



Design, analysis and testing of a wind turbine blade substructure
by David Wright Combs

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:

This thesis presents the development of a substructure test for wind turbine blade materials (E-glass and polyester resin) and the initial experimental results obtained from this testing procedure. On going research at MSU has established baseline data for the fatigue response of rotor blade materials using coupon geometries to 10^8 stress cycles. The necessity for substructure testing is based on the accepted engineering procedure of incremental scaling towards full scale testing. In the case of composite wind turbine blades the necessity for this approach derives additional motivation due to the lack of experience with dynamic structures design for the expected lifetime of wind turbines, approaching 10^9 fatigue cycles in a 30 year service life, and the lack of experience with E-glass composite material applications at this level of cycling.

A four-point bending fixture was designed and fabricated that allowed static and fatigue testing of composite I-beams using a servo-hydraulic material testing machine. The I configuration was chosen to represent the region of the shear web and skin immediately above and below the web, of a rotor blade. Four-point bending was selected for the loading configuration due to the simplified stress state in the gage section of the beam, i.e, no shearing stress. The beams were manufactured using two resin transfer molds: one mold for the C-channels and the other for flat plates from which flanges and beam details were fabricated.

Fatigue testing of the beam pointed to the significance of structural details in fatigue design. Load and support pad failure, adhesive failure of the flange joints due to shear stress concentrations, ply-drop delaminations and shear web failure were the major developmental problems encountered. All were satisfactorily resolved except ply-drop delaminations and shear web failure. It is believed that thickening the web of the C-channels will eliminate shear web failure. Ply-drop delaminations warrant further investigation as they are commonly used in composite structures where a change in thickness is required.

The final beam design withstood over 2.2 million cycles at or above 6000 microstrain in the flanges. Of those cycles, 285,735 were at approximately 9000 microstrain. Both the static and cyclic beam flange strains at failure are close, slightly above, values predicted by coupon S-N data coupled with the finite element analysis.

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Bozeman, Montana

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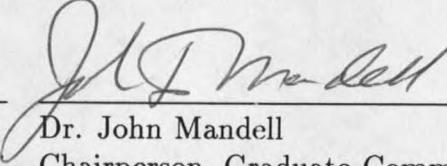
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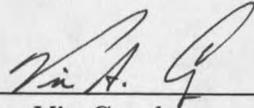
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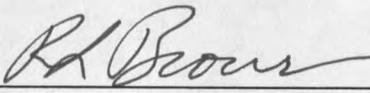
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ACKNOWLEDGEMENTS

As with any project there are a variety of people without whose help this thesis would not have come to fruition.

First, thanks to Dr. John Mandell, who conceived the project, and provided insight, encouragement and prodding along the way. Thanks also to other committee members, Dr. Aleksandra Vinogradov and Dr. Michael Wells. The test fixture and numerous fabrication details were expertly handled by Gordon Williamson and Lyman Fellows. A debt of gratitude is acknowledged for Andrew Belinky, Chuck Hedley and Daniel Samborsky, members of the Materials Group at MSU who provided comradery and the all important sounding board for ideas. Dan Ruff and David Doles, undergraduate students at MSU helped to build Beams 2 and 3 and completed some of the coupon testing, for altruistic and academic reasons. The National Renewable Energy Laboratory under subcontract XF-1-11009-5 provided the funding for this project. Dr. Dan VanLuchene of the Civil Engineering Department at MSU helped tremendously in the the area of finite elements. Shawna Lockhart of the Mechanical Engineering Department helped to extract me from the AutoCAD cauldron of solid modeling.

Mary Heath, my wife, and Nathan Combs, my son, are a constant source of inspiration and support.

TABLE OF CONTENTS

	Page
LIST OF TABLES	vii
LIST OF FIGURES	viii
ABSTRACT	x
1. INTRODUCTION	1
A Brief History of Wind Turbines	1
Wind Turbines as Electrical Generators	3
Fatigue Design	5
Lifetime Analysis for Metal Structures	7
Lifetime for Composite Structures	8
Statement of Purpose	10
2. PROCEDURES	11
Coordinate Systems	11
Shape of Substructure	12
Test Configuration	12
Beam Design	12
Materials	16
Fabrication of I-Beams	17
Units	18
Orthotropic Material Properties	19
Strain Gages	19
Center Point Displacement - Beams 4 & 5	20
Coupon Tests	21
Beam Fatigue Tests	21
Finite Element Analysis	21
3. BEAM DEVELOPMENT	23
First Iteration - Configuration 1	24
Second Iteration	29

Shear Failure at the Flange Adhesive Line	34
Beam 4	36
Beam 5 - Static Test	36
4. RESULTS AND DISCUSSION	42
Overview	42
Deflection Curve Equation	42
Theoretical, FEA and Experimental Comparisons	43
Damage Development	48
Change in Stiffness	54
Strain Gage Failure	59
Failure Modes	59
Coupon Correlation	63
5. CONCLUSIONS	67
Recommendations	68
REFERENCES CITED	70
APPENDICES	73
APPENDIX A - Mold Design	74
APPENDIX B - Test Fixture	78

LIST OF TABLES

Table		Page
1	E-glass fabrics used in fabrication of I-beam.	16
2	C-channel layup schedule.	18
3	v_f for C-channels.	18
4	Lay-up schedule and v_f for flat pieces of I-beam.	18
5	Isotropic material properties for E-glass and polyester resin:	19
6	Orthotropic material properties for composite I-beam.	19
7	A summary of beam configurations and testing regime.	24
8	Test history Beam 1.	27
9	Summary of cycles and loads for beam 1.	27
10	Test history Beam 2.	27
11	Test history Beam 3.	31
12	Test history Beam 4.	40
13	Load, micro-strain and cycles summary, Beam 4. Micro-strain values are the average magnitudes of tension and compression strain measured at the initiation of each sequence.	40
14	Comparison of FEA, beam theory and experimental strain vs load slopes, Beam 2.	45
15	Comparison of FEA, beam theory and average 1 st cycle experimental displacement and micro-strain vs load slopes, Beams 4 & 5.	45
16	Ratios of predicted displacement and micro-strain slopes over average experimental slopes for Beams 4 and 5. The experimental slopes listed are those derived from the 1 st cycle of testing.	45
17	Comparison of FEA and experimental strain vs load slopes, Beam 1.	46
18	Comparison of FEA and experimental strain vs load slopes, Beam 3.	46
19	Comparison of FEA, theoretical and experimental displacement vs load slopes, Beams 4 & 5.	47
20	Comparison of FEA, theoretical and experimental micro-strain vs load slopes, Beams 4 & 5.	47
21	Micro-strain at failure for coupons made from flange 1 material and the compression flange of Beam 5. All geometries were tested in a static ramp loading regime.	65

LIST OF FIGURES

Figure		Page
1	Wind turbines configurations.	2
2	Configuration of original VAWT's.	3
3	Conservative estimate of fatigue cycles.	4
4	Configuration of coupon test specimens.	5
5	Fatigue design flow chart.	6
6	Laminate and beam coordinate systems.	11
7	Cross section of NREL 9.6 meter aerofoil.	12
8	Input signal from MTS control panel.	13
9	Geometric and elastic entities for composite I-beam.	15
10	Thickness variation in C-channels.	17
11	Convergence of FEA solution for Configuration 1.	22
12	Beam configurations.	25
13	Alignment of FEA coordinate system.	26
14	Pad damage Beam 1.	28
15	Compression damage zone, tension side, Beam 1.	28
16	Shear failure of adhesive line, Beam 2.	31
17	Ply drops, Configuration 3, xy plane.	32
18	Front view of tempered glass from flat plate mold with polycarbonate sheets attached for ply terminations.	32
19	Delamination of ply drops, Beam 3.	33
20	Shear damage in adhesive layer, tension flange, Beam 3.	33
21	Shear stress XY at the adhesive interface of flanges, Configuration 2.	37
22	Shear stress XY at the adhesive interface of flanges, Configuration 3.	37
23	Shear stress XZ at the adhesive interface of flanges, Configuration 2.	38
24	Shear stress XZ at the adhesive interface of flanges, Configuration 3.	38
25	Shear stress YZ at adhesive interface of flanges, Configuration 3.	39
26	FEA shear stress XY at flange interface, Configuration 2, with isotropic material properties.	39
27	Accumulated damage on inner surface of tension flange, off axis plies, 518,945 cycles, Beam 4.	50
28	Accumulated damage on inner surface of compression flange, off axis plies, 518,945 cycles, Beam 4.	50
29	Accumulated damage on inner surface of tension flange, off axis plies, 2.24 million cycles, Beam 4.	51

30	Accumulated damage on inner surface of compression flange, off axis plies, 2.24 million cycles, Beam 4.	51
31	Outer surface of tension flange, 2.26 million cycles, Beam 4.	53
32	Outer surface of compression flange, 2.26 million cycles, Beam 4. . . .	53
33	Damage in shear web of Beam 4, immediately in front of the shear web stiffener, at 2.2 million cycles.	54
34	Change in micro-strain vs cycles, Beams 3 & 4. The sharp increase in the tension micro-strain values for Beam 3 is a reflection of the growth of adhesive failure in the flange interface due to shear.	55
35	FEA and experimental strain vs load data, Beams 1 & 2.	56
36	FEA and experimental strain vs load data, Beam 3:	56
37	Piston and center point displacement vs load, Beam 4.	57
38	FEA and experimental micro-strain vs loads, Beam 4.	57
39	FEA and experimental displacement vs load results, Beam 5.	58
40	FEA and experimental strain vs load results, Beam 5.	58
41	Micro Strain and milli-volt response to strain gage failure.	60
42	Failure of Beam 1.	61
43	Failure of Beam 4.	61
44	Failure of Beam 5.	62
45	Compression failure of flange 1 coupon.	62
46	Normalized flange compressive stress with damage in shear web. . . .	63
47	Comparison of flange 1 tensile coupon results with Beam 4.	66
48	Comparison of flange 1 compressive coupon results with Beam 4. . . .	66
49	3-d and top view of plate mold.	76
50	3-d and side view of c-channel mold.	77
51	Load fixture mounted in MTS load frame with composite beam in place.	80

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CHAPTER 1

INTRODUCTION

A Brief History of Wind Turbines

Human kind has employed the wind, for both commerce and recreation, since antiquity. The inception of the windmill, or in present day terminology, wind turbine, precedes recorded history [1]. Throughout history there have been two main configurations for wind machines, horizontal and vertical axes. Fig. 1 is a conceptualization of today's horizontal axis wind turbine, HAWT, and vertical axis wind turbine, VAWT.

Vertical axis windmills appear first in historical records [1], A.D. 600-800. The rotor assembly of these machines resembled paddle wheels found on steam driven paddle boats of Sammuel Clemen's day. These machines relied upon momentum transfer or drag to produce mechanical work. In order for a moment to be created about the axis of rotation it was necessary to shield part of the rotor assembly from the wind (Fig. 2).

HAWT's, incorporating a 90° angle in the drive train appeared in the 9th-10th century [1]. This shift in axis orientation necessitated the inclusion of an oblique orientation of the blades with respect to the wind. While the designers of the day certainly did not understand the principles, aerodynamic lift was being employed, albeit rather crudely [1, 2]. This genre of windmill was prevalent in the United States, starting in the mid to late 1800's. As a testament to the basic design, it is

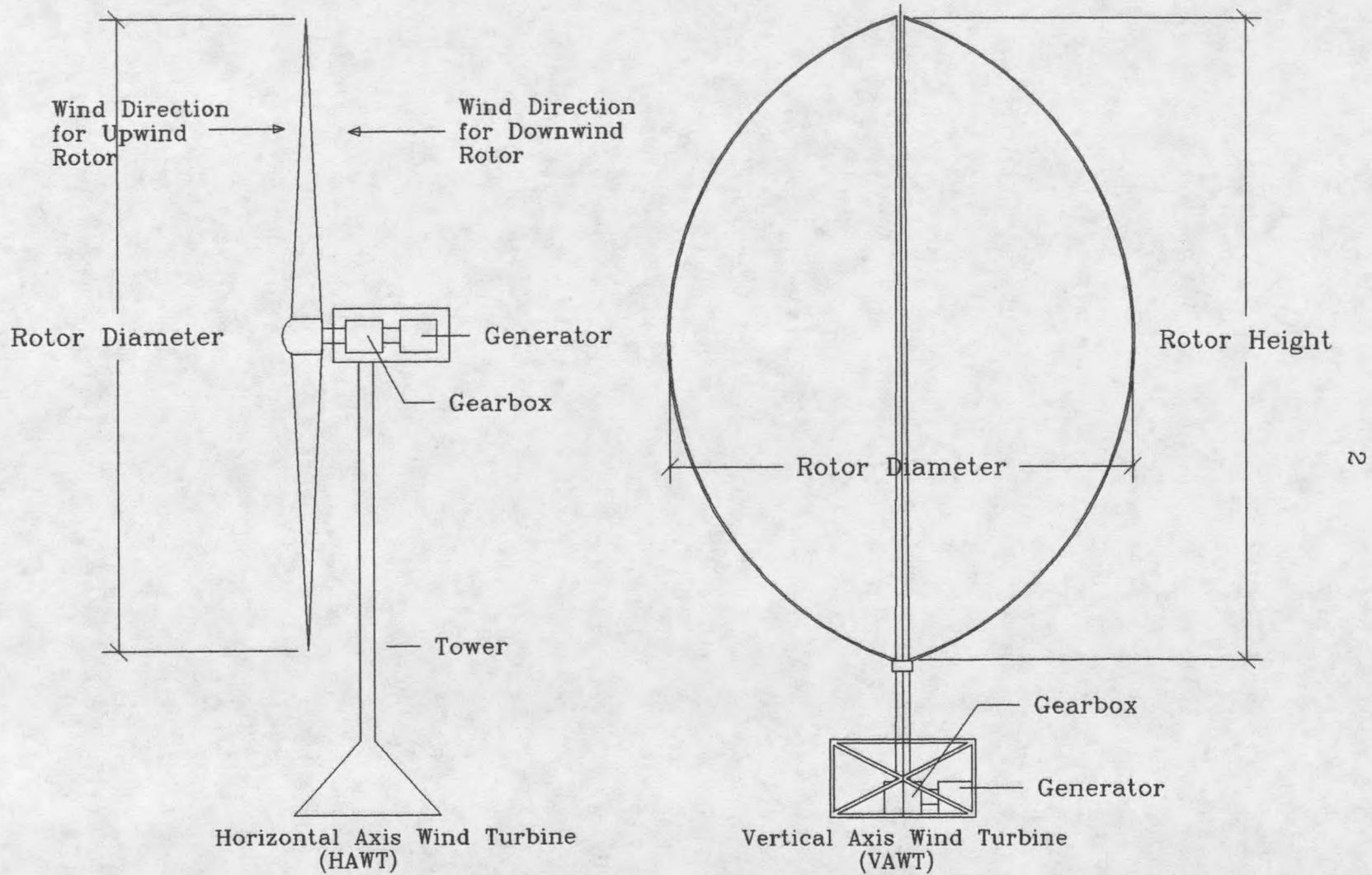


Figure 1: Wind turbine configurations.

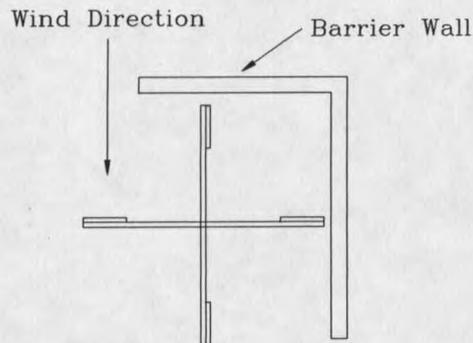


Figure 2. Configuration of original VAWT's.

estimated that there are 100,000 windmills of this variety operating in the United States today [3].

Wind Turbines as Electrical Generators

Modern wind turbines are a sophisticated synthesis of materials, aerodynamics, structural dynamics, electronic control and electrical generators. As of 1993 there were 1600 megawatts (MW) of wind energy capacity in the United States [4]. The American Wind Energy Association has set a goal of 10,000 MW of installed wind energy capacity in the United States by the year 2000 [4]. The size range of the most common wind turbines is 100-1000 kilowatts. To add perspective to these wattage numbers, at present there are approximately 16,000 wind turbines in the state of California. While California accounts for a majority of the wind turbines in the United States, wind energy is expanding throughout the United States and is a significant source of power in Europe as well.

The economic viability of wind turbines is, in part, dependent on a life expectancy of 20 to 30 years. A conservative estimate for fatigue cycles vs time for a

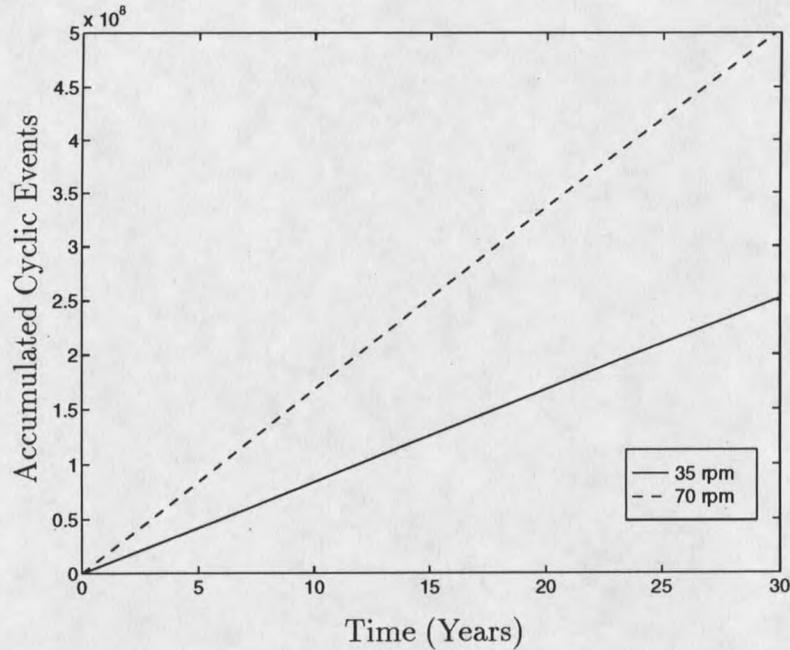


Figure 3. Conservative estimate of fatigue cycles.

wind turbine [5] is given by the equation,

$$N = 60 k \omega H_{op} t. \quad (1.2)$$

N is number of accumulated cyclic events, k is the number of cyclic events per revolution, H_{op} is the operating hours per year and t is time in years.

Fig. 3 is a plot of Equation 1.2) using $k = 1$, $H_{op} = 4000$, typical values range from 3000 to 4500 hours/year, and 35 and 70 rpm values for ω . Small wind turbines may operate at angular frequencies approaching 100 rpm while large turbine speed is approximated by 35 rpm. The use of $k = 1$ is the most conservative choice available, representing only the periodic influence of tower shadow for HAWT's. The actual loading regime experienced by a wind turbine is extremely complicated making this forecast an absolute minimum, although most cycles may experience stress amplitudes that are below levels where damage occurs in the rotor material. Wind turbines are one of the first large scale machines to be designed with a fatigue life of 10^8 to 10^9

