High cycle compressive fatigue of unidirectional glass/polyester performed at high frequency

by Andrew Jay Belinky

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

Abstract:
This thesis is part of current materials research aimed at studying the behavior of polymer matrix composites at high cycles. The need stems from wind turbines which experience roughly 10^8 to 10^9 fatigue cycles (application and relaxation of load) during their 20 to 30 year lifetimes. Conventional fatigue testing is limited to 20 Hz (cycles per second) because of hysteresis heating problems caused by poor heat transfer capabilities of polymer matrix composites. However, at 20 Hz it would take 58 days to almost 1.5 years to reach the desired 10^8-10^9 cycle range. Previous work by Creed [3] demonstrated that high frequency (75 to 100 Hz) tensile fatigue testing can be accomplished using a specimen that is sufficiently thin that hysteretic heating is no longer a problem. The purposes of this research were to develop a high frequency compressive fatigue test method and obtain base line fatigue data for unidirectional glass/ polyester composites at R values (minimum stress/ maximum stress) of ten and two.

Two-ply specimens were cut from composite plates manufactured by resin transfer molding (RTM). Specimen geometry measured 2.2 inches long by 0.25 inches wide by approximately 0.035 inches thick. Fiber volume fraction was found to vary between the composite plate and individual specimens depending on the number of fiber bundles present in an individual specimen; however, no significant effects. of fiber content were observed in the S/N (stress versus number of cycles to failure) curves. Specimen porosity ranged from 2% to 4%.

S/N data and specimen failure modes for R=10 were in good agreement with literature data and with data from standard sized coupons manufactured from the same material as the high frequency specimens but tested at lower frequencies (10-20 Hz). The data approximately followed an 8% per decade decay line. For R=2 the data approximately followed a least squares 5.5% per decade decay line. Above 10^5 cycles the S/N curves for R=10 and R=2 flattened, and least square curve fits of these points (including runouts) showed that projected failure stresses at 10^9 cycles rose for both curves compared to curve fits using the entire data set. Frequency effects were examined using high frequency specimens tested at various frequencies but the same stress level. Data at 30 and 50 Hz correlated well, but some specimens at 10 Hz had longer lifetimes.

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4/25/94

Date

Chairperson, Graduate Committee

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Apr 25, 1994

Date

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Date 4/25/94

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ABSTRACT

This thesis is part of current materials research aimed at studying the behavior of polymer matrix composites at high cycles. The need stems from wind turbines which experience roughly 10^8 to 10^9 fatigue cycles (application and relaxation of load) during their 20 to 30 year lifetimes. Conventional fatigue testing is limited to 20 Hz (cycles per second) because of hysteresis heating problems caused by poor heat transfer capabilities of polymer matrix composites. However, at 20 Hz it would take 58 days to almost 1.5 years to reach the desired 10^8-10^9 cycle range. Previous work by Creed [3] demonstrated that high frequency (75 to 100 Hz) tensile fatigue testing can be accomplished using a specimen that is sufficiently thin that hysteretic heating is no longer a problem. The purposes of this research were to develop a high frequency compressive fatigue test method and obtain base line fatigue data for unidirectional glass/ polyester composites at R values (minimum stress/ maximum stress) of ten and two.

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CHAPTER ONE

INTRODUCTION

Within the past 30 years composite materials have made their way into a variety of structural components. From aircraft to automobiles, the desire to reduce weight while maintaining or increasing strength and stiffness has led engineers to turn to composites. This is nowhere more evident than in the newly resurgent wind energy industry. Based on the wooden windmills used by farmers to pump water for decades, the new wind power turbines are designed to be inexpensive, light weight, efficient, and produce electricity for communities at a rate competitive with current gas and possibly coal facilities. To achieve these objectives, manufacturers chose E-glass/ polyester or vinylester composites for their turbine blades. A dearth of information on material fatigue properties and blade service loading, as well as design and fabrication flaws, resulted in poor early machines that often failed far short of their projected 20 to 30 year life.

It is now known that wind disruption by the generator tower causes the turbine blade loads to change significantly each time they pass the structure (one per revolution). Each bending constitutes a major fatigue cycle where the blade experiences a loading and unloading of the applied wind load. Given that turbines rotate at one to three revolutions per second, a blade can experience between 10^8 and 10^9 fatigue cycles in its proposed 20 to 30 year lifetime [1]. Turbulence and other factors can also excite other vibration modes in the blades, causing higher frequency but usually lower amplitude fatigue cycles [2].

Presently, fatigue data for blade materials out to the high cycle range are very scarce, due mainly to the limited speed at which conventional fatigue tests can be performed. For E-glass/ polyester, 20 Hz (cycles per second) is a typical upper frequency limit; above this, internal heating becomes a major concern, and thermal failure can actually precede mechanical failure. At 20 Hz, though, a test to 10^8 cycles would last 58 days, and to reach 10^9 cycles would require almost one and a half years [1]. This is very important since it would take many years to characterize the fatigue behavior of a single material, and complications with testing equipment such as breakdowns and power outages would make successful long term tests very difficult to complete. The only alternative has been to extrapolate lower cycle data to high cycles, with no confidence in the extrapolation procedure. Therefore, current materials research is aimed at developing high frequency test methods which allow fatigue data to be obtained out to the 10^8-10^9 region in a reasonable amount of time. The basis for high frequency tests is to minimize test specimen thickness in order to improve heat transfer while maintaining the basic failure mode of larger specimens.

This thesis is a part of the overall materials testing program. Previous work focused on tensile fatigue and designing a test method to run longitudinal unidirectional specimens at high frequencies (75 to 100 Hz) [3]. The present study extends this work to longitudinal compression fatigue at high frequencies (75 to 100 Hz).

CHAPTER TWO

BACKGROUND

General Fatigue Properties

The fatigue behavior of fiber composites varies greatly compared with that of homogeneous materials. This is due primarily to the high degree of heterogeneity and anisotropy in composites. In isotropic materials such as metals, most of the fatigue life is spent nucleating and growing a single dominant crack. When the crack reaches a critical size, catastrophic failure results. With fiber-reinforced composites, however, damage often occurs on the very first cycle and there are numerous failure modes such as matrix cracking, fiber failure, interfacial debonding, and delamination. These can occur separately or interactively, making the study and prediction of composite fatigue behavior difficult. As a result, there is not as adequate a database on composite fatigue properties and performance as there is for metals. This section provides a brief overview of the fatigue process under predominantly tensile fatigue loading, including the damage mechanisms and their effects. For a more in-depth treatment of the topic the reader is directed to References 4-8.

Fatigue damage in composite materials has been defined as the cycle-dependent degradation of internal integrity [4]. This degradation is generally observed as a loss in stiffness and residual strength when the material is cycled at loads lower than the original ultimate strength. The process of damage development is widely dispersed in localized areas. Ultimate failure results when these localized regions have developed an intense enough state of damage to nucleate fracture of the entire specimen. Damage development in composites is dependent upon geometry, mode of loading, material properties and structural arrangement, and environment. Most literature studies have been concerned with fatigue under cyclic tensile loading.

Early work on fatigue of glass reinforced plastics (GRP) has established that matrix cracking is the initial form of damage in multidirectionally reinforced composites [9-11]. The matrix cracks form in resin rich areas between fibers that are aligned perpendicular to, or at large angles to the load direction. As cyclic loading continues, these cracks grow in the matrix and fiber/matrix interface until they reach the fibers of an adjacent layer. If the stress concentrations are great enough, the fibers will break; otherwise, the cracks may propagate along the fiber/matrix interface of the adjacent ply causing delamination. Owen and Dukes, using chopped strand mat, discovered that matrix cracks developed at stress levels as low as 20% of ultimate strength [10]. Chopped mat is composed of randomly arranged fiber strands rather than plies, and they found that cracks first initiated along fibers, or portions of fibers, lying nearly perpendicular to the load direction.

When Broutman and Sahu [11] studied glass/epoxy prepreg arranged in alternating 0° and 90° layers loaded in the 0° direction, they observed matrix cracks forming at stress levels as low as 10% and 20% of the ultimate strength. At 10% it took several thousand cycles, but at and above 20%, cracks developed on the first cycle in plies oriented at 90°. For plies oriented at 0° (parallel to the load) the stress level had to exceed 75% of the ultimate strength for cracks to initiate on the first cycle. At lower stresses cracks would initiate after a few percent of the specimen life. Furthermore, they observed that the crack density for 90° plies rapidly increased to its maximum value in the first one percent of the lifetime. Crack density in the 0° plies (matrix cracks parallel to the 0° fibers), however, increased rapidly during initial cycling, then leveled off until the late stages of life, whereupon it rapidly increased again prior to complete failure. They also observed that the residual strength of specimens decreased with increasing cycles and that delamination between layers occurred in the later stages of life.

Tanimoto and Amijima [12] examined woven glass cloth and polyester resin in tension fatigue and classified the progression of damage into three stages. The first stage occupied the first 2% of the lifetime and was characterized by numerous matrix cracks but no decrease in residual strength. The second stage occupied 2% to 50% of the life and was characterized by propagating cracks and a decrease in residual strength as cycles increased. The third and final stage occupied the second half of the life and was characterized by a slowing in the rate of reduction of residual strength until failure occurred. Tanimoto and Amijima observed the same crack density increase behavior as Broutman and Sahu and hypothesized that the large number of cracks in the resin regions acted to relieve high stress concentrations without affecting the residual strength. This hypothesis was later supported by Reifsnider [4].

Dharan [13] also examined the progression of damage using unidirectional glass/epoxy cycled in tension. He classified damage development into three regions based on the slope changes apparent on the S-N (maximum stress versus cycles to failure) curve. In Region I, (<200 reversals) the specimen exhibited an increase in matrix cracks with an increase in applied stress. There were also a large number of fiber failures which coalesced to cause catastrophic failure. The first half-cycle often caused the most damage, with large cracks being produced. In Region II, (200 to 10^6 reversals) matrix cracks developed on the first half cycle and then propagated perpendicular to the applied load. As the cracks grew they broke fibers, eventually reaching a condition where they moved along the fiber/matrix interface causing interfacial debonding, delamination, and finally catastrophic failure. In Region III, ($>10^6$ reversals) matrix cracks nucleated after several cycles but no specimens failed. Dharan hypothesized that in this case the applied stress level was below that required to propagate a crack through the glass fibers. The maximum number of cycles in these tests was $2x10^6$.

Recent work by Reifsnider [4] has refined the understanding of damage progression. He, like the other researchers mentioned above, separates fatigue life into three stages for a typical multidirectional laminate: stage I occupies the first 10-15% of life and is characterized by rapid damage development; stage II occupies the next 70-80% of life and is characterized by a decrease in the rate of damage increase; and stage III occupies the final 10-15% of life where the specimen is severely damaged, and continued cycling accelerates damage growth until final failure occurs.

Reifsnider's research has also provided more information on the damage modes present during fatigue. He has found that matrix cracking is present prior to failure in virtually all high-modulus continuous fiber multidirectional composites. These cracks form the basis for other damage which occurs during fatigue. For a given cyclic load level, Reifsnider concurred with Broutman and Sahu that the number of matrix cracks reaches a saturation state. Only by increasing the load could more cracks be grown. This saturation state is termed the Characteristic Damage State [4], and is unique to each laminate.

Fiber fractures, the second form of micro damage, occur throughout the fatigue lifetime but can become noticeable within the first third of life. In addition to breaking, these fibers experience local debonding around the newly created tips. As cycling continues these debonded regions can grow along the fiber/matrix interface, leading to interfacial debonding and eventual delamination between plies.

The third form of damage is the development of secondary matrix cracks. These occur in adjacent plies normal to primary matrix cracks and are caused by the stress field around the primary crack tips. Secondary cracks do not develop until later in the fatigue process and are more limited in extent than primary cracks.

The region where primary and secondary cracks cross each other forms the fourth damage mode, local delamination. Delamination is the separating of adjacent plies and is noticeable macroscopically (usually as discoloration in fiberglass reinforced composites) in the latter stages of life. Figure 1 illustrates the fatigue damage process outlined by Reifsnider.

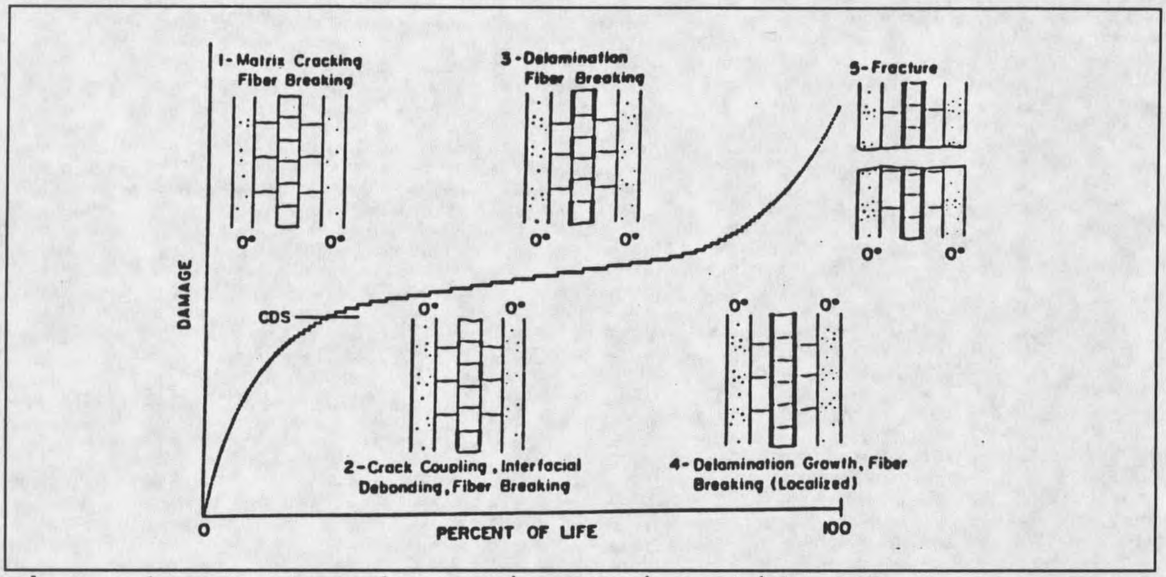

Figure 1. Damage Modes During Fatigue Life [4].

Compression Dominated Fatigue

Compression behavior of composites is not as well understood as tensile behavior. One major reason is sensitivity to test procedures. The method of specimen loading and whether deformation is laterally constrained can produce varying compressive strengths and failure modes. As a result, comparison of data obtained through different testing procedures is difficult. A review of current commonly used compression testing procedures is covered in the following section.

In unidirectional composites, the longitudinal compressive strength is generally lower than the tensile strength. Failure is usually sudden, with very little ply cracking or delamination preceding it. Some factors that influence compressive strength are constituent properties of the matrix and fibers, fiber diameter and alignment with the applied load, fiber volume fraction, and presence of defects, to name a few [14]. These factors are not much different than those affecting tensile strength; however, compression tests are generally more sensitive to variations in these parameters. Regarding alignment, for example, a five degree fiber misalignment from the load direction was found to cause a 22 percent decrease in compressive strength in graphite/epoxy specimens [14].

Another point of debate with compression is the identification of valid failure modes. In initial work in this area, Rosen [15] modelled a composite as a series of columns (fibers) on an elastic foundation (matrix). As a compressive load was applied to the model, an eventual critical point would be reached when the columns would elastically buckle and the composite fail. This model identified two failure modes, extension and shear (Figure 2). At low fiber volume fractions (below 30%) the extension mode was found to be dominant, while at higher fiber volume fractions (above 30%) shear dominated. However, the drawback with Rosen's model was its consistent over-prediction of

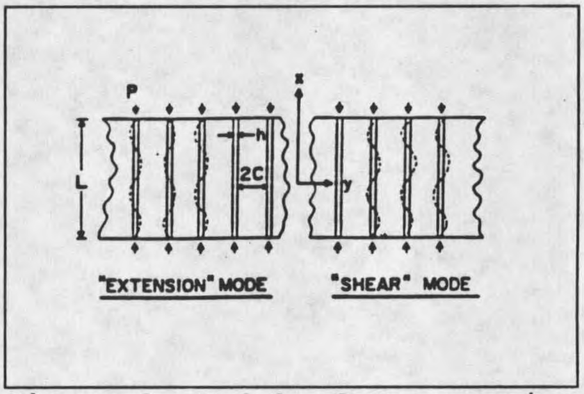

Figure 2. Model of Compressive Failure Modes [15].