MONTANA STATE UNIVERSITY

High cycle tensile fatigue of unidirectional fiberglass composite tested at high frequency
by Richard Francis Creed, Jr

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University
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Abstract:
This thesis is part of a more general study of high cycle fatigue resistance of composite materials for use in wind turbine blades. Wind turbine blades experience roughly 10^8 to 10^9 significant loading-unloading fatigue cycles in their 20 to 30 year lifetime. This number of fatigue cycles would require 100 to 1000 days for a single fatigue test using a typical test frequency of 10 Hz. (cycles per second). Frequency limitations with conventional composite fatigue tests derive from hysteretie heating and poor thermal conductivity. The objectives of this research were to develop a test method for unidirectional fiberglass composites which would allow testing at a frequency of up to 100 Hz, and to obtain tensile fatigue (R=0.1) data beyond 10^8 cycles.

Attempts were made to develop a very small specimen while maintaining the fundamental material properties in order to improve the heat transfer. By modelling the heat transfer in a finite element analysis, it was shown that the thin specimens used in this study should not generate significant heating. This was confirmed by surface temperature measurements. Stress distributions in the specimen tab area were also analyzed by finite element analysis.

Fatigue tests were run over a range of stresses and lifetimes out to 1.8 x 10^8 cycles at frequencies ranging from 30 to 100 Hz. The S/N data trend was consistent with standard coupon data tested at low frequency in the low to moderate cycle range. Direct comparisons of 75 and 10 Hz tests show a slightly longer average lifetime at 10 Hz. The high cycle data indicate a less-steep S/N trend at higher cycles than is commonly observed in low to moderate cycle data sets for fiberglass materials.

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APPROVAL

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Richard Francis Creed, Jr.

This thesis has been read by each member of the thesis 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

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Signature _Richard Reed Jr_

Date _March 29, 1993_

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ABSTRACT

This thesis is part of a more general study of high cycle fatigue resistance of composite materials for use in wind turbine blades. Wind turbine blades experience roughly 10^8 to 10^9 significant loading-unloading fatigue cycles in their 20 to 30 year lifetime. This number of fatigue cycles would require 100 to 1000 days for a single fatigue test using a typical test frequency of 10 Hz (cycles per second). Frequency limitations with conventional composite fatigue tests derive from hysteretic heating and poor thermal conductivity. The objectives of this research were to develop a test method for unidirectional fiberglass composites which would allow testing at a frequency of up to 100 Hz, and to obtain tensile fatigue (R=0.1) data beyond 10^8 cycles.

Attempts were made to develop a very small specimen while maintaining the fundamental material properties in order to improve the heat transfer. By modelling the heat transfer in a finite element analysis, it was shown that the thin specimens used in this study should not generate significant heating. This was confirmed by surface temperature measurements. Stress distributions in the specimen tab area were also analyzed by finite element analysis.

Fatigue tests were run over a range of stresses and lifetimes out to 1.8×10^8 cycles at frequencies ranging from 30 to 100 Hz. The S/N data trend was consistent with standard coupon data tested at low frequency in the low to moderate cycle range. Direct comparisons of 75 and 10 Hz tests show a slightly longer average lifetime at 10 Hz. The high cycle data indicate a less-steep S/N trend at higher cycles than is commonly observed in low to moderate cycle data sets for fiberglass materials.

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CHAPTER ONE

INTRODUCTION

Fatigue in windmill blade materials is an important design consideration which has been based on an inadequate data base to date. The primary reason fatigue is so important with windmill materials is that each time a blade passes the tower, there is a lull in the wind and the blade flexes. Since a windmill usually operates at between one and three revolutions per second, the materials in the blade may see thirty million significant fatigue cycles each year, and in the twenty to thirty year lifetime they may see between one hundred and nine hundred million cycles. Catastrophic service failures early in the expected lifetime were not uncommon with many earlier blade designs [1].

Much of the previous research done in the area of glass reinforced polymers (GRP) under fatigue loading was only carried out to moderate numbers of cycles. There is a clear need for fatigue data in the 10^8 to 10^9 cycle range experienced by blades over their 20 to 30 year lifetime. Existing fatigue test methods for fiberglass have been limited to the 10 to 20 Hz range because of hysteretic heating and poor thermal conductivity, which overheat the material [2]. At 10 Hz, 10^8 cycles in a single test would

take about 100 days, and is , therefore, impractical. The
objectives of this study were to develop a test method for
tensile fatigue of unidirectional fiberglass which would
allow testing in the range of 100 Hz, and to obtain data
beyond 10^8 cycles. The approach was to use a small enough
volume of material so that heat could be rapidly dissipated,
while still maintaining the behavior of larger volumes.

CHAPTER TWO

BACKGROUND

Review of General Composite Fatigue Testing

The basic principle behind any cycle dependent behavior is that nonconservative changes occur in internal nature or geometry due to the loading history. In general, this implies that some of the energy introduced into a system is not stored as strain energy, but dissipated as any number of possible events, such as crack formation, heat loss, stress-corrosion, etc. [3].

Many early investigators of the fatigue of composite materials experimented with polyester reinforced with chopped strand E-glass mat. Owen and Dukes [4] performed many cyclic tests on this material, and proposed several mechanisms for failure. The first damage mechanism was debonding, initially of the fibers lying normal to the tensile stress. The next mechanism was the initiation of cracking in resin rich areas. The third and final mechanism was fiber failure, and separation into two pieces. Each of these mechanisms occurred upon higher stress or increased cycles.

Many of the investigations into unidirectional fiber-glass fatigue ended without testing beyond one million

cycles. Dharan [5] performed an investigation of unidirec-
tional fiberglass and described the failure mechanisms in
three regions. The first region was dominated by fiber
catastrophic failure, and usually occurred up to two hundred
cycles with a corresponding high stress. Region II was
once again dominated by fiber failure, but the broken fibers
were far enough apart that failure was not immediate. These
breaks were initiated by cracks in the matrix emanating from
the surface. At later stages of Region II, the crack was
said to follow the along the interface between fiber and
matrix. The third region, which was beyond one million
cycles, had no fiber failures. Dharan concluded that the
stress level was below that which would be required to
propagate a crack since the glass fiber stress corrosion
mechanism requires a minimum stress, below which the crack
tip radius in glass increases. This increase in crack tip
radius results in little further crack growth [6]. Dharan
discontinued testing at two million cycles because of this
hypothesis.

Defining failure in a fatigue test is somewhat
ambiguous. Many researchers consider that the specimen has
failed when there are two pieces; others define failure as
when there has been a degradation of modulus, or stiffness,
to a percentage of the original value [7,8,9]. In windmill
applications, a loss of modulus above a particular value
will allow the blade to have a much greater flex than

originally expected and may allow the blade to hit the tower.

Fundamental testing of fatigue in GRP has been concentrated on laminates made from different fabrics and matrices. Fabrics can be made from chopped strands with random orientation or axial fibers stitched together with organic thread. Different matrices would include primarily epoxies, vinylesters, and polyesters for windmill applications. With a majority of laminates there are fibers in multidirectional arrays, a large portion of which are in the primary loading direction. Fibers in the other directions are for loads in other directions, but are responsible for damage initiation with loading along the primary axis. Fibers in the transverse direction act as stress concentrations in the very brittle matrix material. This causes the matrix in these layers to crack, and eventually cause damage in the axial layers which, in turn, will fail at some point. With the failure criterion of loss of stiffness, however, the material may be considered failed when the transverse layers fail [6].

Owen and Dukes performed many tests on chopped strand mat impregnated with polyester resin. Upon static and fatigue testing, damage was apparent at only thirty per cent of the ultimate strength of the material. This damage was associated with fibers perpendicular to the loading direction, and was initiated at many points on the strands.

At a load of twenty percent of the ultimate strength, damage was found along the interface between fibers and matrix at only one thousand cycles. The laminate could be expected to survive at least one million cycles before breaking into two pieces even though damage had begun two orders of magnitude of cycles earlier [4].

The effect of matrix on the fatigue strength of a composite has been described by Broutman and Sahu [10]. They concluded that epoxies had the best properties for high cycle low stress fatigue, and phenolics had the best properties for short term high stress tests. Polyester matrix materials started out with properties between phenolic and epoxy, but dropped off rapidly. For long life tests, polyester had slightly lower properties than phenolics, but much lower than epoxide materials [10].

Determinations of residual (remaining) strength at different stages of fatigue lifetime were performed by Broutman and Sahu [10]. The strength of a GRP decreases with increasing cycles, although there is much associated scatter. The methodology for determining the decrease in residual strength was to initially determine the stress versus number of cycles (S/N) curve for crossplied prepreg laminate. Based on expected lifetimes, for particular load levels, specimens were fatigued to percentages of that lifetime and then broken. Plots of number of cycles versus residual strength for different fatigue load levels were

reported. At higher load levels the ultimate strength tends to drop off rapidly, but at low load levels the strength tends to remain almost constant. Unfortunately, the report does not show the strength of the low stress specimens at high cycles [10]. Similar work was done by Rotem [11] who developed a mathematical model for predicting residual strength from cumulative fatigue theory. Resulting calculations show that the degradation of residual strength only occurs near the end of the fatigue life. Experimental results from Rotem [11] and Broutman and Sahu [10] show that the model closely predicts actual behavior.

Reifsnider *et al* [3] reported extensive research with unidirectional carbon fiber/epoxy laminates with 0, 90, and ± 45 degree plies. By utilizing light microscopy and edge replications, characterization of damage processes within laminates has been possible. Initially, cracks occur in the matrix of the off-axis plies either in the matrix material, or more commonly, in the interface between fiber and matrix. This is commonly called interfacial debonding. These initial cracks form and meet axial plies and eventually begin to cause damage in these main load bearing plies. This damage comes in the form of broken fibers and delamination. At some point, the amount of damage in the laminate tends to level off for a period of time. This area is called the Characteristic Damage State (CDS). Up to this point, the amount of stress necessary to cause localized

cracking has been enough to cause cracks spaced far apart in a ply. At a transverse crack surface the stress in the axial (0°) direction is zero, building up to the overall applied stress some distance from the crack face. Eventually, the stress or cycles will increase to a level high enough to cause another crack in the off axis ply. At some point, there will be a saturation level of cracks because the stress level between cracks will not be able to reach a high enough value to cause further cracking. This state is the Characteristic Damage State as described above. Further cycling beyond this point will cause delamination and fiber failure in the axial plies, eventually generating total separation [3].

One interesting characteristic of composite materials is the ability to withstand a large amount of damage without a significant loss of strength. In some cases where the specimen has a flaw such as a hole in the center or a notch in the edge, the strength of the composite actually goes up after some cycles have been put on the specimen. Such an example was reported by Stinchcomb and Bakis [12]. In the case where a static test is performed on a composite specimen with a round hole machined through the center, failure occurs on a line across the center of the hole. The hole generates a stress concentration and damage begins at its edges. When a fatigue test is run on a similar specimen, cracks and delaminations occur in the region

around the hole. This damage allows the stress to be redistributed around the hole, and consequently the specimen will have a higher static strength than one with no cycling. Although the static strength of the composite is improved with some damage from cyclic loading, the alteration of the stress field around the hole will eventually cause wear out of the specimen upon further cycling [12].

Much of the research covered thus far has considered matrix cracking as a primary concern in the fatigue of composite materials. Work by Mandell *et al* [13] has shown that the matrix has little effect on the fatigue sensitivity of fiber dominated GRP. When comparisons are made between the slope of maximum stress versus number of cycles (S/N) curves and corresponding single cycle strengths for different strength materials, fiber orientations, distribution of fibers, fiber length, and fiber content, the fatigue resistance seems to be insensitive to the listed factors. Typically, all types of glass fiber dominated composites, with the exception of woven fabric composites, tend to lose about ten percent of their initial strength per decade of cycles. This corresponds to a slope of negative one tenth on a normalized S/N curve for most E-glass reinforced composites [13].

Single strand tests were performed by Mandell *et al* both with and without matrix material, and the S/N curves for both were similar. This led to the conclusion that the

fatigue behavior derives primarily from the reinforcement
[13]. This conclusion derives from a comparison of the
ratio of ultimate strength of many composite materials to
the slope of their S/N curves. The slope of an S/N curve
usually fits a linearized semi-logarithmic curve of the form
[14]:

$$\frac{S}{S_0} = 1 - b \cdot (\log N) \qquad (1)$$

Where S is the maximum stress on each cycle and S_0 is the
one-cycle (static) strength. This comparison was made for
many different matrices and volume percent fibers, as well
as for fibers alone, and always came out to be about b=0.1
[14].

Although the fibers provide the dominant factor in
material properties as well as fatigue performance, other
factors may play significant roles in the breakdown of the
composite in fatigue. Several sources note a sudden drop in
modulus with different fibers and matrices, mostly
attributable to debonding of the fiber matrix interface and
matrix cracking. A study of the flexural fatigue of
unidirectional fiberglass by Shih and Ebert, run in stroke
control, showed significant fiber/matrix cracking
corresponding to a loss in stiffness. Since the tests were
run in stroke control, any loss in stiffness results in a
lower load on the specimen [15].

Review of Windmill Composite Material Fatigue

A great deal of research has been completed specifically for wind turbine applications of composites. The major concern, as has been stated previously, is the reduction in properties with continued cycling which has been the emphasis of a majority of the work.

One of the most complete studies was done by Bach [8]. Several types of tests were run including tension-tension (R = 0.1, where R = minimum stress/maximum stress), reverse loading (R = -1.0), and variable amplitude (WISPER, wind energy-specific load spectra) tests. Test specimens for the R = 0.1 tests were standard coupon sized specimens run at frequencies between 1 and 20 Hz and stresses between 35 and 65 percent of the ultimate strength of the unidirectional glass reinforced polyester. Conclusions from the tests were that a fatigue limit would only be reached in the range of fifteen percent of the ultimate strength and greater than one billion cycles. Another significant conclusion was that the data tended to follow a negative ten percent slope similar to that reported in other studies.

Appel and Olthoff [from Ref. 8] utilized this data to statistically arrive at a prediction for lifetime of composites. This prediction is a modification of that made by Mandell and includes the possibility of a fatigue limit (equation 2 [8]).

$$S_n = S_0 \left(1 - \left(0.15 \left(1 - \frac{signS_{min} * |S_{min}|}{signS_{max} * |S_{max}|}\right) + 0.08\right) \log N\right) \quad (2)$$

Tabs on the specimens used by Bach were 50 mm by 25 mm by 1.5 mm and had an angle tapered toward the gauge section for the last 5 mm. The author noted that almost all the specimens began delamination at the point of contact with the tab which spread as failure was imminent [8].

Much of the work done on windmill materials has either been done with reverse loading of full blades or coupon sized specimens. Conclusions by Kensche and Kalkuhl [16] show that even in the reverse loading regime there appears to be no fatigue limit before 100 million cycles for either coupon tests or full scale tests. WISPER loading on spar beams indicated that local instabilities, such as buckling, are the cause of most failures. When these instabilities are constrained, a spar can withstand more than five hundred WISPER cycles equivalent to eighty years of service. This conclusion was based on maximum strain levels of 0.6 percent on the spar. These results imply that higher design limits are possible on large diameter blades, greater than 25 meters, and therefore lighter more economic blades can be utilized [17].

The European design criterion for blade certification has a limit of 0.3 percent strain in the tension zone and 0.2 percent strain in the compression zone. Much of the work done shows that these values are quite conservative and

blades could be made much lighter and have adequate

lifetimes to those made presently. Design criteria are

often developed from laboratory scale testing which shows a

large decrease in stiffness shortly before failure. Fatigue

failure of larger components may not have this noticeable

stiffness decrease, and therefore, failure prediction

requires some method of inspection [18].

Recent studies reported by Mandell *et al* [19] on high

cycle fatigue of windmill blade materials have led to

several conclusions. Uniaxially reinforced materials were

found to have an S/N data trend falling below the 10 percent

loss of static strength per decade of cycles at high

stresses expected from previous studies. The trend followed

by the data is a power law with exponent of about m = 13.5.

$$\frac{S}{S_0} = N^{-(\frac{1}{m})} \qquad (3)$$

Effects of specimen width were studied by a comparison of

data for 1 and 2 in. wide specimens. The study reported

similar lifetimes at similar stress levels for the different

width coupons. Specimens used in testing usually are

machined and, therefore, have free (cut) edges. To study

the effects of free edges, standard size specimens machined

from sheets of material were tested and compared to

specimens molded 2 in. wide, with reinforcement wrapped

around at the edges. The resulting S/N data trend showed

little or no effect of the free edges. Comparisons of

specimens with similar reinforcement but different matrix materials (polyester or vinylester) revealed that the matrix has little effect in overall composite lifetime. However, vinylester composites tend to have slightly higher static strength [19].

Effects of Frequency on Fatigue

Effects of testing frequency on fatigue have been studied for many types of chopped strand fiber composites with the following areas of concern: hysteretic heating, rate of damage generation, and strain rate effects on the residual strength on the last cycle [20].

Hysteretic heating is the greatest problem with obtaining high cycle fatigue data for fiber reinforced plastics. The heat transfer within the plastic is very poor and even small amounts of strain energy absorbed in cycling can build up and cause the plastic to fail. To determine the amount of hysteresis for a particular stress level, one method is to find the loss factor (η), sometimes referred to as the tangent decrement. The loss factor can be arrived at experimentally with the use of a torsion pendulum and equation 4 [21]:

$$\eta = \frac{\ln \frac{A_n}{A_{n+1}}}{\pi} \qquad (4)$$

where A_n and A_{n+1} are amplitudes of successive cycles [21].

Relating the loss factor to the amount of energy dissipated in one cycle is done with equation 5 [22]:

$$D_s = 2\pi Q \eta \qquad (5)$$

where D_s is the strain energy at the maximum displacement and Q is the heat generation. Gibson [22] has shown that PPG SMC-65 has a constant loss factor over the frequency range from 10 to 1000 hertz and typically falls around 0.01.

Although frequency does not play a role in the loss factor, the amplitude of the input wave does. Kensche [17] has shown that η decreases nonlinearly with decreasing amplitude. The results show a drop of about a factor of two in the loss factor with a drop in amplitude of about twenty to thirty percent for many specimens.

Frequency effects other than from hysteretic heating are small. Glass fibers and polymeric matrices can show significant effects of constant load (static) fatigue, and it has been shown that time at maximum load causes much higher damage than the strain rate used in reaching that load [20,23]. However, fatigue behavior tends to be most influenced by the number of cycles not the frequency of cycling, particularly at high cycles [20,21].

CHAPTER THREE

EQUIPMENT AND MATERIALS

Test Facility

The procedure used for fatigue testing of E-glass
unidirectionally reinforced polyester is similar to that of
testing larger coupons, but on a smaller scale. Fatigue
testing was done on a servohydrolic Instron Model 8511 with
a load capacity of 2248 pounds force. The machine is
controlled by an Instron Model 8500 controller and computer
software. This low force machine is designed for high
frequency testing, with low friction bearings, a hydraulic
supply of 20 gallons per minute, a ten gallon per minute
servovalve, and a system pressure of 3000 psi. Figure 1 is
a photograph of the Instron 8511.

The specimens were clamped into the load train by grips
developed in this study (see Figure 22 in Appendix C).
Gripping force is provided by four screws tightened to 10
in.-lbf. torque. Force and displacement were measured by a
load cell, -5000 to 5000 pounds force capacity, and an LVDT
(linear variable displacement transducer) respectively. An
oscilloscope was used to define waveform quality at
different frequencies. Specimen surface temperature was
measured with Omega Templaq liquid crystal paints.

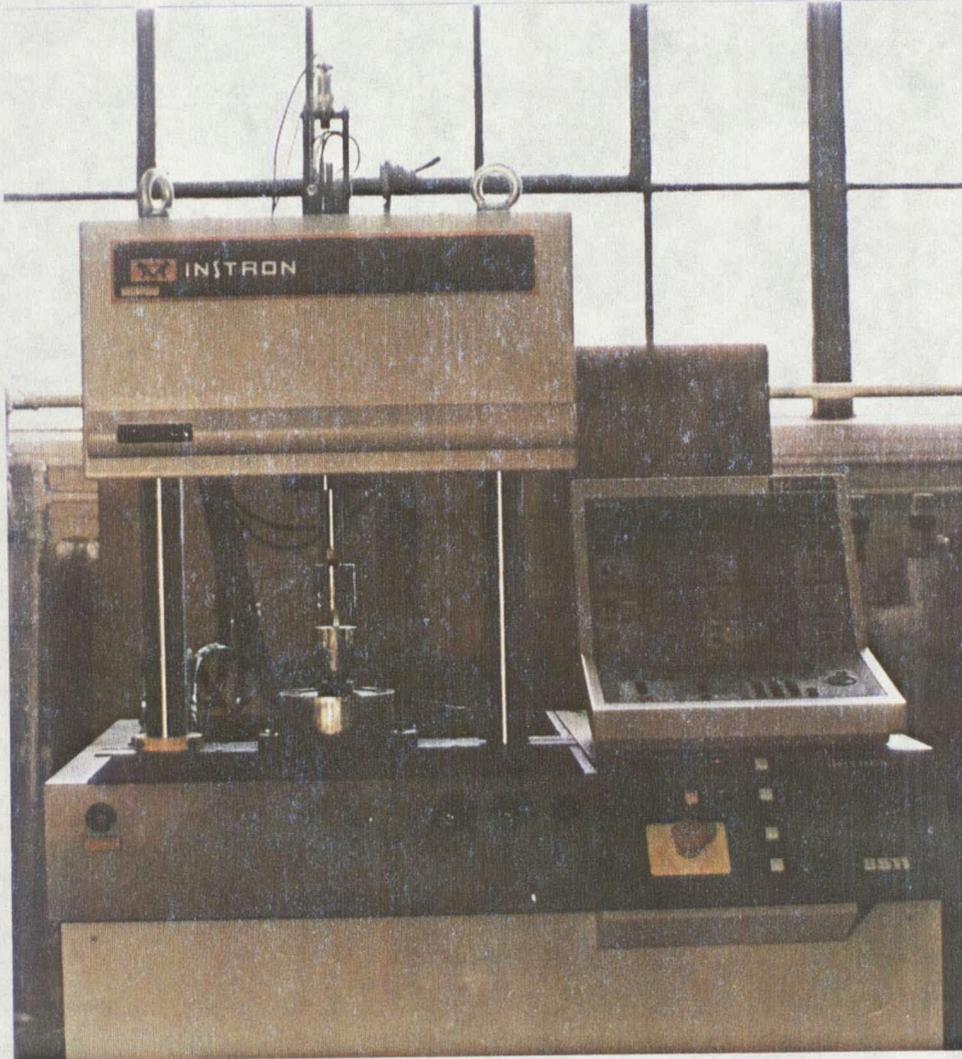All tests were run in load control with a constant sine

Figure 1. Photograph of Instron 8511.

wave input. The loading rate (maximum load/time to maximum load) was generally held constant between load levels by varying test frequency. Loading rate was varied somewhat because some testing frequencies gave poor waveforms and either speeding up or slowing down gave much better waveforms. Typical loading rates were between 8000 and 15000 pounds per second. The value chosen for single cycle tests was 4000 pounds per second, which was between one half and one third of the cyclic loading rate, in order to take many data points on a stress-strain curve. With higher loading rates, the stress-strain curve would be based on only a few points. This difference in loading rate should not significantly affect results [21].

All tests were conducted in ambient laboratory air. These ambient conditions are generally low humidity with temperatures between 65° and 80° F.

Materials

Raw materials were supplied by Phoenix Industries, and consisted of Manville Star Rove 502 EA glass fiber roving, one-quarter in. wide, and slow set orthopthalic polyester. Properties supplied by the manufacturer of the polyester are as follows: 0.68 msi modulus, 8.5 ksi ultimate tensile strength, and 1.10 g/cm^3. Figure 2 is a photograph of the glass roving showing the inherent fiber misalignment. The specimens were made in the laboratory by applying enough