Detection of Localized Structural Damage in Large Wind Turbine Blades

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ABSTRACT

Vibration-based prognostics and health management (PHM) of large composite wind turbine blades requires damage-sensitive features that are both globally observable and spatially diagnostic for localized damage. Natural frequencies, the most commonly used vibration indicators, are global by construction and may be insensitive to localized stiffness changes in large composite structures. Higher-order mode-shape derivatives offer theoretical advantages, but they have not been systematically compared on a reference-scale composite blade under controlled damage parametrization. This dissertation develops a parametric framework that introduces localized stiffness degradation at the composite-layup level and compares natural frequencies, mode shapes, and their spatial derivatives across a structured matrix of damage cases. Preliminary results show that frequency shifts remain below 1% for most mode–case combinations involving spatially localized stiffness degradation, while curvature-based indicators provide the strongest spatial signatures only in specific mode-and-component combinations. Selected curvature signatures also remain stable under the single rated-speed rotating condition examined. The remaining program expands the damage matrix, refines the derivative-extraction step, and cross-validates the beam-level results against shell-element models. The resulting features will then be evaluated as candidate inputs for prognostic modeling.

Keywords: Wind turbine blade, Structural health monitoring, Localized damage, Modal analysis, Mode shape curvature

1. INTRODUCTION AND PROBLEM STATEMENT

Wind energy is a central pillar of the global low-carbon energy transition, and offshore deployment in particular continues to grow as turbines move into deeper water, larger rotor diameters, and longer service lives. The blades of these machines are among their most consequential structural components: they capture aerodynamic energy, carry highly variable loads over decades of operation, and dominate both operations-and-maintenance (O&M) cost and downtime risk (Du et al., 2020). It is increasingly important to ensure the integrity of blades through condition-based monitoring as they become longer and more complex, especially offshore, where inspection access can be restricted, weather-dependent, and costly.

Blades are vulnerable to multiple damage mechanisms, such as delamination, matrix cracking, adhesive-joint failure, shear-web debonding, and leading-edge erosion, most of which originate as small, spatially confined defects before propagating into structurally significant damage (Ciang, Lee, & Bang, 2008; Du et al., 2020). From a Prognostics and Health Management (PHM) standpoint, this means the diagnostic challenge is not merely to detect catastrophic damage but to identify localized damage early enough to enable condition-based maintenance and to support prognostic estimates of remaining useful life. Vibration-based monitoring is widely regarded as well suited to this purpose because it is non-invasive, global in coverage, and compatible with the accelerometer instrumentation already present in many large turbines (Ciang et al., 2008; Griffith, 2015).

A fundamental limitation is that natural frequencies, the most commonly used vibration-based feature, are global indicators that may not respond to localized stiffness changes in large composite structures. This creates a clear PHM gap: practitioners need damage-sensitive features that retain global

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observability while preserving enough spatial information to localize damage along the span. Mode shapes and their higher-order spatial derivatives, especially curvature, are theoretically attractive candidates (Fan & Qiao, 2011; Pandey, Biswas, & Samman, 1991; Wang, Liang, & Xiang, 2014), but few studies have systematically compared their relative sensitivity within a consistent framework on a reference-scale composite blade under controlled damage parametrization and both stationary and rotating conditions.

This dissertation addresses that gap. The overarching research questions are:

- (Q1) Which modal indicators are most effective for diagnosing localized damage in a large composite wind turbine blade, and how does that ranking change with the structural pathway perturbed by the damage?
- (Q2) How does damage detectability vary with damage severity, affected structural region, spanwise location, and operating condition (standstill vs. rotation)?
- (Q3) How can the most diagnostic features from Questions 1 and 2 be characterized as candidate inputs to a PHM workflow for damage-progression monitoring and condition-based maintenance decision support?

The work is computational at present and is anchored on a high-fidelity composite-layup-level reference blade model, with prognostic extension planned and experimental validation pursued as resources and project collaboration permit.

2. EXPECTED NOVEL CONTRIBUTIONS

The dissertation is expected to advance vibration-based PHM of large composite wind turbine blades through four contributions:

- C1.** A reproducible parametric framework for isolating localized damage at the composite-layup level on a reference-scale blade. The framework defines a structured case matrix that varies damage severity, affected structural region, spanwise location, and operating condition, with each case implemented as material-property knockdowns within a high-fidelity composite layup model and consistently propagated to a reduced-order modal solver. Preliminary results from the healthy baseline and nine damaged configurations indicate that the framework can discriminate among cases whose global signatures are otherwise nearly indistinguishable.
- C2.** A comparative ranking of modal indicators for localized blade damage within a single consistent framework. While frequency, mode-shape, and curvature-based methods have each been studied in isolation (Fan & Qiao, 2011; Pandey et al., 1991; Wang et al., 2014), few comparative studies have been performed on a

reference-scale composite blade with controlled damage parametrization. Preliminary results suggest that curvature-based indicators are more spatially diagnostic than displacement-level mode shapes or frequency shifts alone, but that this advantage is mode and component-dependent rather than uniform across the modal hierarchy.

- C3.** Identification of mode-and-component selection as a methodological choice for indicator extraction. A preliminary finding is that diagnostic information in coupled modes can be carried almost entirely by one motion component. At the same time, another component may remain effectively silent, and some modes carry their damage signature predominantly in a secondary, non-dominant motion component. This suggests that derivative-based monitoring of coupled modes should be component-resolved rather than aggregated, with implications for sensor placement and signal processing in field deployment.
- C4.** A PHM-oriented bridge from indicator sensitivity to prognostic feature selection. The diagnostic features identified through C2 and C3 will be characterized along three axes relevant to deployment: stability under representative measurement noise, sensitivity bounds across the parametric case matrix, and sensor-placement implications arising from the component-resolved findings in C3. These evaluations will identify which modal features remain usable once measurement noise and realistic sensor placement are taken into account. The same feature set will then support preliminary inverse mapping from simulated modal responses to damage location and severity, which is most valuable on offshore platforms where inspection access is constrained.

3. RESEARCH PLAN

The remaining approximately 2.5 years of the doctoral program build directly on the parametric framework and preliminary indicator-comparison study completed to date. The plan is organized in three phases: completed work and preliminary results, in-progress work, and proposed work for the remaining program.

3.1. Phase 1: Completed Work and Preliminary Results

A reference-scale composite wind turbine blade, approximately 63 m in span and 16.4 tonnes in mass, was modeled using a publicly documented IEA Wind reference platform (Bortolotti et al., 2019). The blade geometry, full composite layup, and segmented structural region definitions were implemented in a layup-level preprocessor (Berg & Resor, 2012), and the sectional stiffness and mass distributions were transferred to a coupled flap-lag-torsion-axial beam solver (Bir, 2005) for stationary (0 rpm) and rated-speed rotating (11.75 rpm) modal analyses.

A structured matrix comprising the healthy baseline H0 and nine damage cases, C1–C9, was defined within this framework, as summarized in Table 1.

Table 1. Parametric damage cases used in the present study

Case	Affected regions	Reduction	Notes
H0	—	—	Healthy baseline
C1	Shell skin	$0.1 \times$	Surface laminate only
C2	C1 + LE/TE reinf.	$0.1 \times$	Reinforcement added
C3	C2 + balsa core	$0.1 \times$	Core added
C4	C3 + spar caps	$0.1 \times$	Full through-thickness
C5	C3 + spar caps	$0.1 \times / 0.5 \times$	Moderate spar-cap severity
C6	C3 + spar caps	$0.1 \times / 0.8 \times$	Mild spar-cap severity
C7	As C5	$0.1 \times / 0.5 \times$	Inboard station only (19–20)
C8	As C5	$0.1 \times / 0.5 \times$	Outboard station only (20–21)
C9	As C5	$0.1 \times / 0.5 \times$	Rotating at 11.75 rpm

The elastic properties of selected composite regions, including the shell skin, leading- and trailing-edge unidirectional reinforcement, balsa core, and spar caps shown in Fig. 1, were reduced to controlled fractions of their baseline values.

Damage severity is varied parametrically across the matrix. The initial cases reduce the elastic constants of the shell skin and reinforcement to 10% of baseline. Intermediate cases additionally degrade the balsa core, and the most severe cases extend the degradation into the spar caps. Spar-cap residual stiffness is varied in a graded sequence of 80%, 50%, and 10% of baseline to control load-path involvement.

The case matrix varies damage severity, affected structural region, spanwise location, and operating condition; all cases use a common 2.52 m damage window centered near 26% blade span. Extracted indicators comprise natural frequencies, the first seven coupled flapwise, edgewise, and torsional mode shapes, and their spatial derivatives from sixth-order polynomial fits.

Mechanism. Localized damage produced spatially confined reductions in the affected sectional stiffness terms, as summa-

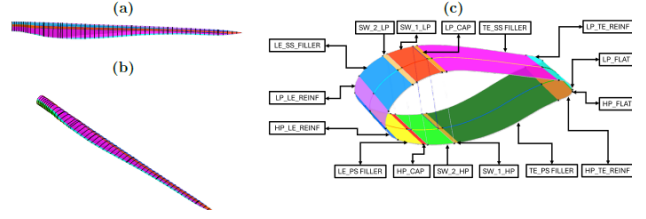


Figure 1. Representative composite-blade cross-section showing the segmented structural regions used for localized damage definition.

rized in Fig. 2. Torsional stiffness was the most consistently and severely perturbed property across the case matrix, even for cases in which the spar caps were not involved, while flapwise stiffness responded most strongly once spar-cap participation was activated.

Indicator sensitivity. Natural-frequency shifts remained below 1% for most mode–case combinations and were unable to discriminate reliably between damage at adjacent spanwise stations. This indicates that frequency-based screening alone is insufficient for detecting and distinguishing localized damage with limited global modal influence (Doebling, Farrar, & Prime, 1998; Fan & Qiao, 2011). Table 2 lists the shifts for three representative cases, from shell-only damage (C1) to moderate spar-cap involvement (C5).

The location-restricted cases C7 and C8, in which the same damage pattern was confined to station pair 19–20 or 20–21, respectively, made this limitation concrete. The frequency differences between the two cases were a few tenths of a percent at most. The spatially resolved indicators did track the shift because the localized stiffness reduction moved with the imposed damage window.

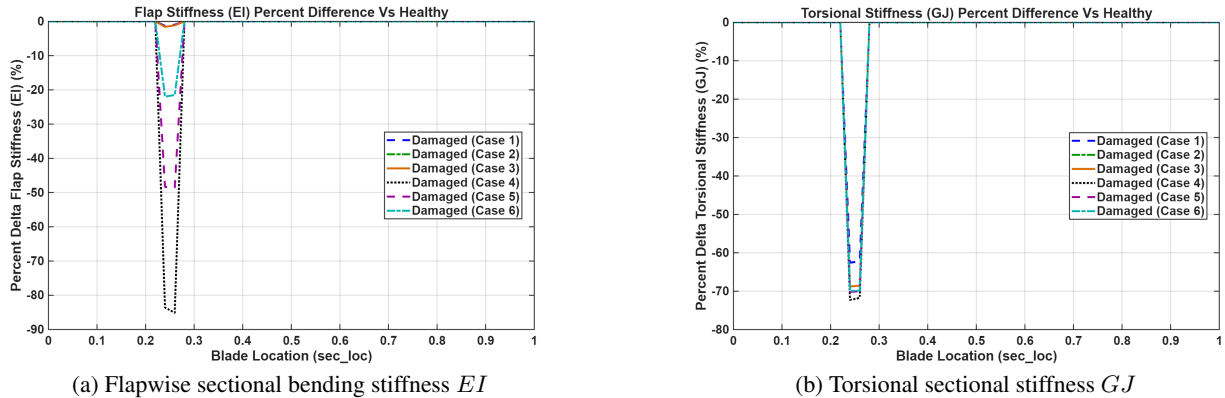


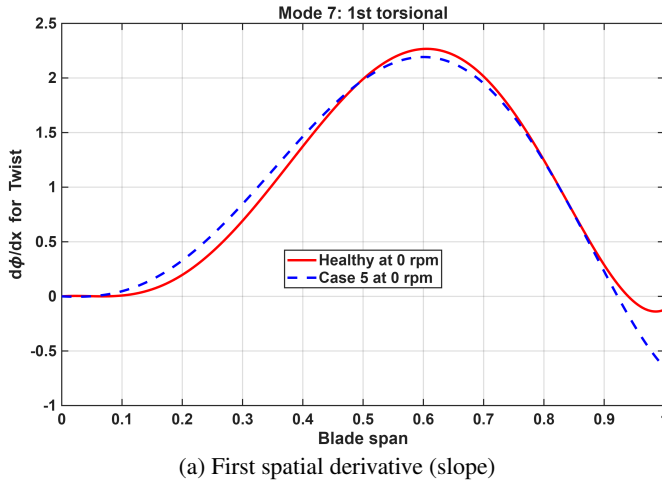
Figure 2. Spanwise percent change in (a) flapwise sectional bending stiffness EI and (b) torsional sectional stiffness GJ relative to the healthy baseline, for damage cases C1–C6.

One qualification applies to all of the spatial indicators, however. Most of the visible derivative signatures appear in the outboard portion of the blade, rather than directly at the in-board damage zone near 26% span, because a beam mode shape integrates a local stiffness change over the remaining span. A strong curvature feature therefore identifies a sensitive monitoring zone, not necessarily the physical damage site itself.

Table 2. Percent shifts in the first seven coupled-mode natural frequencies relative to H0 for representative damage cases

Mode	Healthy (Hz)	C1 (%)	C3 (%)	C5 (%)
1st flapwise	0.7714	−0.06	−0.07	−2.72
1st edgewise	1.0053	−0.16	−0.33	−0.83
2nd flapwise	2.3282	−0.05	−0.06	−0.47
2nd edgewise	3.1804	−0.01	−0.03	−0.08
3rd flapwise	5.1790	−0.15	−0.19	−0.35
Edgewise–torsion coupled	7.4568	−0.06	−0.11	−0.30
1st torsion	7.9048	−2.58	−3.25	−3.45

The displacement profiles of the modes provided partial spatial information, but curvature distributions of selected modes carried the most diagnostic information, particularly the twist component of the first torsional mode and the edgewise–torsion coupled mode.



These signatures were preserved at the rated speed of 11.75 rpm. The first-torsional frequency reduction was 3.45% at standstill and 3.44% under rotation, and the spatial structure of the curvature signatures was unchanged. This indicates that the selected signatures remain stable under the single rated-speed rotating condition examined.

Figure 3 shows the first and second spatial derivatives of the twist component of the first torsional mode for the healthy blade and damage case C5. At the displacement level, the two twist distributions nearly coincide. The slope separates over the inboard half of the span, and the curvature separates further, with a sustained gap between the healthy and damaged curves beyond approximately 0.65 span.

Of the eight derivative comparisons performed so far, this comparison produced the widest healthy-to-damaged separation. The same mode also produced the largest frequency reduction among the seven modes reported for case C5, at 3.45%. The curvature of this twist component is therefore carried forward as the primary candidate input for the PHM-oriented workflow described in C4.

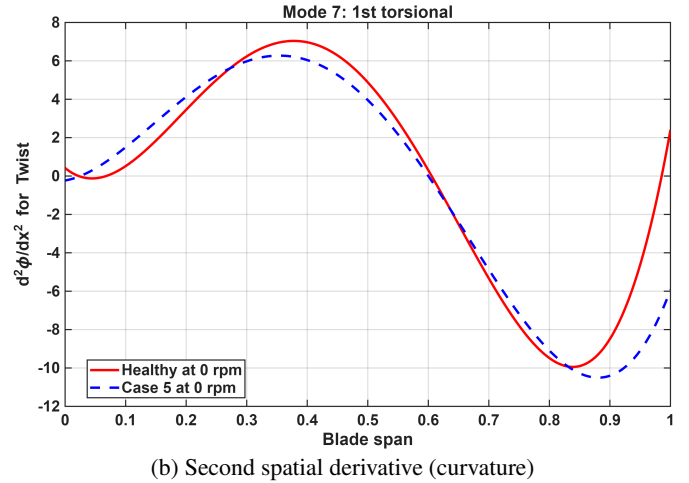


Figure 3. First and second spatial derivatives of the twist component of the first torsional mode for the healthy blade and damage case C5 at 0 rpm: (a) slope; (b) curvature.

Mode-and-component dependence. Diagnostic information in coupled modes is component dependent. In the edgewise–torsion coupled mode, the damage signature was carried almost entirely by the twist component, while the edgewise component remained effectively silent. Figure 4 illustrates this dependence: the flapwise and edgewise components overlap between the healthy and damaged configurations, while the twist component deviates visibly over the outboard region. Frequency-only screening would therefore rank this mode as weakly sensitive despite its clear spatial twist signature.

At the displacement level, the first torsional mode showed its clearest separation in its secondary bending components. After spatial differentiation, however, the curvature of the dominant twist component produced the strongest derivative-based separation examined to date.

3.2. Phase 2: In-Progress Work

A journal manuscript is in preparation that consolidates Phase 1 and compares sectional properties, natural frequencies, mode shapes, and spatial derivatives. In-progress work includes sensitivity checks on polynomial-fit order and end-of-

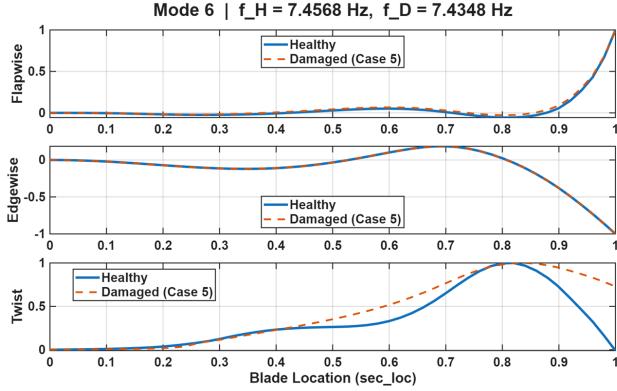


Figure 4. Edgewise-torsion coupled mode shapes of the healthy blade and damage case C5: flapwise, edgewise, and twist components.

span behavior, together with a component-resolved comparison of curvature signatures.

In parallel, shell-element modeling of trailing-edge disbond cases has begun in ANSYS using an initial G_{12} -reduction surrogate intended to represent the loss of interlaminar shear transfer. The adequacy and limitations of this approximation will be evaluated through the high-fidelity cross-validation study. This work supports the expanded damage matrix in WP1 and the cross-validation study in WP3.

3.3. Phase 3: Proposed Work

Four work packages are planned for the remaining program.

WP1: Expanded damage parametric study. The current case set is centered on leading-edge damage with progressive spar-cap involvement. Phase 3 will expand the matrix to include trailing-edge damage, simultaneous multi-region damage, and a finer spanwise resolution of damage location. This expanded matrix is expected to test the generality of the mode-and-component findings in C3 and characterize the dependence of indicator sensitivity on damage geometry more comprehensively.

WP2: Refined feature extraction. Preliminary curvature estimates rely on a sixth-order polynomial fit, which becomes unconstrained near the blade boundaries and can amplify modest displacement changes into large derivative magnitudes. Phase 3 will develop alternative curvature-estimation procedures, such as local spline fitting, regularized differentiation, and statistical confidence bands, and benchmark them against the polynomial baseline. The objective is to distinguish repeatable damage-sensitive curvature changes from numerical amplification introduced by the differentiation procedure.

WP3: Cross-validation between reduced-order and high-fidelity models. Beam-level results will be cross-compared

with shell-element analyses of the same damage cases to identify where the reduced-order representation captures the relevant damage physics and where higher fidelity is required. Prior experimental-computational work on composite laminates showed that manufacturing variability and idealized material modeling can produce substantial differences between measured and predicted structural responses, reinforcing the need for systematic model validation (Ahmed, Dutta, & Zhao, 2024).

WP4: Toward physics-informed PHM. Features identified through C2-C3 will be characterized as candidate inputs for prognostic modeling and condition-based maintenance decision support, with emphasis on stability under measurement noise, sensor-placement requirements, and spatial resolution, without yet selecting a specific prognostic model class. The expanded case matrix will form a labeled feature-response database for preliminary inverse mapping. These studies will test whether the simulated feature set contains enough independent information to estimate damage location, affected structural region, and severity from modal observations. Experimental validation on a sub-scale or full-scale blade specimen, pursued with project partners, remains a stretch objective for the final year. Prior development of an instrumented rotating-system dynamometer provides relevant experience in synchronized sensing, calibration, data acquisition, and uncertainty-aware experimental measurements for such validation studies (Ahmed et al., 2025).

4. CONCLUSION

This dissertation addresses a central challenge for vibration-based PHM of large composite wind turbine blades: identifying modal features that a practical monitoring system can measure and that still respond to damage confined to a short span of the blade, under stationary conditions and a preliminary rated-speed rotating condition. The preliminary work has established a parametric framework for systematically isolating localized damage effects at the composite-layup level on a reference-scale blade, and has developed a ranking of indicators that suggests curvature-based features are the strongest diagnostic indicators only for specific combinations of modes and components. The remaining program will extend this framework through expanded damage configurations, refined feature-extraction methods, and cross-validation against higher-fidelity models, before evaluating the selected indicators as candidate inputs for prognostic modeling. The expected outcome is a defensible, physics-informed feature set for blade PHM that complements frequency-based screening with targeted curvature-based monitoring of selected modes and components, and that supports the eventual transition from forward sensitivity analysis to inverse damage localization and severity estimation.

5. ACKNOWLEDGEMENT

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