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

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.

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APPROVAL

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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.

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Date July 21, 2001

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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.

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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

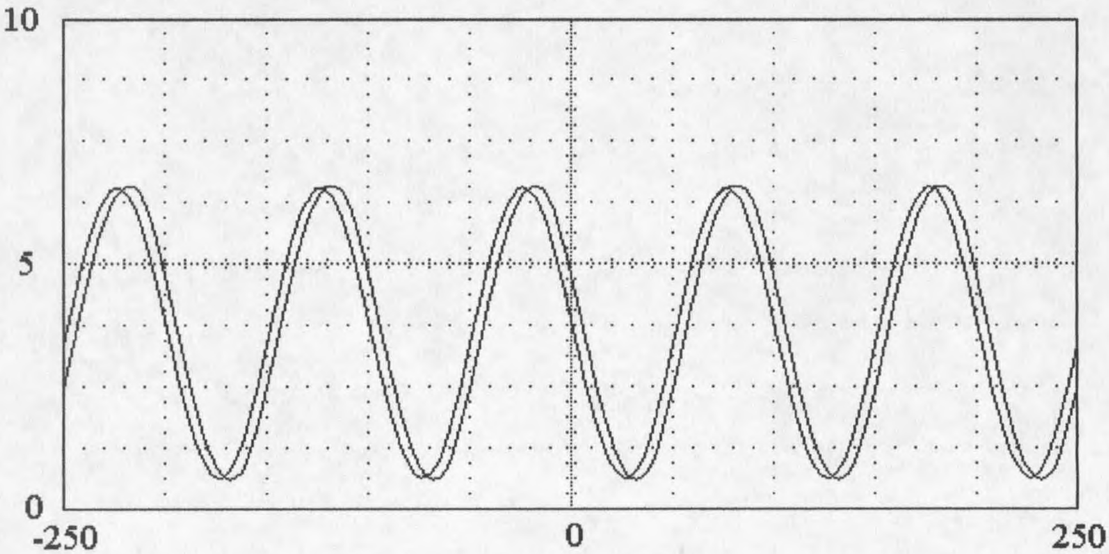

Figure 1. Constant Amplitude Load History

of a digital storage oscilloscope. The data is typical of load cycles used in constant amplitude fatigue testing. In the test; the cycle rate was10 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

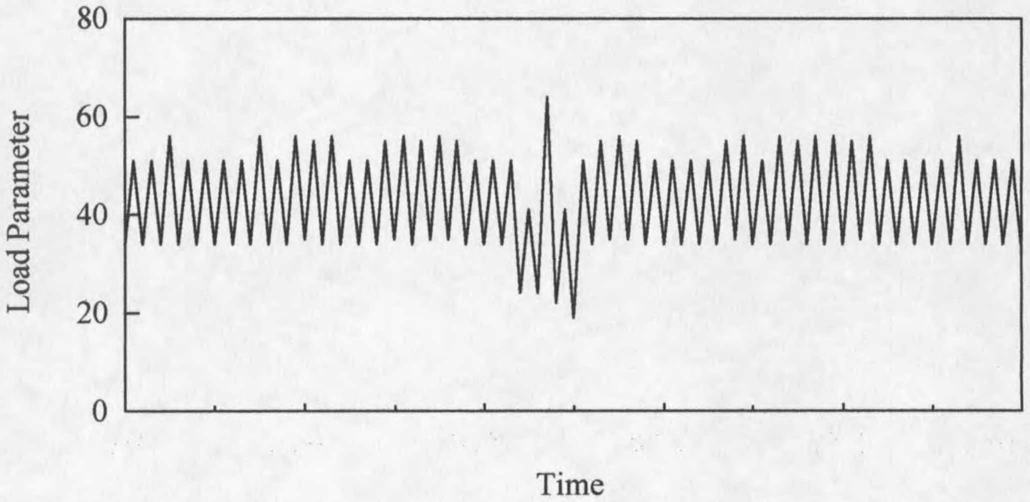

Figure 2. Portion of European Standard Variable Amplitude Fatigue Load History