



Spectrum fatigue lifetime and residual strength for fiberglass laminates  
by Neil Kelly Wahl

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering  
Montana State University  
© Copyright by Neil Kelly Wahl (2001)

Abstract:

Engineering design of cyclically loaded mechanical components requires an understanding of the ability of the chosen material to fulfill a desired lifetime that is dictated by the fatigue properties of the material. Present fatigue lifetime prediction models for fiberglass laminates are non-conservative, prompting inefficient designs and this investigation for improved models.

This dissertation addresses the effects of spectrum loading on lifetime and residual strength of a typical fiberglass laminate configuration used in wind turbine blade construction. Over 1100 tests have been run on laboratory specimens under a variety of load sequences. Repeated block loading at two or more load levels, either tensile-tensile, compressive-compressive, or reversing, as well as more random standard spectra have been studied. Data have been obtained for residual strength at various stages of the lifetime. Several lifetime prediction theories have been applied to the results.

The repeated block loading data show lifetimes that are usually shorter than predicted by the most widely used linear damage accumulation theory, Miner's sum. Actual lifetimes are in the range of 10-20 percent of predicted lifetime in many cases. Linear and nonlinear residual strength models tend to fit the data better than Miner's sum, with the nonlinear providing a better fit of the two. Direct tests of residual strength at various fractions of the lifetime are consistent with the residual strength models. Load sequencing effects are found to be insignificant. The more a spectrum deviates from constant amplitude, the more sensitive predictions are to the damage law used. The nonlinear model provided improved correlation with test data for a modified standard wind turbine spectrum. When a single, relatively high load cycle was removed, all models provided similar, though somewhat non-conservative correlation with the experimental results. Predictions for the full spectrum, including tensile and compressive loads were slightly non-conservative relative to the experimental data, and accurately captured the trend with varying maximum load. The nonlinear residual strength based prediction with a power law S-N curve extrapolation provided the best fit to the data in most cases. The selection of the constant amplitude fatigue regression model becomes important at the lower stress / higher cycle loading cases.

The residual strength models may provide a more accurate estimate of blade lifetime than Miner's rule for some loads spectra. They have the added advantage of providing an estimate of current blade strength throughout the service life.

SPECTRUM FATIGUE LIFETIME AND RESIDUAL STRENGTH

FOR FIBERGLASS LAMINATES

by

Neil Kelly Wahl

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

Doctor of Philosophy

in

Mechanical Engineering

MONTANA STATE UNIVERSITY  
Bozeman, Montana

July 2001

D378  
W1259

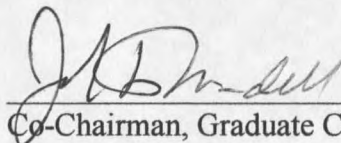
## APPROVAL

of a dissertation submitted by

Neil Kelly Wahl

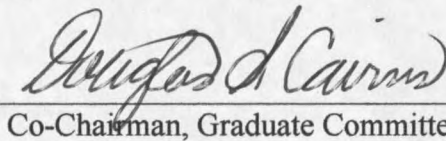
This dissertation has been read by each member of the dissertation committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. John F. Mandell

  
 Co-Chairman, Graduate Committee

7/20/01  
 Date

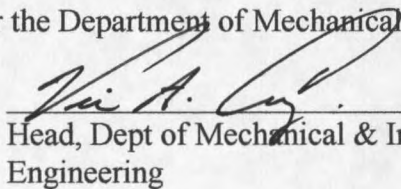
Dr. Douglas S. Cairns

  
 Co-Chairman, Graduate Committee

7/20/01  
 Date

Approved for the Department of Mechanical Engineering

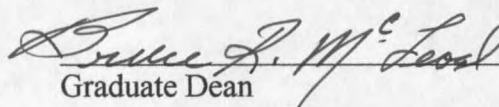
Dr. Vic A. Cundy

  
 Head, Dept of Mechanical & Industrial  
 Engineering

7/23/01  
 Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod

  
 Graduate Dean

7-23-01  
 Date

## STATEMENT OF PERMISSION TO USE

In presenting this dissertation in partial fulfillment of the requirements for a doctoral degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of Library. I further agree that copying of this dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for extensive copying or reproduction of this dissertation should be referred to Bell & Howell Information and Learning, 300 North Zeeb Road, Ann Arbor, Michigan 48106, to whom I have granted "the exclusive right to reproduce and distribute my dissertation in and from microform along with the non-exclusive right to reproduce and distribute my abstract in any format in whole or in part."

Signature Neil KWahl

Date July 21, 2001

## ACKNOWLEDGMENTS

This work evolved over the past six years and would not have been completed without the guidance of Drs. John Mandell, Douglas Cairns and Herb Sutherland and most certainly would not have been successful without the assistance and friendship of Mr. Daniel Samborsky. I offer them, my sincere appreciation and acknowledge their contributions.

Further thanks are extended to Mr. Samborsky for his photographic contributions to this dissertation.

This study was supported by Sandia National Laboratories through subcontracts AN-0412 and BC 7159, and the U. S. Department of Energy and the State of Montana under the EPSCoR Program, Contract DE-FC02-91ER75681.

## TABLE OF CONTENTS

|   |      |
|---|------|
| LIST OF TABLES .....  | viii |
| LIST OF FIGURES .....                                       | ix   |
| ABSTRACT .....  | xvii |
| 1. INTRODUCTION .....                                       | 1    |
| 2. FATIGUE OF MATERIALS .....                               | 6    |
| Background .....  | 6    |
| Metals .....  | 10   |
| Fiberglass Laminates .....                                  | 21   |
| Laminate Fatigue Description .....                          | 22   |
| Fatigue Trends of Fiberglass Laminates .....                | 24   |
| 3. LIFETIME PREDICTION MODELS FOR COMPOSITE MATERIALS ..... | 29   |
| Miner's Linear Damage Rule .....                            | 30   |
| Residual Strength Based Models .....                        | 32   |
| Residual Stiffness Based Models .....                       | 34   |
| 4. EXPERIMENTAL PROGRAM .....                               | 37   |
| Laminate Selection .....                                    | 38   |
| Coupon Design .....   | 41   |
| Tension-Tension Coupons .....                               | 41   |
| Compression-Compression Coupons .....                       | 45   |
| Reverse Loading Coupons .....                               | 47   |
| Testing Equipment .....                                     | 49   |
| Control Software .....                                      | 53   |
| Wind Turbine Data Acquisition System .....                  | 54   |
| 5. CONSTANT AMPLITUDE FATIGUE TESTING AND RESULTS .....     | 56   |
| Constant Amplitude Test Results .....                       | 56   |
| Residual Strength of Laminate Under Fatigue .....           | 69   |

## TABLE OF CONTENTS - CONTINUED

|   |     |
|---|-----|
| 6. BLOCK SPECTRUM FATIGUE TESTING AND RESULTS .....                   | 73  |
| Sequence Effects .....  | 74  |
| Two-Block Fatigue Testing .....                                       | 77  |
| Multi-Block Fatigue Testing .....                                     | 91  |
| 7. RANDOM SPECTRUM FATIGUE TESTING AND RESULTS .....                  | 94  |
| WISPER and WISPERX .....  | 94  |
| WISPERX Modifications .....   | 96  |
| Modified WISPERX Spectrum Test Results .....                          | 100 |
| Unmodified WISPERX Spectrum Test Results .....                        | 103 |
| 8. LIFETIME PREDICTIONS .....   | 105 |
| Constant Amplitude Fatigue Life Predictions .....                     | 106 |
| Block Spectrum Fatigue Life Prediction Mechanics .....                | 107 |
| Miner's Rule Lifetime Prediction Methodology .....                    | 107 |
| Residual Strength Rule Based Lifetime Prediction Methodology .....    | 108 |
| Two-Block Spectrum Fatigue Life Predictions .....                     | 110 |
| General Observations .....  | 111 |
| Comparison of Residual Strength Based Lifetime Prediction Rules ..... | 112 |
| Fatigue Model Selection Effect on Predictions .....                   | 113 |
| Three and Six-Block Spectrum Fatigue Life Predictions .....           | 114 |
| Modified WISPERX Spectra Fatigue Life Predictions .....               | 116 |
| Block or Cycle Damage Contributions .....                             | 121 |
| Unmodified WISPERX Spectrum Fatigue Life Predictions .....            | 127 |
| 9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS .....                     | 132 |
| Lifetime Observations and Application to Blade Design .....           | 133 |
| Comments on Spectrum Effects .....                                    | 134 |
| Stress Level Sequencing Effects .....                                 | 135 |
| Fatigue Model Selection .....   | 136 |
| Recommendations for Future Work .....                                 | 137 |
| Spectrum Considerations .....   | 137 |
| Compressive Residual Strength .....                                   | 137 |
| Failure Mode Transition .....   | 138 |
| Residual Strength Model Refinement .....                              | 138 |
| High Cycle Spectrum Fatigue Testing .....                             | 139 |

## TABLE OF CONTENTS - CONTINUED

|  |     |
|--|-----|
| REFERENCES CITED .....   | 140 |
| APPENDICES .....   | 146 |
| Appendix A - Spectrum Fatigue Database .....                         | 147 |
| Appendix B - Constant Amplitude Fatigue Test Summary .....           | 169 |
| Appendix C - Multi-Block Fatigue Test Summary .....                  | 182 |
| Appendix D - WISPERX Fatigue Test Summary .....                      | 193 |
| Appendix E - Wind Turbine Blade Strain Data Acquisition System ..... | 196 |
| Appendix F - Programs for Lifetime Prediction .....                  | 225 |



## LIST OF TABLES

| Table   | Page |
|---|------|
| 1. Summary of Ply Orientation Effect on Fatigue Trends .....                    | 28   |
| 2. Fiberglass Laminates .....   | 38   |
| 3. Instron 8800 Controller Tuning Parameters .....                              | 50   |
| 4. Exponential Regression Analysis Parameters for Constant Amplitude Fatigue .. | 60   |
| 5. Power Law Regression Analysis Parameters for Constant Amplitude Fatigue ..   | 62   |
| 6. Two-Block Testing Campaigns .....  | 77   |
| 7. Three-Block Test Results .....   | 91   |
| 8. Six-Block Spectrum .....   | 92   |
| 9. Six-Block Test Results .....   | 92   |
| 10. Exponential Regression Analysis Parameters for WISPERX Fatigue .....        | 100  |
| 11. Power Law Regression Analysis Parameters for WISPERX Fatigue .....          | 101  |
| 12. Descriptive Statistics for Constant Amplitude Miner's Sum .....             | 106  |
| 13. Lifetime Prediction Methods .....   | 110  |
| 14. Three-Block Spectrum Fatigue Life Predictions .....                         | 114  |
| 15. Six-Block Spectrum Fatigue Life Predictions .....                           | 115  |

## LIST OF FIGURES

| Figure  | Page |
|---|------|
| 1. Constant Amplitude Load History .....  | 2    |
| 2. Portion of European Standard Variable Amplitude Fatigue Load History .....   | 3    |
| 3. Micon 65/13 Wind Turbine Blade Edge Bending Moment History .....   | 4    |
| 4. Cyclic Loading Test Parameters .....   | 7    |
| 5. Load Regimes and R-Values .....  | 7    |
| 6. S-N Curve for 7075-T6 Aluminum Alloy, Fully Reversed<br>(R-value = -1) Axial Loading .....   | 8    |
| 7. Goodman Diagram .....  | 9    |
| 8. Hydro-Turbine Shaft Failure .....  | 11   |
| 9. Stress Intensity Factor and Crack Growth Rate Trends .....   | 14   |
| 10. Crack Growth Based Predictions of S-N Fatigue for 7075-T6 Aluminum<br>Plotted on Log-Log Coordinates (Constant Amplitude) .....                       | 15   |
| 11. Crack Growth Based Predictions of S-N Fatigue for 7075-T6<br>Aluminum Plotted on Linear Stress - Log Cycles<br>Coordinates (Constant Amplitude) ..... | 16   |
| 12. Typical Two-Block Spectrum, Second Block Continued Until Failure .....  | 18   |
| 13. Crack Growth Prediction for Two-Block Fatigue of 7075-T6 Aluminum<br>Second Block Continued Until Failure .....                                       | 19   |
| 14. Calculated Two-Block Fatigue Crack Growth Curves<br>for 7075-T6 Aluminum, Repeated Blocks .....   | 20   |
| 15. Typical Fracture Mechanics Based Predictions for 7075-T6 Aluminum<br>Two-Block Fatigue Miner's Sums .....   | 21   |
| 16. Schematic representation of the development of damage during the<br>fatigue life of a composite laminate .....  | 23   |

## List of Figures - continued

| Figure  | Page |
|---|------|
| 17. Comparison of Exponential and Power Law Constant Amplitude Laminate Fatigue Trends on Semi-Log Plot ..... | 25   |
| 18. Laminate Fatigue Trends for Tensile, Compressive and Reversing Constant Amplitude Loads .....             | 26   |
| 19. Normalized Goodman Diagram for Fiberglass Laminates Based on the MSU/DOE Data Base .....                  | 27   |
| 20. Effect of Exponent on Residual Miner's Sum Model (Constant Amplitude Fatigue) .....                       | 32   |
| 21. Effect of Exponent on Residual Strength Model (Constant Amplitude Fatigue) .....                          | 34   |
| 22. Laminate Residual Stiffness Experimental Trend (Constant Amplitude Fatigue, Carbon/Epoxy) .....           | 35   |
| 23. DD11 Constant Amplitude Fatigue, Preliminary Tests for Scatter, R = 0.1 ....                              | 39   |
| 24. DD16 Laminate Dry Fabrics .....   | 40   |
| 25. Pin Router .....  | 42   |
| 26. Test Coupon Configurations .....  | 43   |
| 27. Tensile Coupon Failure Examples .....   | 44   |
| 28. Compressive Coupon Failure Examples .....   | 45   |
| 29. Compressive Coupons at Runout .....   | 47   |
| 30. Reversing Coupon Failure Examples .....   | 48   |
| 31. Instron 8872 .....  | 50   |
| 32. Load Demand and Feedback Signals .....  | 51   |
| 33. Constant Amplitude Fatigue Test Results for R = 0.1 .....   | 57   |

## List of Figures - continued

| Figure   | Page |
|--|------|
| 34. Constant Amplitude Fatigue Test Results for $R = 0.5$ .....                                | 57   |
| 35. Constant Amplitude Fatigue Test Results for $R = -1$ .....                                 | 58   |
| 36. Constant Amplitude Fatigue Test Results for $R = 10$ .....                                 | 58   |
| 37. Constant Amplitude Fatigue Test Results for $R = 2$ .....                                  | 59   |
| 38. Goodman Diagram Based Upon Exponential Regression Analysis,<br>Including All Data .....    | 63   |
| 39. Goodman Diagram Based Upon Exponential Regression Analysis,<br>Excluding Static Data ..... | 64   |
| 40. Goodman Diagram Based Upon Power Law Regression Analysis,<br>Including All Data .....      | 64   |
| 41. Goodman Diagram Based Upon Power Law Regression Analysis,<br>Excluding Static Data .....   | 65   |
| 42. Normalized Fatigue Models, Exponential Regression,<br>Including All Data .....             | 65   |
| 43. Normalized Fatigue Models, Exponential Regression,<br>Excluding Static Data .....          | 66   |
| 44. Normalized Fatigue Models, Power Law Regression,<br>Including All Data .....               | 66   |
| 45. Normalized Fatigue Models, Power Law Regression,<br>Excluding Static Data .....            | 67   |
| 46. Exponential Fatigue Regression Models For All R-Values,<br>Including All Data .....        | 67   |
| 47. Exponential Fatigue Regression Models For All R-Values,<br>Excluding Static Data .....     | 68   |
| 48. Power Law Fatigue Regression Models For All R-Values,<br>Including All Data .....          | 68   |

## List of Figures - continued

| Figure   | Page |
|--|------|
| 49. Power Law Fatigue Regression Models For All R-Values,<br>Excluding Static Data .....   | 69   |
| 50. Residual Strength Data for R = 0.1 .....   | 71   |
| 51. Residual Strength Data for R = 0.5 .....   | 72   |
| 52. Excerpt of WISPER Spectrum .....   | 73   |
| 53. Two-Block Sequences (Blocks Repeated to Failure) .....   | 74   |
| 54. Two-Block Sequence Test .....  | 75   |
| 55. Overall Two-Block Miner's Sum, Stresses 325 and 207 MPa,<br>High Amplitude Cycle Ratio of 0.01 .....   | 76   |
| 56. Two-Block Test Results for R = 0.1, 414 & 325 MPa; Exponential<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions ..... | 80   |
| 57. Two-Block Test Results for R = 0.1, 414 & 325 MPa; Power Law<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions .....   | 80   |
| 58. Two-Block Test Results for R = 0.1, 414 & 235 MPa; Exponential<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions ..... | 81   |
| 59. Two-Block Test Results for R = 0.1, 414 & 235 MPa; Power Law<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions. ....   | 81   |
| 60. Two-Block Test Results for R = 0.1, 325 & 235 MPa; Exponential<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions ..... | 82   |
| 61. Two-Block Test Results for R = 0.1, 325 & 235 MPa; Power Law<br>Fatigue Model With Linear and Nonlinear Residual<br>Strength and Miner's Rule Lifetime Predictions .....   | 82   |

## List of Figures - continued

| Figure  | Page |
|---|------|
| 62. Two-Block Test Results for $R = 0.1$ , 325 & 207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 83   |
| 63. Two-Block Test Results for $R = 0.1$ , 325 & 207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 83   |
| 64. Two-Block Test Results for $R = 0.1$ , 235 & 207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 84   |
| 65. Two-Block Test Results for $R = 0.1$ , 235 & 207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 84   |
| 66. Two-Block Test Results for $R = 0.5$ , 414 & 325 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 85   |
| 67. Two-Block Test Results for $R = 0.5$ , 414 & 325 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 85   |
| 68. Two-Block Test Results for $R = 0.5$ , 414 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 86   |
| 69. Two-Block Test Results for $R = 0.5$ , 414 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 86   |
| 70. Two-Block Test Results for $R = 0.5$ , 325 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 87   |
| 71. Two-Block Test Results for $R = 0.5$ , 325 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 87   |

## List of Figures - continued

| Figure  | Page |
|---|------|
| 72. Two-Block Test Results for R = 10, -275 & -207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 88   |
| 73. Two-Block Test Results for R = 10, -275 & -207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 88   |
| 74. Two-Block Test Results for R = 10, -325 & -207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions ..... | 89   |
| 75. Two-Block Test Results for R = 10, -325 & -207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions .....   | 89   |
| 76. Two-Block Test Results for R = -1, 173 & 104 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Sum Lifetime Predictions .....    | 90   |
| 77. Two-Block Test Results for R = -1, 173 & 104 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Sum Lifetime Predictions .....      | 90   |
| 78. WISPERX Spectrum .....  | 95   |
| 79. Scaled WISPERX Spectrum .....   | 96   |
| 80. Modified WISPERX Spectrum Example .....   | 97   |
| 81. Mod 1 Spectrum for R = 0.1 .....  | 98   |
| 82. Mod 1 Spectrum for R = 0.5 .....  | 99   |
| 83. Mod 2 Spectrum for R = 0.1 .....  | 99   |
| 84. Mod 1 Spectrum Fatigue S-N Curve, R = 0.1 .....   | 101  |
| 85. Mod 1 Spectrum Fatigue S-N Curve, R = 0.5 .....   | 102  |

## List of Figures - continued

| Figure  | Page |
|---|------|
| 86. Mod 2 Spectrum Fatigue S-N Curve, $R = 0.1$ .....   | 102  |
| 87. Unmodified WISPERX Spectrum Fatigue S-N Curve .....   | 103  |
| 88. Miner's Sum Lifetime Prediction Methodology .....   | 108  |
| 89. Lifetime Prediction Cycle Trace, Residual Strength Models .....   | 109  |
| 90. Mod 1 Spectrum Lifetime Prediction, $R = 0.1$ , Exponential Fatigue Model<br>Including All Data .....   | 118  |
| 91. Mod 1 Spectrum Lifetime Prediction, $R = 0.1$ , Power Law Fatigue Model<br>Including All Data .....   | 118  |
| 92. Mod 1 Spectrum Lifetime Prediction, $R = 0.5$ , Exponential Fatigue Model<br>Including All Data .....   | 119  |
| 93. Mod 1 Spectrum Lifetime Prediction, $R = 0.5$ , Power Law Fatigue Model<br>Including All Data .....   | 119  |
| 94. Mod 2 Spectrum Lifetime Prediction, Exponential Fatigue Model<br>Including All Data .....   | 120  |
| 95. Mod 2 Spectrum Lifetime Prediction, Power Law Fatigue Model<br>Including All Data .....   | 120  |
| 96. Two-Block Stress Level Damage Contributions .....   | 122  |
| 97. WISPERX Spectrum Cycle Count .....  | 123  |
| 98. Stress Level Damage Contributions, Mod 1 Spectrum, $R = 0.5$ , 414 MPa ....   | 124  |
| 99. Stress Level Damage Contributions, Mod 1 Spectrum, $R = 0.5$ , 241 MPa ....   | 125  |
| 100. Two-Block Load Level Sensitivity, Low-Block Amplitude as Percent<br>of High-Block Amplitude (nonlinear residual strength model<br>prediction with $v = 0.265$ , exponential fatigue model) ..... | 126  |
| 101. Transition From Tensile to Compressive Failure Mode,<br>Constant Amplitude .....   | 127  |



## List of Figures - continued

| Figure   | Page |
|--|------|
| 102. Unmodified WISPERX Spectrum Lifetime Predictions,<br>Exponential Fatigue Model Including All Data .....               | 130  |
| 103. Unmodified WISPERX Spectrum Lifetime Predictions,<br>Power Law Fatigue Model Including All Data .....                 | 130  |
| 104. Comparison of WISPERX Lifetime Predictions; data and predictions<br>normalized by the ultimate tensile strength ..... | 131  |
| 105. Data Acquisition System .....   | 199  |
| 106. Data Acquisition GUI .....  | 200  |
| 107. Playback Software Screen .....  | 208  |
| 108. Goodman Diagram .....   | 226  |

## ABSTRACT

Engineering design of cyclically loaded mechanical components requires an understanding of the ability of the chosen material to fulfill a desired lifetime that is dictated by the fatigue properties of the material. Present fatigue lifetime prediction models for fiberglass laminates are non-conservative, prompting inefficient designs and this investigation for improved models.

This dissertation addresses the effects of spectrum loading on lifetime and residual strength of a typical fiberglass laminate configuration used in wind turbine blade construction. Over 1100 tests have been run on laboratory specimens under a variety of load sequences. Repeated block loading at two or more load levels, either tensile-tensile, compressive-compressive, or reversing, as well as more random standard spectra have been studied. Data have been obtained for residual strength at various stages of the lifetime. Several lifetime prediction theories have been applied to the results.

The repeated block loading data show lifetimes that are usually shorter than predicted by the most widely used linear damage accumulation theory, Miner's sum. Actual lifetimes are in the range of 10-20 percent of predicted lifetime in many cases. Linear and nonlinear residual strength models tend to fit the data better than Miner's sum, with the nonlinear providing a better fit of the two. Direct tests of residual strength at various fractions of the lifetime are consistent with the residual strength models. Load sequencing effects are found to be insignificant. The more a spectrum deviates from constant amplitude, the more sensitive predictions are to the damage law used. The nonlinear model provided improved correlation with test data for a modified standard wind turbine spectrum. When a single, relatively high load cycle was removed, all models provided similar, though somewhat non-conservative correlation with the experimental results. Predictions for the full spectrum, including tensile and compressive loads were slightly non-conservative relative to the experimental data, and accurately captured the trend with varying maximum load. The nonlinear residual strength based prediction with a power law S-N curve extrapolation provided the best fit to the data in most cases. The selection of the constant amplitude fatigue regression model becomes important at the lower stress / higher cycle loading cases.

The residual strength models may provide a more accurate estimate of blade lifetime than Miner's rule for some loads spectra. They have the added advantage of providing an estimate of current blade strength throughout the service life.

## CHAPTER 1

## INTRODUCTION

One of the many tasks in the design process for any engineered product has to be the consideration of component life. Life for these products is defined as the length of time that the component is capable of performing its intended service. The lifetime may be limited to a short life of a one time use or cycle in something as simple as a kitchen match. Conversely, a product may experience many millions of cycles of loading, such as that endured by rotating power generation machinery. Such long-life equipment that is subjected to cyclical loading and unloading is susceptible to fatigue failure.

Engineers need some fatigue lifetime estimating tools to assist in the design of products for consumer or industrial use. These tools can provide insight into material selection, size and shape, all to allow the product to achieve a desired lifetime. Development of estimating tools, also termed rules or laws, has proven to be quite successful for metals. A concise history of the evolution of the fatigue work in metals is contained in Reference 1, tracing the evolution from stress-cycle diagrams to linear elastic fracture mechanics and fatigue crack growth life predictions. References 2 and 3 also provide a history of the development of models for metal fatigue.

The development of predictive design tools for fiberglass laminates has lagged that of metals for a number of reasons, one of which is the anisotropic nature of the laminates. While metals have the single damage metric or parameter of crack size, composites have

many more complicated failure modes. Failure of composites may include matrix cracking, delamination, fiber debonding, fiber pullout, fiber buckling, ply delamination, ply failure, and fiber fracture; a typical failure may involve a complex contribution of some or all these possible mechanisms. Although rules based upon nearly every laminate property have been proposed, many seem to have limited validity, with theoretical and actual lifetimes sometimes decades apart [4]. The more complicated models do not seem to yield better results than the linear damage accumulation law first proposed by M. A. Miner in the 1940's [3, 5, 6]. Despite this law's shortcomings, it is used throughout the wind industry, for estimating laminate wind turbine blade lifetimes, e.g., Sandia National Laboratories' computer code LIFE2 [7-9], as well as by many researchers in laminate fatigue [10-12].

Fatigue testing of fiberglass laminates typically involves the constant amplitude sinusoidal loading of a specimen until failure. Illustrated in Figure 1 is data, captured by use

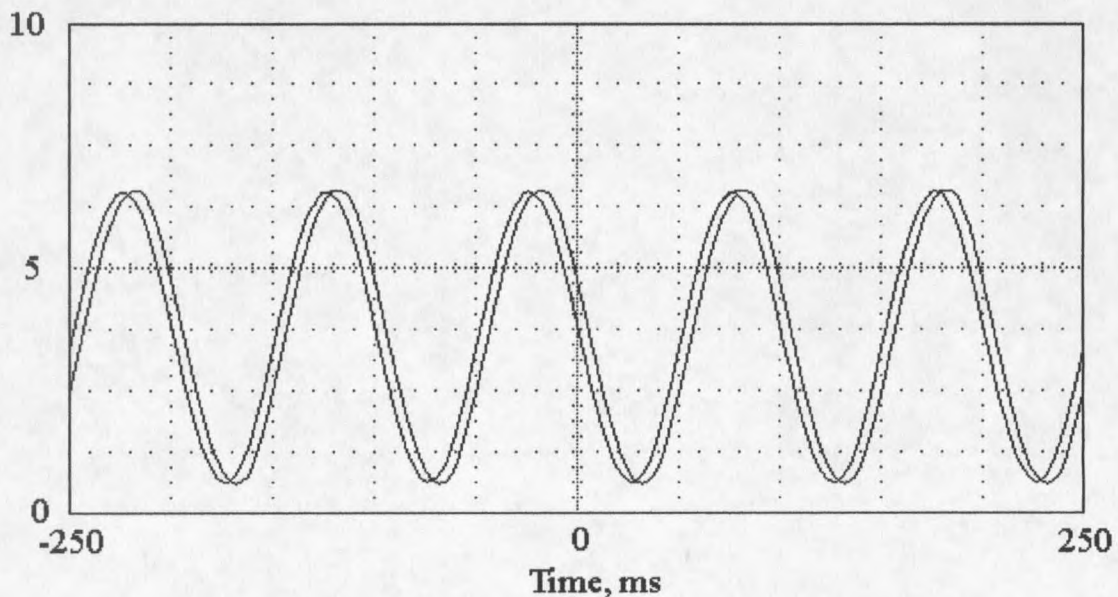


Figure 1. Constant Amplitude Load History

of a digital storage oscilloscope. The data is typical of load cycles used in constant amplitude fatigue testing. In the test; the cycle rate was 10 Hz, with maximum and minimum loads of 6.4 and 0.64 kN, respectively. Shown on the oscilloscope screen capture are both the demand and feedback signals from the test machine controller. The demand signal slightly leads the feedback signal. There is a slight amplitude deviation between the demand and feedback of approximately 1 percent in this example. The variation is a function of the laminate, test frequency, load levels and controller tuning.

Data such as found in References 13 and 14, which consist of the results of constant amplitude testing, are readily available. Unfortunately, constant amplitude testing and the Miner's rule ignore any possibility of load interaction and load sequence effects, which may be particularly important for load spectra that are random in nature. Shown in Figures 2 and 3 are variable amplitude spectrum loading histories for wind turbine blades. Figure 2 is a portion of a European standard loading spectrum [15, 16]; note the single, relatively large

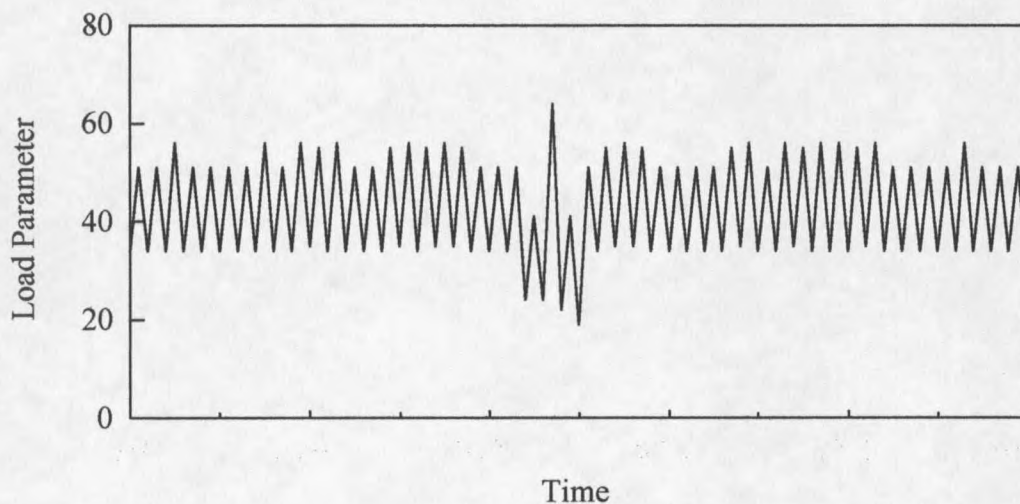


Figure 2. Portion of European Standard Variable Amplitude Fatigue Load History









































































































































































































































































































































































































































































































































































