November 2004 • NREL/CP-500-37112

Conference Paper

Tower Design Load Verification on a 1-kW Wind Turbine

Preprint

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To be presented at the 43rd AIAA Aerospace Sciences Meeting and Exhibit
Reno, Nevada
January 10-13, 2005

National Renewable Energy Laboratory
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Tower Design Load Verification on a 1-kW Wind Turbine

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Wind turbine testing at the National Wind Technology Center (NWTC) has been done to characterize both tower top loads and thrust loads for small wind turbines, which is part of an ongoing effort to model and predict small wind turbine behavior and the resulting stresses imposed on the supporting tower. To these ends, a 1-kW furling wind turbine mounted on a 10-meter tower was instrumented and monitored via a data acquisition system for nearly a year. This test was conducted to verify the design loads as predicted by the simple design equations provided in the draft revision of the International Electrotechnical Commission (IEC) Small Wind Turbine Safety Standard 61400-02 CDV (hereafter called "the draft Standard"). Data were captured for several operating conditions covered by the draft Standard. This paper addresses the collected data and what conclusions can be made from it.

Nomenclature

V_{hub}	=	wind speed at hub height averaged over 10 minutes
V_{design}	=	design wind speed
V_{ave}	=	annual average wind speed at hub height
V_{e50}	=	expected extreme wind speed (averaged over 3 seconds: 59.3 m/s)
V_{ref}	=	reference wind speed averaged over 10 minutes (42.5 m/s)

I. Background

The IEC 61400-2 Standard addresses the safety, quality, integrity, and design requirements of small wind turbines. The draft revision IEC 61400-2 CDV (hereafter referred to as "draft Standard") was released in early 2004 [1]. The draft was an improvement to the first edition of the Standard released in 1996. The draft Standard embodies revisions that enhance the load model, improve the safety factors, and clarify the test requirements. This paper addresses the simplified load model under the structural design section of the draft Standard. The equations from the simplified load model estimate the loads (forces, moments, torque) at specific locations on the wind turbine, such as the rotor shaft or blade root. The loads at these locations were translated to specific locations on the tower where measurements were collected, as the simplified load equations do not give loads for the tower. Moreover, it is important to note that the results from the simplified load equations are meant to be conservative but not overly so.

An earlier paper compared the draft Standard simplified load model to measurements and model predictions [2]. At that time, very little measured tower-loads data for small wind turbines were available to make a valid comparison between the simplified load model and measured data. The validity and usability of the draft Standard is important because tower costs for small wind turbines are a substantial portion of the overall cost; it would greatly assist manufacturers if the tower loads were accurately predicted so that tower costs can be reduced. Therefore, a project was undertaken at the National Renewable Energy Laboratory (NREL) to characterize the tower loads and to compare these measured loads to the simplified load model from the draft Standard.

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A. Load Model and Assumptions

The draft Standard gives several simplified load cases, as shown in Table 1. These load cases attempt to cover a wide range of conditions under which high loads can be expected. Load Cases B through J give ultimate loads. Load Case A gives load ranges for six load components for fatigue analysis. For each load case, the draft Standard provides equations to estimate simplified loads on the turbine. To calculate the draft Standard simplified loads, several parameters are needed, as listed in Appendix A. Most input parameters can easily be obtained from the test turbine. For design power, design rotor speed and maximum rotor speed measurements are required to obtain these parameters. To calculate other needed parameters, such as maximum yaw rate and drive train efficiency, equations are provided in the draft Standard. In addition, it was assumed that the testing site was a class II wind site, with corresponding assumptions for average wind speed and reference wind speed.

Table 1. Design load cases for the simplified load calculation method.

Design Situation	Load Cases		Type of Analysis	Remarks
Power production	**A**	Normal operation	Fatigue	
	B	Yawing	Ultimate	
	C	Yaw error	Ultimate	
	D	Maximum thrust	Ultimate	Rotor spinning but could be furling or fluttering
Power production plus occurrence of fault	**E**	Maximum rotational speed	Ultimate	
	F	Short at load connection	Ultimate	Maximum short-circuit generator torque
Shutdown	**G**	Shutdown (Braking)	Ultimate	
Parked (idling or standstill)	**H**	Parked wind loading	Ultimate	
Parked and fault conditions	**I**	Parked wind loading, maximum exposure	Ultimate	Turbine is loaded with most unfavorable exposure
Transport, assembly, maintenance and repair	**J**	To be stated by manufacturer	Ultimate	

II. Experimental Description

Data were collected from a Southwest Windpower 1-kW Whisper H80 wind turbine [hereafter referred to as the test turbine] mounted on a 10-meter tubular tilt-up tower with guy wires. The test location was at site 1.3 of the National Wind Technology Center's (NWTC's) test site south of Boulder, Colorado. The configuration of the test site is shown in Fig. 1.

The test turbine is a three-bladed, upwind, variable-speed, free-yawing, furling turbine as shown in Fig. 2b. The test turbine connects to a battery bank and Trace SW 4024 grid tie inverter. The turbine limits power and rotor speed by furling. It does not have a mechanical brake; however, the generator outputs can be shorted together to shut down the turbine.

A meteorological tower stands 6.2 meters (2 rotor diameters) from the turbine at 292°, the prevailing wind direction. The anemometer and the wind vane stand at a height of 9.1 and 8.0 meters respectively.

The test turbine was modified from its normal configuration by inserting an aluminum sleeve

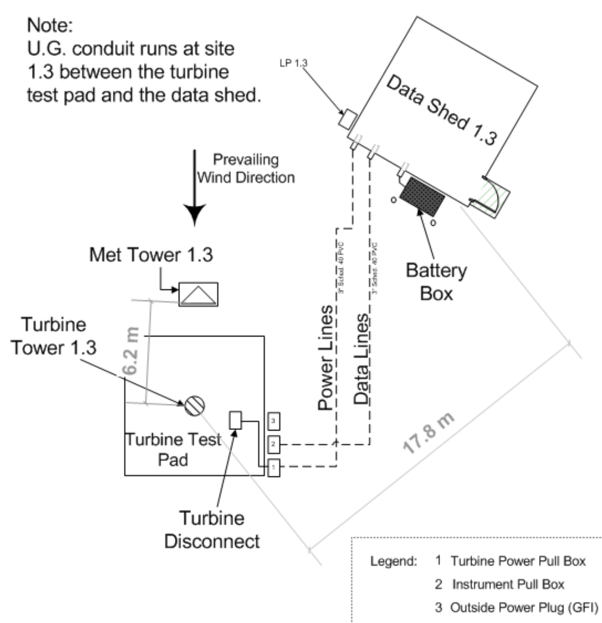

Figure 1. Aerial view of the test site.

between the turbine and the tower (Fig. 2a). The 13-inch aluminum sleeve serves two purposes. First, the sleeve increases the distance between the turbine and the top strain gages, thereby increasing the bending moment at these strain gages and improving sensor resolution. Second, the sleeve houses and protects the optical encoder, which measures yaw position.

Tower loads were measured using two sets of strain gage bridges located at two elevations below the main shaft (1.98 and 0.94 meters). At each elevation, two full parallel bridges were applied to the tower (one bridge mounted 90° away from the other). This strain gage configuration was used to measure both tower-top bending moments and thrust forces. The "downwind" bridge was placed in line with the predominant wind direction of 292°. The "crosswind" bridge was placed 90° from the "downwind" bridge. The strain gage bridges were calibrated by applying known weights at a known distance from the gage bridges with the tower in a horizontal position. Negligible crosstalk was found between the downwind and crosswind bridges.

The signals that were measured are listed in Table 2.

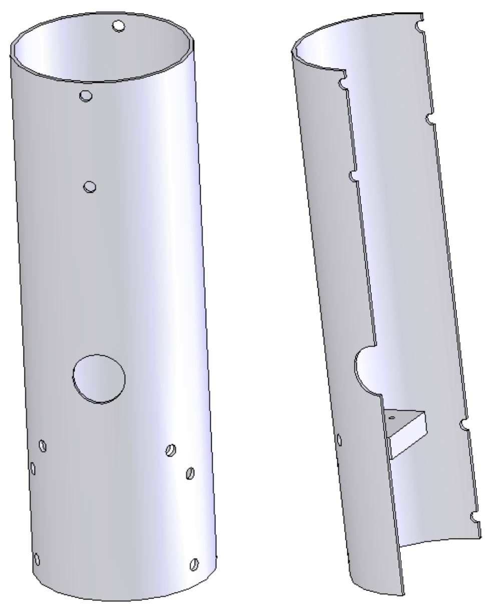

Figure 2a. Aluminum sleeve.

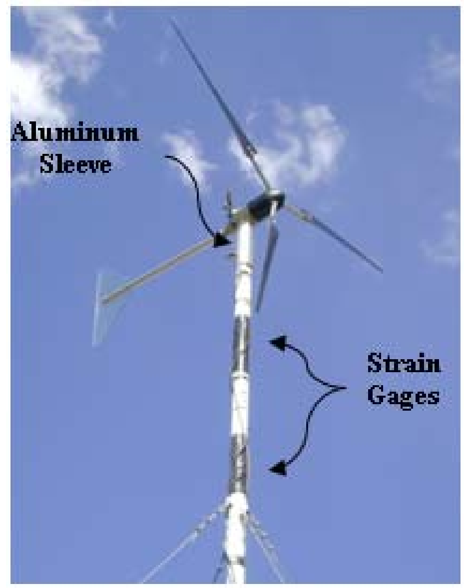

Figure 2b. Tower top: the H80 turbine, aluminum sleeve, and strain gage bridge locations.

Table 2. Measured Turbine Parameters.

Parameter	Units	Instrument
Upper Tower downwind	kN-m	Strain Gage
Upper Tower crosswind	kN-m	Strain Gage
Lower Tower downwind	kN-m	Strain Gage
Lower Tower crosswind	kN-m	Strain Gage
Wind Speed	m/s	Cup Anemometer
Wind Direction	deg.	Wind vane
Rotor Speed*	rpm	Frequency to Voltage
AC Power Output*	W	Power Transducer
Yaw Position*	deg	Slipring/encoder
Tail Angle*	deg	Rotary Variable Inductance Transducer

*Rotor speed, power, yaw position and tail angle data were only available in a very limited part of the data sets. The signals were lost during testing; due to budget and time constraints, no effort was made to recover these signals.

The data were collected in 3-minute files by a Campbell Scientific datalogger that sampled all channels at 50 Hz

III. Data Treatment

For the duration of the test, 8602 3-minute files were collected. These files were then limited only to data with an average wind direction that matches the predominant wind direction (292 degrees) plus or minus 10 degrees. The result was 327 files during normal operation, 129 files with maximum rotational speed (loss of load), and 254 files with the turbine in shutdown mode. This allows the resulting data to be categorized as downwind tower loads or crosswind tower loads. The wind speed distribution of the collected data is shown in Figure 3.

For comparison of measured data against Load Cases D through H, all contiguous 3-minute data files were combined to make 10-minute files because of atmospheric instability constraints. For fatigue comparison and presented data, the 3-minute data files were used.

IV. Analysis

A. Fatigue

The draft Standard provides equations to calculate ranges of thrust force, bending moment on the shaft, and the torque on the shaft. In order to compare these calculated ranges to test turbine tower loads, the simplified load equations were converted into ranges of stress. These act on the tower at the strain gage locations and are used to calculate the fatigue damage.

For both measured and simplified load equations, the loads are calculated to stresses using the tower geometry. The fatigue damage is estimated using Miner's Rule. For the simplified load equations, two partial safety factors are included in accordance with the draft Standard: a partial safety factor for materials of 1.25 and a partial safety factor for loads of 1.0. A design life of 20 years is assumed to calculate the number of fatigue cycles, assuming an S-N curve for structural steel (ASTM-A36) given in Equation (1) [3].

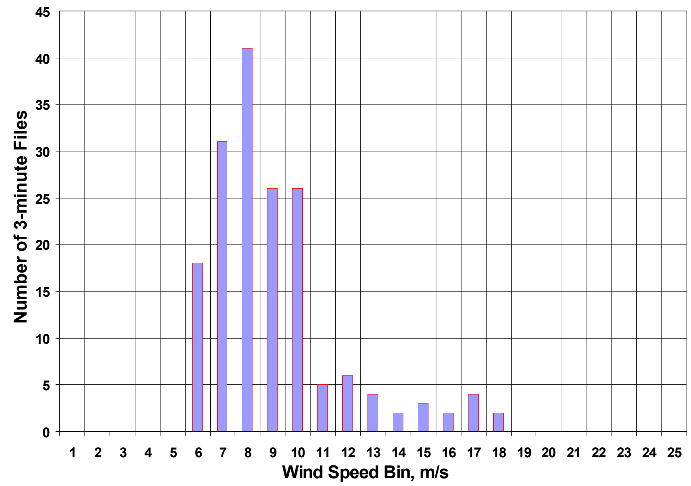

Figure 3. Wind speed distribution of time series data.

$$\log N = \log 13 - 3\,\log S \tag{1}$$

Where S is the stress on the specimen in MPa and N is the number of full fatigue cycles the specimen experiences.

For the measured loads, all measured data were rainflow-cycle counted. For each wind speed bin and for every range, the cycles from all time series were summed. The same S-N curve (Eq. (1)) was used to calculate the simplified load model number of fatigue cycles. Since the measured data did not cover all wind speeds for turbine operation, cut-in wind speed to 25 m/s (as shown in Fig. 3), some extrapolation was done. The wind speeds for which the measured data were extrapolated did not contribute much to the overall damage as most of the damage is done at wind speeds around 16 m/s (Figure 4). A Raleigh wind speed distribution was assumed over 20 years. The damage in each wind speed bin was then weighed by the occurrence according to this distribution. The fatigue damage per bin was then summed for all wind speeds. No partial safety factors were applied.

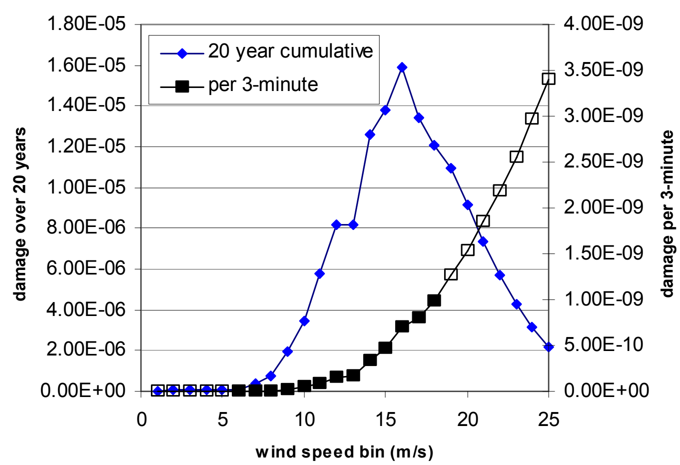

Figure 4. Fatigue damage in the crosswind direction.

Since the draft Standard is unclear on how to combine the fatigue ranges resulting from Load Case A, the fatigue damage was compared in the following manner: The fatigue damage resulting from the thrust force on the shaft was compared to the downwind fatigue damage because the thrust force is aligned with the downwind strain gauge bridges. Similarly, the fatigue damage resulting from the torque range on the shaft was compared to the crosswind fatigue damage. Table 3 shows the resulting fatigue damage comparisons.

The measured crosswind damage is higher than the damage calculated from the simplified load equations. This probably occurs because the turbine furls at higher wind speeds. This underestimation of damage in the crosswind direction by the simplified load equations is not an issue because the tower has to be designed for the higher fatigue damage due to the downwind direction for wind from any direction.

Figure 4 shows the fatigue damage occurring per 3-minutes file at each wind speed. The open markers are the extrapolated values. Despite the increasing fatigue damage with increasing wind speeds, the majority of the total damage occurred at wind speeds between 13 and 20 m/s.

Table 3. Fatigue damage comparison.

Downwind Damage	
Simplified Load Equations	3.4E-01
Measured	7.8E-04
Crosswind Damage	
Simplified Load Equations	2.7E-05
Measured	1.0E-03

B. Ultimate Loads

Using the simplified load equations from the draft Standard, a theoretical total bending moment at the location of the guy wires was calculated. Table 4 shows the results of those calculations for each load case that could apply to this test. The measured bending moments at the guy wires were derived from the strain measurements at the two different strain gage elevations on the tower.

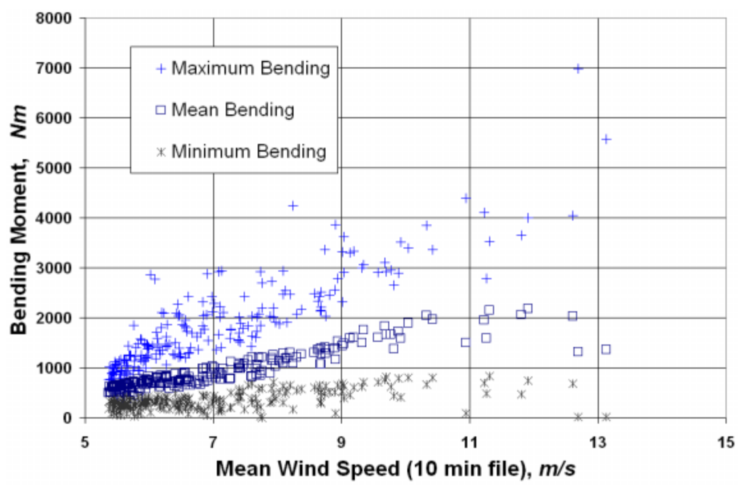

Figure 5. Measured bending at guy wires.

Regarding Table 4, it is important to note that 1) a partial safety factor of 3 (accounting for loads) and a partial safety factor of 1.4 (accounting for material properties) were used to make these calculations, and 2) the maximum theoretical bending is based on V_{ref}. However, the entire test data collected did not have wind speeds higher than 35.5 *m/s* (during Load Case E). Therefore, extrapolations to V_{ref} were done for the measured bending moment in each load case (see results in Table 4). The reader should be aware while looking at

Table 4. Maximum tower bending comparisons.

Load case D: Maximum Thrust		
Theoretical Bending§	8424	Nm
Measured Bending	6980	Nm
Extrapolated Bending**	10909	Nm
Load case E: Maximum Rotational Speed		
Theoretical Combined Bending§	3149	Nm
Measured Bending††	8692	Nm
Extrapolated Bending**	18629	Nm
Load case F: Short at Load Connection		
Theoretical Combined Bending§	185	Nm
Measured Bending	1203	Nm
Extrapolated Bending**	4286	Nm
Load case G: Shut-down (Braking) w/o Mech Brake		
Theoretical Combined Bending§	69	Nm
Measured Bending	1203	Nm
Extrapolated Bending**	4286	Nm
Load case H: Parked Wind Loading		
Theoretical Bending (spinning rotor)§	23078	Nm
Measured Bending	1203	Nm
Extrapolated Bending**	4286	Nm

§ Maximum tower-bending loads based on equations in the draft Standard.

** Extrapolated bending is data that were extrapolated to V_{ref}, 42.5 m/s.

Load Case E in Table 4 that the measured value used occurred while two generator phases were shorted together, whereas the draft Standard suggests that Load Case E should have an open circuit (no phases shorted together) when measured. However, the stated measured value in Load Case E was used because it is the best available data for that load case. Furthermore, because of the configuration of the test turbine, the measured data does not adhere to the draft Standard; Load Case H does.

Load Cases F and G are reduced to having the same criteria for collecting measured data as was used for Load Case H, which was not reduced from what the draft Standard suggests.

It is also important to note that for every extrapolation performed, the data were fit with a Brown and Mood robust resistant line. It was assumed that a linear extrapolation could predict bending loads at higher wind speeds.

Moreover, as shown in Figure 5, the test data display a positive correlation between bending moment and wind speed despite the fact that the onset of furling occurs at wind speeds of approximately 10 m/s. As the wind turbine starts to furl, the mean bending moment seems to remain constant as the wind speed increases. However, the maximum bending moment continues to increase with wind speed.

C. Turbine Events

The data that yielded the necessary information for Load Cases E and G were captured from a unique event. The turbine was in shutdown mode (Load Case G) while in 8 to 15 m/s average winds (15 to 23 m/s 1-second peaks). While in this state, the short-circuited electrical torque (SCET)‡ was sufficient to hold the turbine in an idling mode, which complies with a normal shutdown condition. However, as the average wind speed jumped to 18-23 m/s (17 to 40 m/s 1-second peaks), the SCET was not enough to keep the turbine in idle. The rotor then gained rotational speed and maintained an elevated rotational speed, which resulted in the failure of one generator phase at some unknown amount of time after the rotor was no longer held in idle. It is assumed that the turbine then obtained the maximum rotor speed (Load Case E) that was observed during this test. Furthermore, in the transition from Load Case G to Load Case E, the maximum measured tower bending increased by more than a factor of six (Fig. 6).

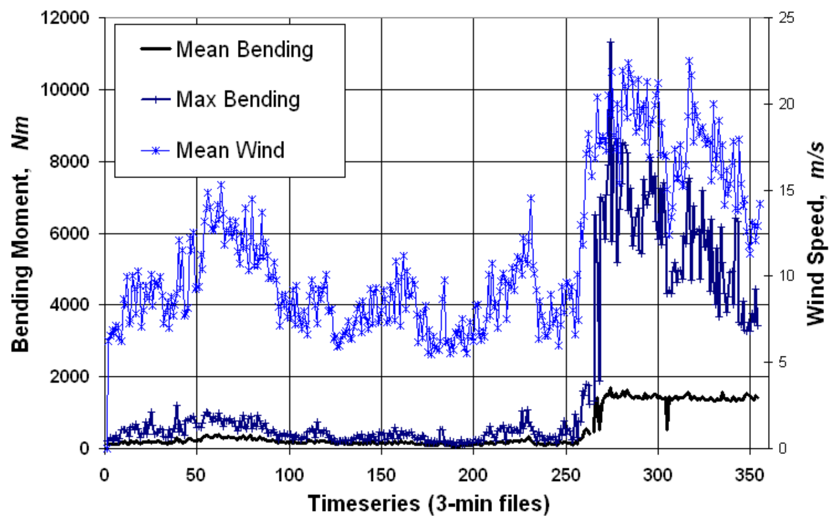

Figure 6. Mean Wind Speed with Mean and Maximum Bending Moment

V. Conclusions

The fatigue load ranges from the draft Standard simplified loads are conservative by a factor of six when compared to the measured fatigue loads. This factor of six was found using the lowest allowed safety factor for materials. For the draft Standard simplified load equations, the fatigue damage due to the torsion range is negligible compared to the damage due to thrust force.

When comparing the maximum measured tower-bending moment to the draft Standard maximum tower-bending moment, an extrapolation is necessary for proper comparison. The extrapolations of the test data suggest Load Cases D through G are not conservative enough to account for tower loads up to V_{ref}, the 50-year wind extreme for a 10-minute data set, whereas Load Case H is too conservative.

‡ Short-circuited electrical torque is the torque produced from shorting the generator windings together, which opposes the rotational velocity of the turbine rotor.

A. Future Work

Data will be collected on another small wind turbine of a different configuration (stall controlled, downwind, non-furling) and size to further investigate the accuracy of the simplified load equations in the draft Standard.

To further validate the simplified load equations, it would be helpful to add channels, such as rotational speed, turbine power output, and strain gages on the main shaft. It was our intention to do so, but unfortunately these channels were not available because of budget and time constraints. Furthermore, it would also be useful to collect data for wind events reaching the 50-year extreme so that extrapolation would not be necessary. This paper only covers one small wind turbine—it would be valuable to test different turbines of different sizes with different configurations.

Appendix A. Needed Parameters for Simplified Load Model

Parameter	Value
Number of blades	3
Rotor radius	1.5 m
Design power	1000 Watts
Design rotor RPM	800 RPM
Maximum rotor RPM	1200 RPM
Maximum yaw rate	169 °/sec
Annual mean wind speed	8.5 m/s
Extreme wind speed	59.5 m/s
Design wind speed	11.5 m/s
Air density	1.225 kg/m^3
Average chord of blade	0.078 m
Blade mass	0.6 kg
Blade c.g. from rotor center	0.425 m
Inertia of blade about hub center	0.118 kg-m^3
Distance hub to yaw axis	0.25 m
Mass of hub	3.9 kg
Distance from hub to first bearing	0.094 m

Acknowledgments

The authors would like to thank everyone who contributed to this work, including Mark Meadors for his diligent hard work throughout the testing phase, Jeroen van Dam and Rick Santos for their invaluable guidance and mentorship through the entire process, Sandy Butterfield for enabling this test to go forth, and Neil Kelley and John Peterka for lending their expertise in handling atmospheric data.

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[1] IEC 61400-2 Ed. 2 Wind Turbine Generator Systems – Part 2: Safety of Small Wind Turbines, International Electrotechnical Commission (IEC), 88/181/CDV, February 2004.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
November 2004	Conference Paper	

4. TITLE AND SUBTITLE
Tower Design Load Verification on a 1-kW Wind Turbine: Preprint

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A. Huskey and D. Prascher

5d. PROJECT NUMBER
NREL/CP-500-37112

5e. TASK NUMBER
WER5 4301

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-37112

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
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15. SUBJECT TERMS
wind energy; wind turbine; small wind turbine testing; wind turbine tower; load verification

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		
					19b. TELEPONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18