IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

BARI

Enhancing fatigue life of wind turbines through an innovative passive control device

E. Sorge [1], C. Riascos [2], N. Caterino [1,3]

[1]*Department of Engineering, University of Naples "Parthenope", Napoli, Italy, ettore.sorge@collaboratore.uniparthenope.it, nicola.caterino@uniparthenope.it*
[2] *Department of Mechanics of Continuous Media and Theory of Structures, Università Politécnica de Valencia, 46022, Spain*
[3] *Construction Technologies Institute, Italian National Research Council, Napoli, 80146,*

SUMMARY
Wind turbines, as key components of renewable energy systems, are constantly subjected to variable wind loading conditions that induce cyclic stresses and lead to the progressive accumulation of fatigue damage. This phenomenon significantly affects the structural integrity of the turbine, especially in critical regions such as the tower, and often results in increased maintenance requirements with notable economic consequences at the wind farm level. With the continuous growth in size and rated power of modern wind turbines, the ability to reliably estimate long-term fatigue behavior from short-term load data has become a fundamental aspect for ensuring structural safety and optimizing operational costs. In this context, the present study reviews existing approaches for long-term fatigue assessment and proposes a methodology to extrapolate fatigue damage computed over 10-minute intervals to the entire service life of the turbine. The proposed framework is further applied to a case study involving a hinge-spring-friction device (HSFD), used as a passive control system to mitigate dynamic loads, with the aim of reducing fatigue damage and enhancing overall structural durability.

Keywords: wind turbine, vibration reduction, fatigue.

1. INTRODUCTION

The demand for wind energy continues to grow as turbines become larger and more powerful, making them increasingly susceptible to fatigue-related structural issues, particularly in the tower base (Chou et al., 2019). These turbines experience highly variable, continuous wind stresses that accumulate as fatigue damage over time, gradually reducing their lifespan and increasing maintenance demands. Accurate life-cycle fatigue predictions often rely on short-term data, typically 10-minute wind load histories, which must then be scaled to estimate cumulative damage over the entire operational life. Table 1 provides an overview of recent papers dealing with the phenomenon of fatigue in wind turbines and the estimation of fatigue life.
This study presents an advanced methodology for calculating fatigue life, applied to a specific case study involving a wind turbine equipped with a Hinge-Spring-Friction Device (HSFD), described in Sorge et al. (2024). This device, developed to extend the operating life of the turbine, acts directly on the structure, reducing the cyclic stresses resulting from the operating conditions to which it is constantly exposed. The main objective of this analysis is therefore to verify the effectiveness of the HSFD in mitigating fatigue damage, with a consequent increase in the durability and overall reliability of the turbine. The proposed methodology allows the fatigue life of the turbine to be accurately estimated by considering specific load histories based on 10-minute intervals, which realistically reflect the load fluctuations to which a wind turbine is subjected

during its operation. This calculation approach, based on short but frequent load sequences, allows a detailed evaluation of the effect of the HSFD, comparing two scenarios: one in which the turbine operates without the use of the device and one in which it is used. The results of the comparison show how the integration of the HSFD contributes to a significant reduction in cyclic stresses, with a possible positive impact on the life of structural components. The proposed methodology represents advancement in analysis and optimization techniques to improve sustainability and efficiency in the renewable energy industry.

Table 1. State of the Art paper on fatigue life estimation in wind turbines. OFF=Offshore, ON=Onshore.

Year	Authors	Type	short description
2022	Rincón-Casado et al.	ON-OFF	Experimental residual life assessment of bolts
2022	Sadeghi et al.	OFF	LFFD integration in time domain analysis
2022	Zheng et al.	OFF	Blade-rotor bolt analysis
2023	Bai et al.	ON-OFF	Fatigue estimation using Neural Network
2023	Santos et al.	OFF	Fatigue estimation using Neural Network
2023	Lee et al.	OFF	Fatigue on offshore support structure
2023	Li et al.	OFF	Fatigue analysis on an offshore foundation
2023	Zha et al.	OFF	Fatigue analysis on an offshore foundation
2023	Zhang et al.	ON-OFF	Review methods for fatigue life estimation
2023	Zhao et al.	ON-OFF	Fatigue analysis based on monitored data
2023	Zhu et al.	ON	Fatigue estimation with probabilistic framework
2024	Ren et al.	OFF	Fatigue on mooring lines
2024	Tao et al.	OFF	Yaw influence on bolt fatigue life
2024	Xi et al.	OFF	Fatigue analysis based on monitored data

2. METHODOLOGY FOR ESTIMATING FATIGUE LIFE

This section describes the method of calculating fatigue life from 10-minute stress histories on the tower, calculated for different wind speed scenarios at the hub. For each scenario, 10-minute stress histories were considered and, through the application of the rainflow method (Bai et al., 2023) the fatigue damage (D) was estimated using the Miner equation (Miner, 1945).

The damage calculated for a 10-minute period at a given wind speed (v) was then extended on an annual basis. To determine the average annual damage value, the damage estimate over the individual 10-minute intervals was combined with the frequency distribution of wind speeds, $f(v)$, which represents the number of annual hours corresponding to each speed interval.

To adequately represent the wind speed behavior at a given site, the Weibull distribution (IEC, 2019) was used as a probabilistic model, with its probability density function accurately describing the frequency of the various wind speed intervals. Considering the number of 10-minute periods constituting a year and the frequency distribution and $f(v)$, it is possible to estimate the annual damage of each scenario. This calculation is equivalent to estimating the annual damage considering its frequency on an annual basis in terms of ten-minute periods. The fatigue life of the detail considered was evaluated by again applying the theory of linear damage accumulation, thus allowing an accurate estimate of the fatigue life.

3. CASE STUDY AND RESULTS

The methodology described was applied to the case study of a 5WM wind turbine (Sorge et al., 2024), equipped with a passive Hinge-Spring-Friction Device (HSFD). The application of the HSFD has recently been investigated for fatigue damage reduction in an NREL 5 MW wind turbine, as reported by Sorge et al. (2024). In that study, the HSFD was optimized to reduce the peak bending moment and cumulative fatigue damage, assessing the turbine's behaviour under two specific wind conditions. Building on this research, the present study expands the analysis by considering a wider range of wind conditions during the turbine's normal operation, aiming to provide a more accurate estimate of its fatigue life. To achieve this, the analysis was conducted using the Weibull distribution, as defined by Luo et al. (2025), which provides the shape and scale parameters at an altitude of 100 meters. This statistical model is widely used for wind variability assessment at wind farm sites, as it effectively represents mean wind speed fluctuations, which are crucial factors influencing the turbine's dynamic behaviour. The Weibull curve from Luo et al. (2025) was used as an input for the fatigue damage calculation model, ensuring that the results accurately reflect real operating conditions. The study focuses on cumulative fatigue damage in the wind turbine tower, with particular attention to cracking in the lower flange, the most structurally stressed area according to Eurocode. Two configurations were analysed: the Fixed Base (FB), where the tower is rigidly anchored to the ground, and the Rotating Base (RB), which integrates the HSFD at the base, enhancing energy dissipation and reducing cyclic stresses. In both cases, fatigue damage was estimated using a normal wind model in compliance with IEC 61400-1(2019). The analysis was performed in 10-minute intervals (D_{10}) to provide a detailed evaluation of how damage evolves over time. The results, illustrated in Figure 4, compare the 10-minute fatigue damage curve for the FB configuration with that of the RB configuration. Additionally, the Weibull curve (W) is overlaid on the cumulative damage as a function of the mean wind speed at the hub (v_{hub}), allowing for a more comprehensive assessment of how wind variability influences fatigue damage.

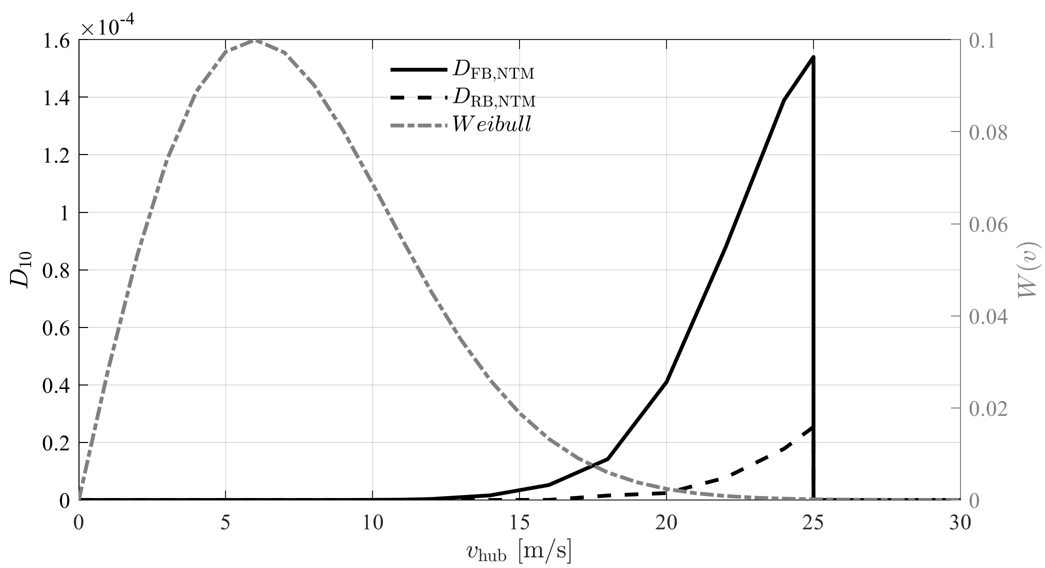

Figure 1 Comparison of the 10-mins damage curve between FB and RB configurations; Weibull curve from Luo et al. (2025).

The results of the analysis show a significant reduction in fatigue damage in the RB scenario with HSFD compared to the FB scenario without the device. This reduction can be expressed in terms of an increase in the fatigue life of the structure and its structural components.

4. CONCLUSION

In conclusion, this work presented an advanced methodology for calculating the fatigue life of wind turbines, based on the analysis of short-term stress histories in 10-minute intervals. This approach provides accurate estimates of long-term damage, which is crucial for assessing the structural durability of turbines under varying and intense wind loads. Subsequently, the methodology was applied to a specific case study of a NEREL5WM turbine equipped with an HSFD device, showing how this passive control system can significantly reduce cyclic stresses and, consequently, cumulative damage over time. The results obtained from the case study confirm the effectiveness of the methodology and HSFD in extending turbine life, reducing maintenance costs and improving overall reliability. These two central contributions make the work relevant to improving the sustainability and efficiency of wind turbines and suggest possibilities for future application and optimization under different operating conditions.

REFERENCES

Bai, H.; Shi, L.; Aoues, Y.; Huang, C.; Lemosse, D., 2023: Estimation of probability distribution of long-term fatigue damage on wind turbine tower using residual neural network. Mechanical Systems and Signal Processing., 190, 110101.

Chou, J. S.; Ou, Y. C.; Lin, K. Y., 2019: Collapse mechanism and risk management of wind turbine tower in strong wind. Journal of Wind Engineering and Industrial Aerodynamics., 193, 103962.

IEC, I. E. C., 2019: 61400-1: 2019 Wind Energy Generation Systems—Part 1: Design Requirements. IEC: Geneva, Switzerland.

Lee, G. N.; Ngo, D. V.; Lee, S. I.; Kim, D. H., 2023: Fatigue Life Convergence of Offshore Wind Turbine Support Structure According to Wind Measurement Period. Energies., 16, 3199.

Li, B.; Shi, H.; Rong, K.; Geng, W.; Wu, Y., 2023: Fatigue life analysis of offshore wind turbine under the combined wind and wave loadings considering full-directional wind inflow. Ocean Engineering., 281, 114719.

Luo, Y.; Zhou, D.; Heng, J.; Dai, K.; Liu, Y.; Qiu, K., 2025: Probabilistic fatigue prognosis of novel ring-flange connections in lattice-tubular hybrid (LTH) wind turbine towers. Thin-Walled Structures., 209, 112908.

Miner, M. A., 1945: Cumulative damage in fatigue.

Ren, C.; Xing, Y.; Patel, K. S., 2024: Application of an active learning method for cumulative fatigue damage assessment of floating wind turbine mooring lines. Results in Engineering., 22, 102122.

Rincón-Casado, A.; Juliá-Lerma, J. M.; García-Vallejo, D.; Domínguez, J., 2022: Experimental estimation of the residual fatigue life of in-service wind turbine bolts. Engineering Failure Analysis., 141, 106658.

Sadeghi, N.; Robbelein, K.; D'Antuono, P.; Noppe, N.; Weijtjens, W.; Devriendt, C., 2022: Fatigue damage calculation of offshore wind turbines' long-term data considering the low-frequency fatigue dynamics. Journal of Physics: Conference Series. IOP Publishing, Vol. 2265p. 32063.

Santos, F. de N.; D'Antuono, P.; Robbelein, K.; Noppe, N.; Weijtjens, W.; Devriendt, C., 2023: Long-term fatigue estimation on offshore wind turbines interface loads through loss function physics-guided learning of neural networks. Renewable Energy., 205, 461–474.

Sorge, E.; Riascos, C.; Caterino, N.; Demartino, C.; Georgakis, C. T., 2024: Optimal design of a hinge-spring-friction device for enhancing wind induced structural response of onshore wind turbines. Engineering Structures., 314, 118305.

Tao, T.; Yang, Y.; Yang, T.; Liu, S.; Guo, X.; Wang, H.; Liu, Z.; Chen, W.; Liang, C.; Long, K., 2024: Time-domain fatigue damage assessment for wind turbine tower bolts under yaw optimization control at offshore wind farm. Ocean Engineering., 303, 117706.

Xi, Y.; Li, H.; Sun, L.; Wang, Z., 2024: Extreme load extrapolation and long-term fatigue assessment of offshore wind turbine tower based on monitoring data. Ocean Engineering., 300, 117180.

Zha, X.; Lai, Y.; Rui, S.; Guo, Z., 2023: Fatigue life analysis of monopile-supported offshore wind turbines based on hyperplastic ratcheting model. Applied Ocean Research., 136, 103595.

Zhang, J. W.; Liang, X.; Wang, L. Z.; Wang, B. X.; Wang, L. L., 2023: The influence of tuned mass dampers on vibration control of monopile offshore wind turbines under wind-wave loadings. Ocean Engineering., 278, 114394.

Zhao, Y.; Li, X.; Wang, X.; Jiang, J.; Wang, Z., 2023: Fatigue Life Evaluation of Wind Turbine Tower Based on Measured Data. Advances in Civil Engineering., 2023.

Zheng, T.; Chen, N. Z., 2022: Time-domain fatigue assessment for blade root bolts of floating offshore wind turbine (FOWT). Ocean Engineering., 262, 112201.

Zhu, D.; Ding, Z.; Huang, X.; Li, X., 2023: Probabilistic modeling for long-term fatigue reliability of wind turbines based on Markov model and subset simulation. International Journal of Fatigue., 173, 107685.