Summaery2025

Towards Reliable Fatigue Life Prediction Of Wind Turbines Under Stochastic Wind Loads

Motivation and Research Problem

With wind energy playing a vital role in the global energy transition, ensuring the structural reliability of wind turbines is more important than ever. One of the key challenges lies in accurately predicting fatigue — the progressive and localized structural damage resulting from repeated cyclic loading over time. This is especially critical for wind turbines, which are continuously subjected to fluctuating wind loads and environmental conditions. As turbines are deployed in increasingly complex onshore and offshore environments, fatigue becomes a major concern affecting their longevity, safety, and maintenance costs.

This research introduces a comprehensive framework that embraces the randomness of wind by integrating stochastic wind modeling, probabilistic simulations, and advanced dynamic response analysis. Wind scenarios are generated using Monte Carlo methods and statistically characterized wind fields. The turbine response is simulated using OpenFAST, employing the widely used NREL 5-MW reference turbine.

By combining Rainflow counting and Miner's rule with site-specific joint probability matrices, the framework delivers a more realistic and automated fatigue assessment pipeline for turbine tower.

Initial results highlight the strong influence of turbulence intensity and wind variability on fatigue life, underlining the importance of moving beyond simplified models. This approach paves the way for smarter, safer, and more cost-effective wind turbine design and maintenance.

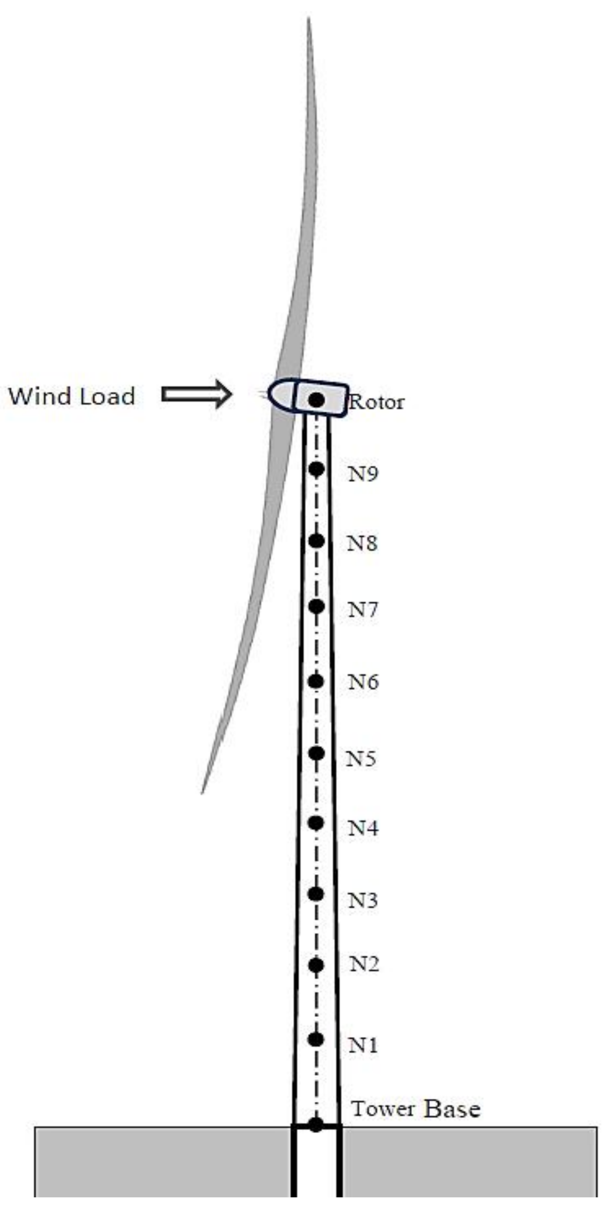
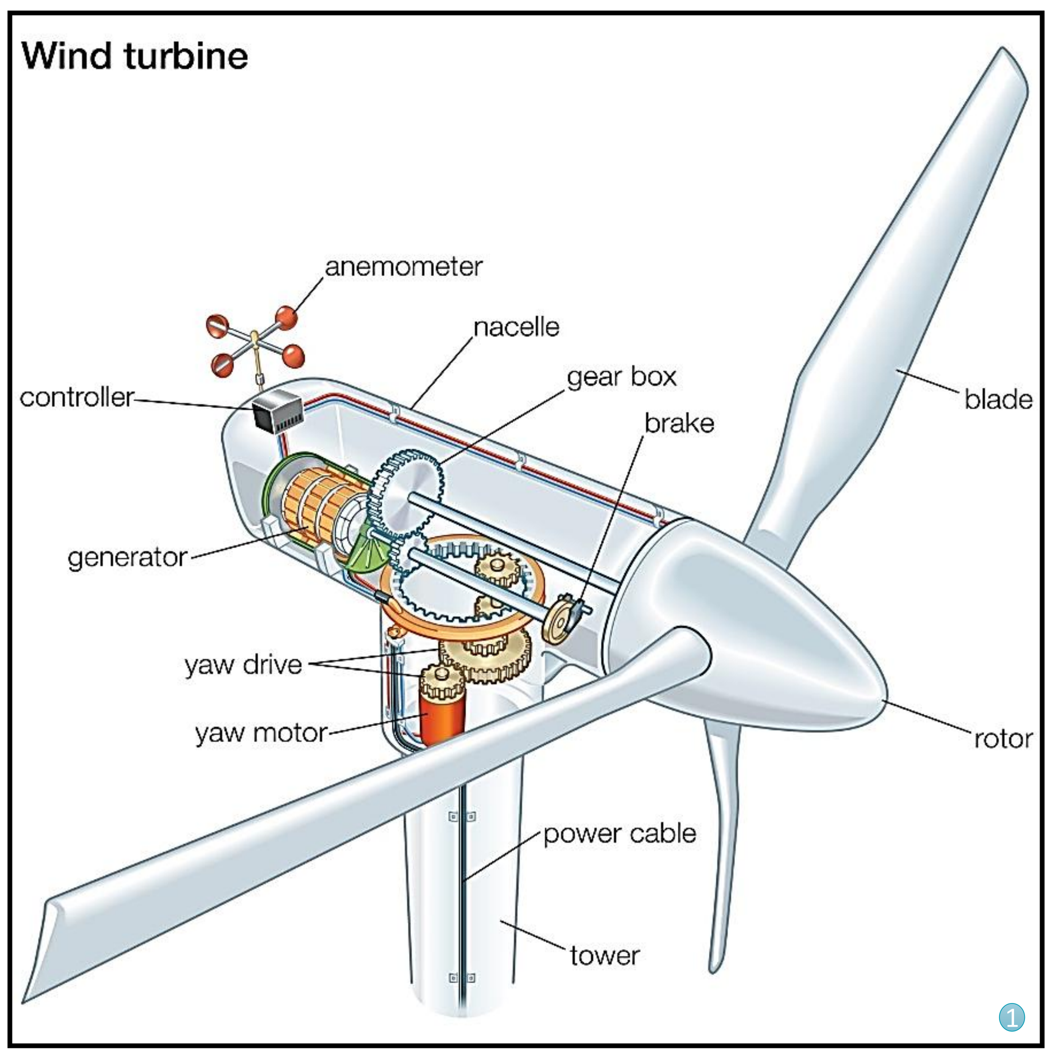


Figure 4: Onshore wind turbine model used in OpenFAST showing nodal distribution along the tower.



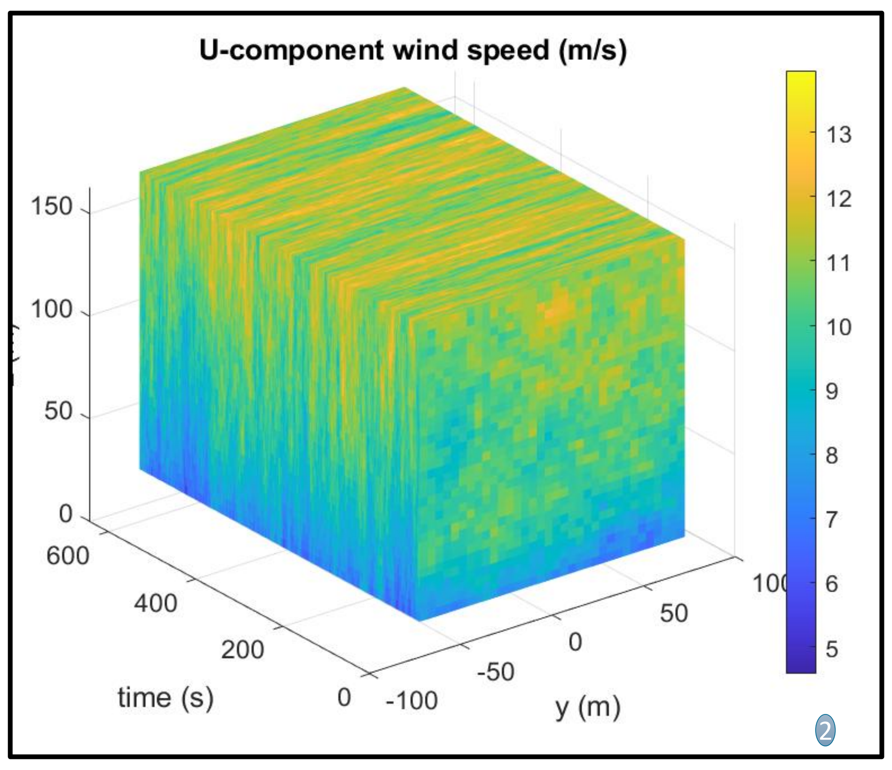
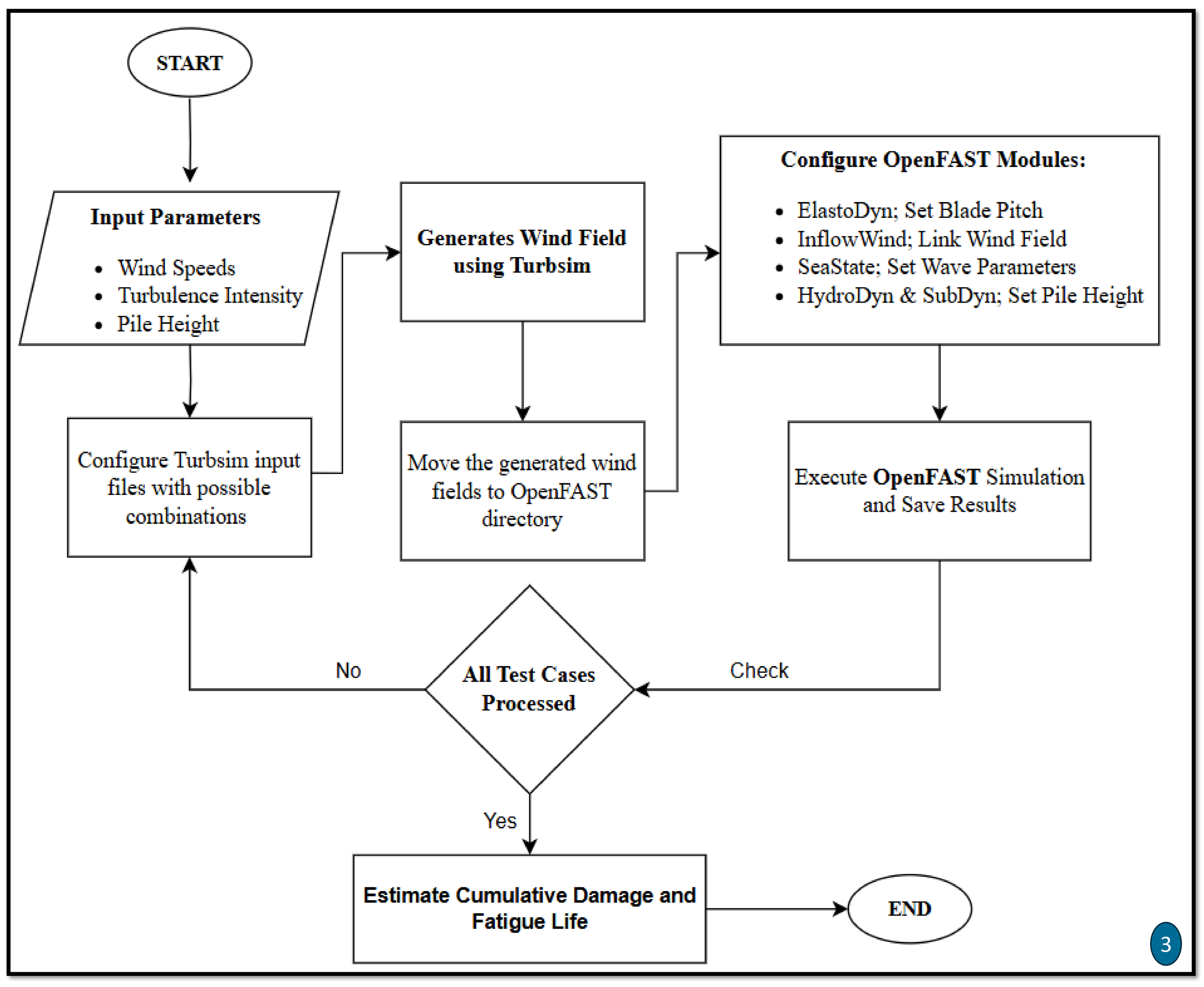


Figure 1. Labeled diagram of a wind turbine with its main components.
Figure 2. Temporal and spatial distribution of wind speed (m/s) generated using TurbSim
Figure 3. Matlab powered automation framework for wind field generation and structural simulations



Methodological Framework

In the study, an integrated simulation framework captures the complete fatigue assessment process, combining stochastic wind field generation, time-domain structural analysis, and damage evaluation. Designed for scalability, the approach enables high-volume scenario testing across both onshore and offshore turbine systems. The practical implementation of the framework includes:

1. Wind Field Generation with TurbSim
Realistic stochastic wind fields were generated using multiple standard turbulence models, covering a broad range of wind speeds and turbulence intensities. This approach captures diverse atmospheric conditions, enabling accurate simulation of real-world wind environments.

2. Structural Simulation Using OpenFAST
OpenFAST, widely trusted and industry-validated in wind turbine simulation, used for time-domain analysis, accurately capturing the complex structural dynamics of turbine towers under a wide range of realistic wind conditions..

3. Fatigue Life Estimation with MLife
Rainflow cycle counting breaks down complex load histories into measurable stress cycles, while Miner's rule stacks damage accumulation to estimate the fatigue life, all supported by MLife's precision. Fatigue estimation is carried at multiple tower nodes for reliability.

4. Onshore & Offshore Case Studies
The methodology was applied to both onshore and offshore wind turbine towers, enabling comparison of fatigue performance under differing environmental and operational conditions.

5. Automated High-Volume Simulation Framework
Leveraging MATLAB automation, over 1000 wind field scenarios were processed seamlessly, enabling fast, scalable, and systematic fatigue analysis.

Benchmark Wind Turbine and Parametric Studies

The simulation framework was built around standardized wind turbine models, incorporating realistic structural properties, wind inputs, and loading conditions.

1. NREL 5 MW Reference Turbine
Employed in both onshore and monopile based offshore configurations, the extensively validated NREL 5 MW model provides a standardized baseline for rigorously comparing fatigue responses under realistic environmental loading.

2. Parametric Input Modelling
Wind speeds from 3 m/s up to the 25 m/s cut-off, paired with turbulence intensities spanning 0% to 20%, capture the full operational spectrum.

Diverse standardized turbulence models generate comprehensive wind fields for both onshore and offshore scenarios. Offshore analyses also introduce monopile height variations to reflect the complex interplay of wind and wave forces on structural response.

3. Integrated Fatigue Life & Damage Probability Framework

Fatigue life is estimated using Miner's rule by processing cumulative damage results from MLife applied to structural loads obtained via OpenFAST across diverse input scenarios.

The resulting damage matrix is combined with site-specific empirical joint probability data to provide a realistic and probabilistic fatigue assessment. The entire workflow is automated for efficient handling of extensive simulation datasets, ensuring robust fatigue life predictions.

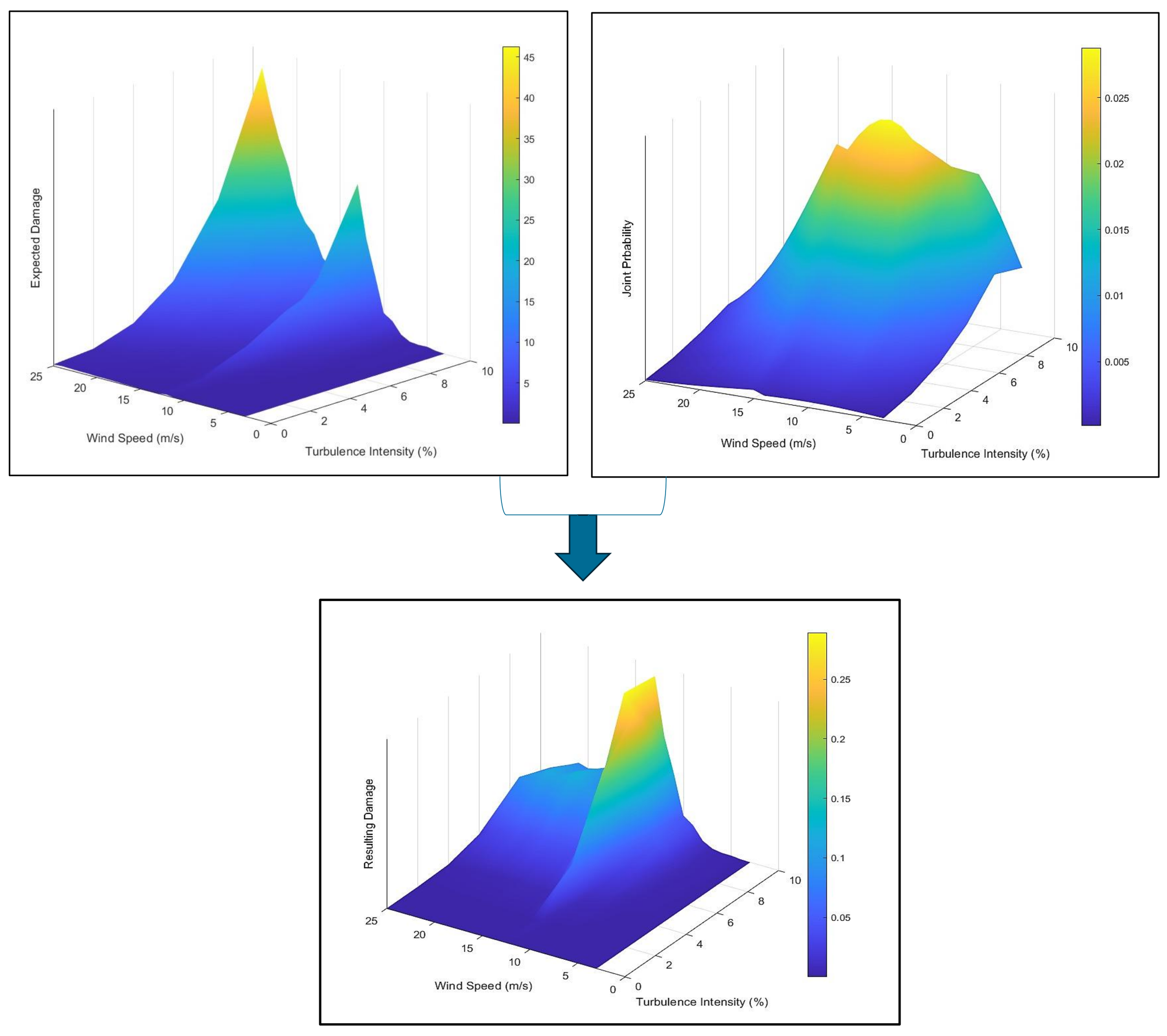


Figure 5: : Surface visualization of cumulative fatigue damage and the joint probability distribution of wind speed and turbulence intensity, merged together to form an expected damage surface. This combined representation reflects the probabilistic influence of varying environmental conditions on fatigue damage accumulation. (The figures are qualitative representations)

Preliminary Results

From over 1000 simulations and comprehensive analyses, the critical insights into fatigue behavior under varied wind conditions and structural responses emerge, underscoring the framework's ability to handle complex fatigue scenarios in multiple turbine contexts.

1. Fatigue damage escalates sharply with higher wind speeds and turbulence intensities, but it's the likelihood of these conditions occurring together that drives the most critical impacts, insights further revealed through sensitivity analysis.

2. In offshore cases, hydrodynamic loads introduce additional stresses at the mudline, making fatigue life assessment at multiple locations essential. While the mudline benefits from thicker piles and experiences lower damage with longer fatigue life, the tower base emerges as the critical location for both onshore and offshore turbines. Results also highlight that wave variability plays an equally important role as wind variability in offshore fatigue.

3. Automating the simulation and analysis workflow enabled efficient processing of large datasets, revealing that fatigue life predictions improve significantly when realistic stochastic wind fields and turbulence characteristics are incorporated, underscoring the value of high-fidelity environmental modeling.

Further Research Scopes

1. Integration of advanced soil-structure interaction models beyond current OpenFAST capabilities

2. Enhanced offshore fatigue assessment through detailed wave modeling and consideration of corrosion and environmental degradation in damage estimation.

3. Extension to multi-turbine layouts to analyze wake-induced fatigue loading

References

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2. Hau, E. (2013). Wind turbines: Fundamentals, technologies, application, economics (3rd ed.). Springer. https://doi.org/10.1007/978-3-642-27151-9

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