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Loads Measurement and Validation of a 2.1-kW HAWT on a Fiberglass Composite Tower

Scott Dana, Rick Damiani, Jeroen van Dam

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Motivation

Ongoing efforts to improve system dynamic modeling and prediction

Assess common industry practice loads derivation methods

Evaluate IEC 61400-2 Simplified Loads Approach

Address fatigue loads more comprehensively

Design Load Derivation Methods

1. Full-Scale Loads Measurements (Field)

- A 2.1-kW, free yaw, variable-speed, downwind machine
- An AnemErgonics, LLC 18-m multisection fiberglass composite tower
- Meteorological data recorded at hub height
- Tower strain measured at 0.8 m above tower hinge plate
- Full bending bridges in two orthogonal directions

2. Aeroelastic Modeling (FAST)

- FAST v 7.02 utilized
- Turbulent wind files, 3 seeds, with reference wind speeds of 2, 4…,24, 26 m/s
- Turbulence intensity of 18%
- Air density of 1.0 kg/m^3 to match site conditions
- Tower drag not modeled

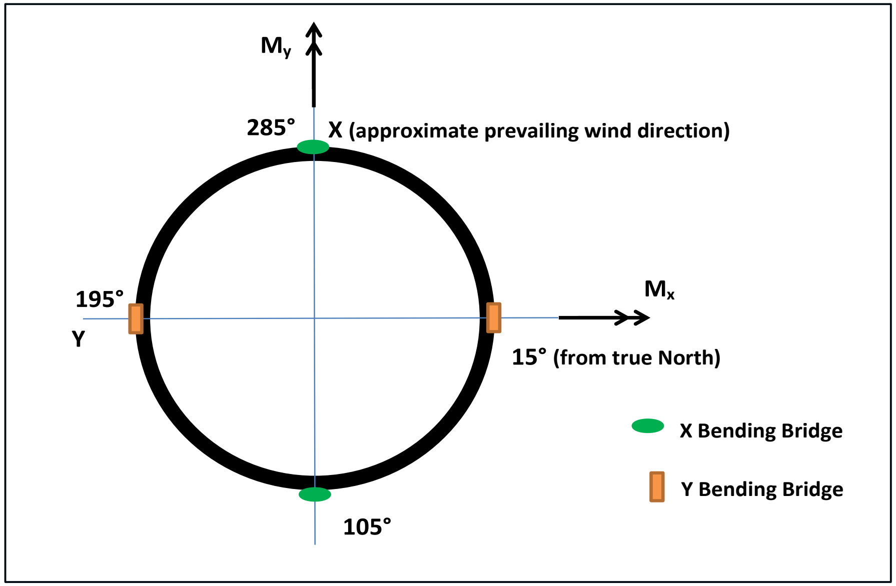
3. Simplified Loads Approach (SLA)

- IEC 61400-2 design load cases (DLCs) A (fatigue), H, and I (ultimate loads)
- Input parameters derived from the FAST model, preliminary test results, and turbine dimensions
- SLA load components used to determine the tower-base bending moment

Full-Scale Loads Measurements Approach

Met tower and instrumentation used for field test campaign (Photo by Scott Dana, NREL)

- Measurement sector of 223° to 333 ° of true north following IEC 61400-12-1
- Measurement methods and loads processing following IEC 61400-13
- Coordinate transformation applied to loads

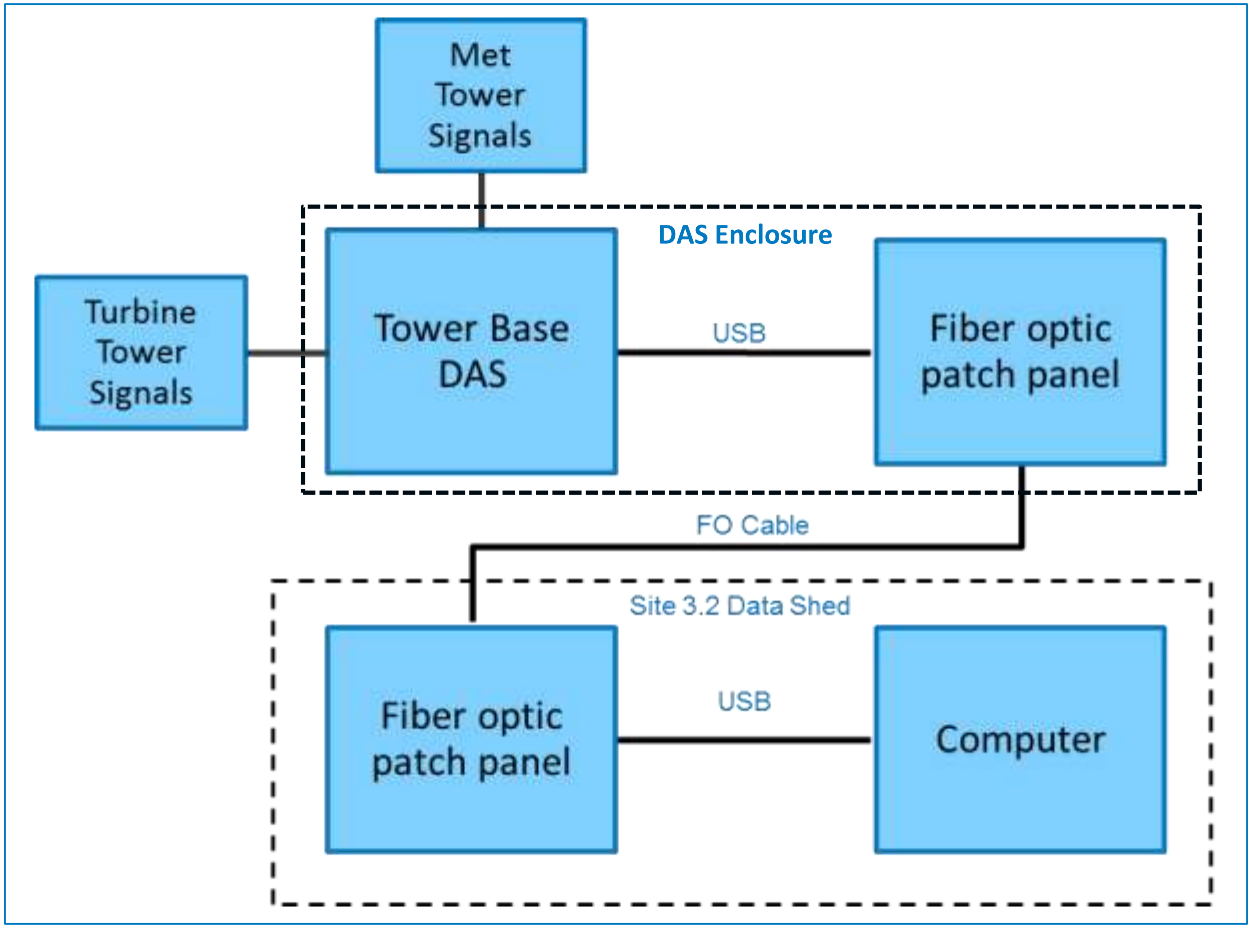


Tower Strain full bridge orientation and loads configuration

Tower-Base Bending Bridge Location

Test article used for full-scale loads measurement with identification of tower strain gage locations (Photo by Rick Damiani, NREL)

Measurement Data Acquisition System



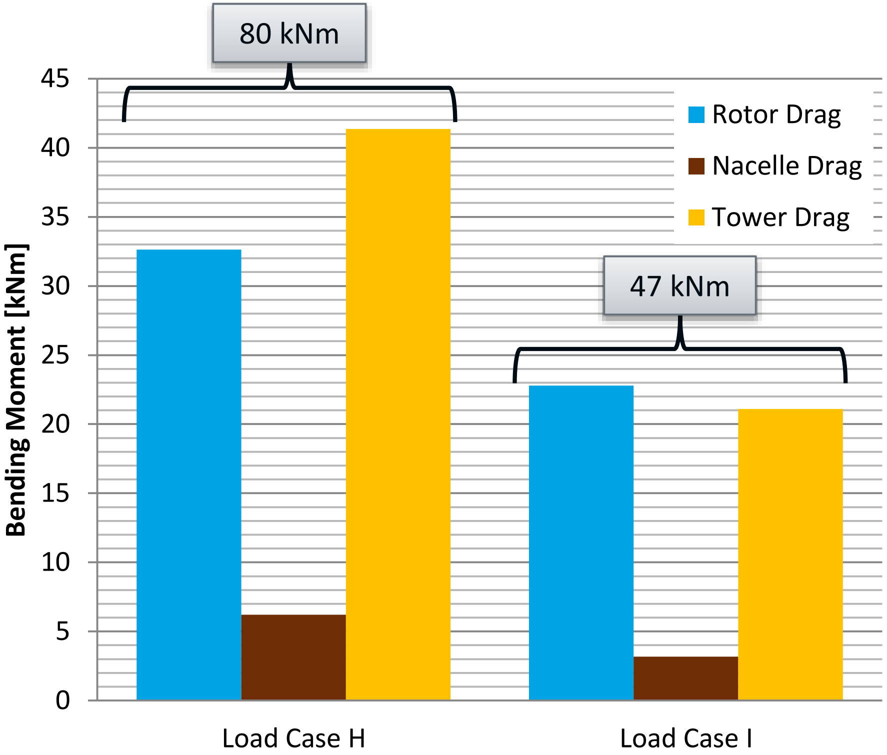
Communication one-line for tower loads DAS

- NI cDAQ Chassis and Input Modules
    - Sampled at 35 kHz
    - Stored at 100 Hz
- 1,332 10-Minute data files within measurement sector for Loads Calculations
- 3,482 10-Minute data files for Fatigue Calculations (all operating data)

Simplified Loads Approach – Maximum Bending Moments

SLA DLCs for tower analysis:

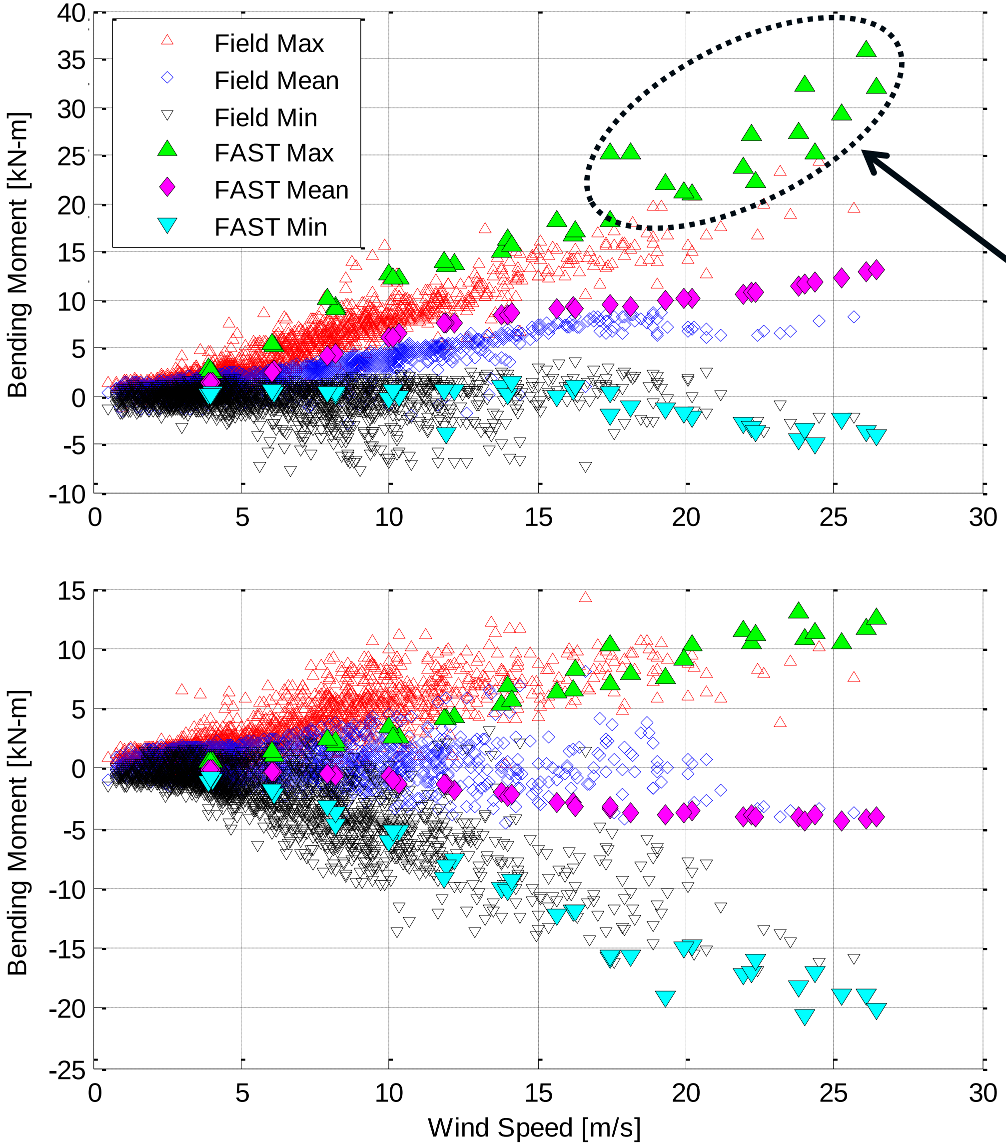
- IEC 61400-2 DLC H
  - Extreme wind speed of 59.5 m/s
  - A normally parked turbine
  - Total Moment = 80 kNm
- IEC 61400-2 DLC I
  - 42.5 m/s wind speed
  - Maximum exposure (yaw mechanism failure)
    - A ‘no-yaw-error’ configuration in this case
    - Total Moment = 47 kNm



Component-drag contributions to the total combined tower-base bending moment for DLCs H and I

DLC H develops the greatest bending moment → Tower Design Driver

FAST and Field Bending Moments Results

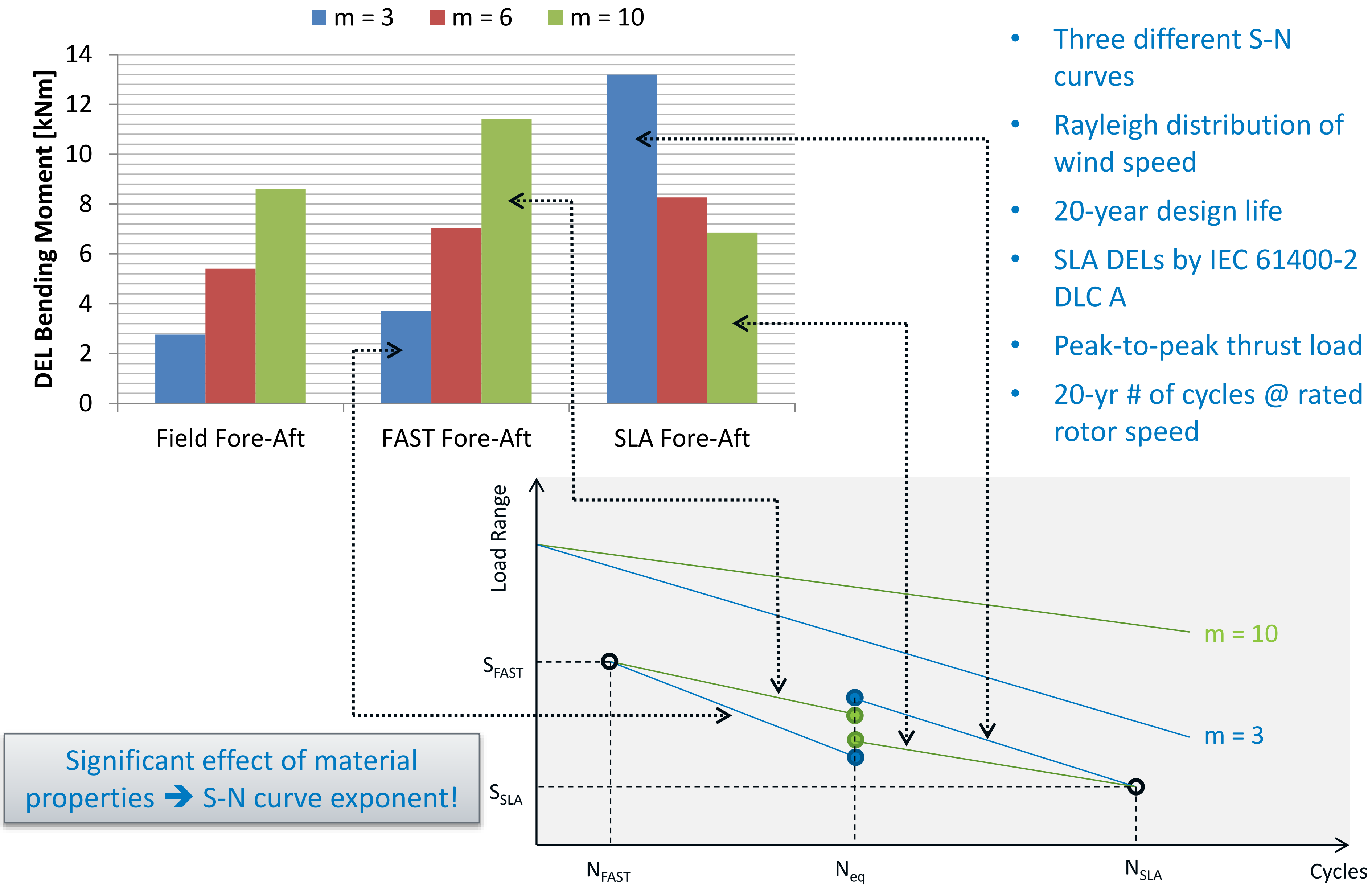


Ten-minute statistical comparison of the Field and FAST tower-base ultimate loads in the fore-aft (top) and side-to-side (bottom) directions

- Deviation between Field and FAST is likely a result of the actual turbine control system mitigating loads at high wind speeds (18 m/s and above)
  - For the captured wind speeds FAST and field loads are within the load envelope of DLCs H and I
    - Less than 47 kNm (DLC I)

Loads extrapolation of the field-measured loads is required for a proper comparison with SLA results — a future work item of this study.

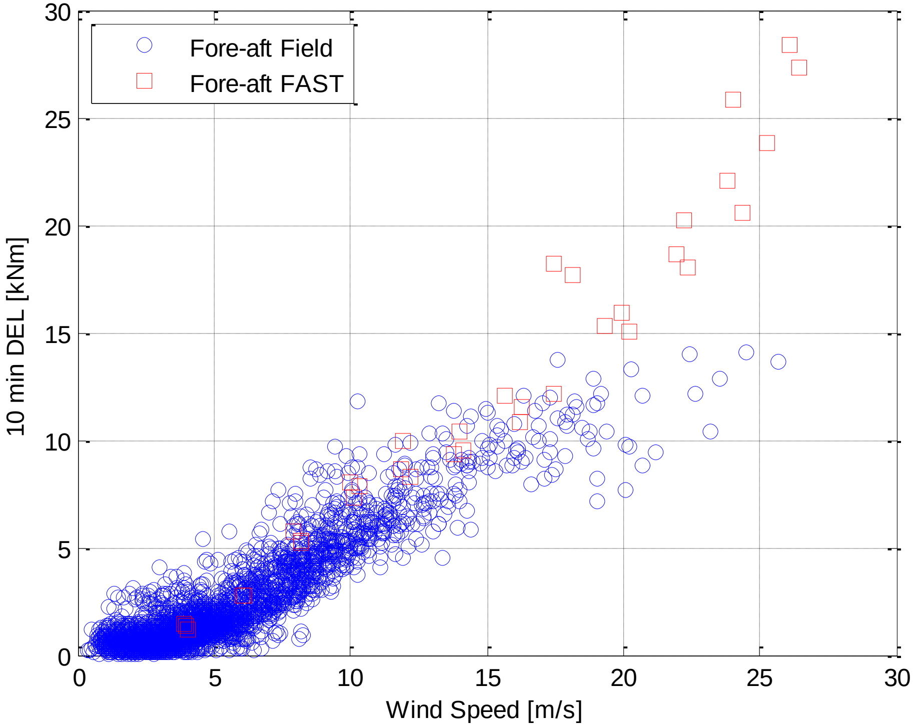
Fatigue Loads Comparison – Damage Equivalent Loads



- Three different S-N curves
- Rayleigh distribution of wind speed
- 20-year design life
- SLA DELs by IEC 61400-2 DLC A
- Peak-to-peak thrust load
- 20-yr # of cycles @ rated rotor speed

Significant effect of material properties ➔ S-N curve exponent!

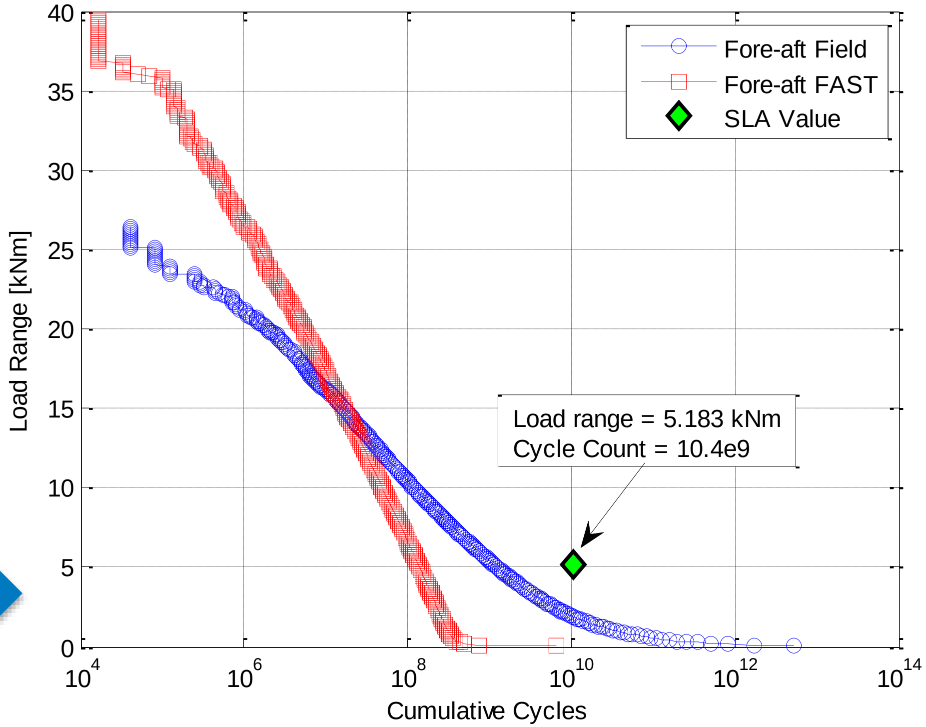
Fatigue Loads Comparison Continued



Short-term (10 minute) fore-aft tower-base bending moment DELs versus the mean wind speed for an S-N curve with m = 10

- Although similar, FAST's over-prediction of high-range loads compared to the Field spectra are demonstrated.
- This outcome is consistent with the ultimate loads comparison.

- The SLA DLC A yields a single fatigue load range value of 5.183 kNm, with a cycle count of 10.4e9.



Fore-aft tower-base bending moment cumulative fatigue spectra comparison of field-measured loads and FAST predictions

Final Remarks

This study focused on tower-base bending moments of a horizontal-axis wind turbine to provide an indication of the overall performance of the load derivation methods. Notable outcomes include the following:

- The SLA DELs are different than those calculated from the Field and FAST data;
    - High dependence on the assumed S-N curve slope and the number of cycles.
    - SLA DEL more conservative for steel (m = 3 to 6) and less conservative for composites (m =10).
- Better agreement between the field and FAST predictions for side-to-side than for fore-aft bending at high wind speeds;
    - Likely caused by a lower fidelity turbine control model used in the FAST simulations.
- The fatigue spectra reveals FAST’s over-prediction of large cycles.
- SLA does not comprehensively address fatigue;
    - Conservative and coarse → one load range at one cycle count.
- We recommend that this study be repeated with wind turbines of different configurations and sizes, and that field load extrapolation be conducted.

Acknowledgements

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Thank you!

Questions?

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