WEST SYSTEM BRAND®

Technical Information

Fatigue

Catalog number 000-545

Fatigue aspects of epoxies and epoxy/wood composites

In materials science, ***fatigue*** is the name for the process of weakening materials and structures by subjecting them to repeated loads. This paper addresses the cyclic fatigue-related degradation of epoxy composite materials and serves as a guide to a better understanding of this very complex composite material failure mode. All materials suffer damage from dynamic loads–some more so than others. This damage usually cannot be seen or in any other way measured until failure is imminent. Understanding this fatigue degradation process is difficult even with homogeneous materials, such as metals. For composites, it is the mix of different materials, directional properties, and load paths, each with its own unique response to fatigue loads, that presents the greatest challenge in characterizing fatigue performance.

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Introduction

Since the early 1980s, Gougeon Brothers, the testing, research and boatbuilding parent of WEST SYSTEM, has conducted an extensive series of fatigue research programs. These were originally designed to support their efforts to build wind turbine blades that could withstand 400 million fatigue cycles over a thirty-year life span. In addition, these testing programs had to provide a basis for developing quality control procedures that could assure 100% success with a given manufacturing process. Optimizing the blade design for weight, performance, and reliability became paramount. The success of this program has been demonstrated with the manufacture of more than 4,200 rotor blades, not one of which has failed under designed operating conditions.

The data presented in this paper relate to the two materials most used in Gougeon wind turbine blade and boat manufacturing: epoxy resins and Douglas fir veneer in the form of wood/epoxy composites. The purpose of presenting this data is not to attempt a definitive materials characterization, but to portray some important issues of wood composite material fatigue. Glass fiber reinforcing materials were also used in Gougeon wind blade and boat manufacturing efforts. Because this material plays a more minor role and its performance characteristics are well reported in other papers, we do not cover its performance characteristics in depth with this paper.

Before proceeding with a discussion of the wood-epoxy fatigue data, some key elements associated with classical fatigue testing need to be explained. First of all, when operating in fatigue mode, test machines apply a force to each material specimen that increases and decreases in a regular pattern, a pattern that corresponds to a mathematical sine-wave function. In other words, the repeating force pattern has smoothly rounded peaks and valleys. One cycle of load consists of one swing from the valley up to the summit and back down to the valley again. Note: The test force is supposed to reach the same prescribed maximum and minimum value on every load cycle, regardless of the condition of the specimen (until it breaks). Test engineers typically present the results of a particular fatigue test in terms of the cycles to failure for a specified ***peak load*** or ***peak stress***. This is the basis of the S-N curve, a graphical display where "S" stands for the peak stress and "N" stands for the number of cycles a given specimen withstood before it broke. Sometimes the peak stress is expressed as a percent of the ultimate strength of a material, as measured in a previous static strength test (see Figure C-1).

Another important term is ***Stress Ratio***, which is sometimes designated as ***R Value***. It is defined as the ratio of the load minimum to the load maximum for a typical fatigue cycle and is a parameter which is always specified (and held constant) in any classical fatigue test series. If the R value was set to 0.1 for a test series, it means that the load in the valley was always one-tenth of the load at the peak for all cycles. The terms "Stress Ratio" and "R Value" are interchangeable. It takes both the peak stress and the stress ratio to adequately characterize a classical fatigue test.

The Fatigue Question

The problem with static test data is that it only explains how a material behaves under a single application of load large enough to cause failure. Boats rarely fail under this kind of static loading. Most failures occur only after many thousands or millions of much smaller loads, which very slowly and systematically unravel a material. All materials respond differently to fatigue stresses and are characterized by a fatigue curve as shown in Figure C-1. All the curves illustrated in Figure C-1 begin at a maximum level, with 100% corresponding to the one-time load-to-failure capability of each material. The curves represent the combined results of many individual samples, each tested at a different peak stress. As the peak stress is decreased, the number of cycles required to produce failure is increased. Each individual peak stress and failure point is then plotted to form a fatigue curve. The goal of fatigue testing is to find the level of peak stress where a material can withstand a given cyclic loading for a very long or indefinite period, without undergoing further degradation.

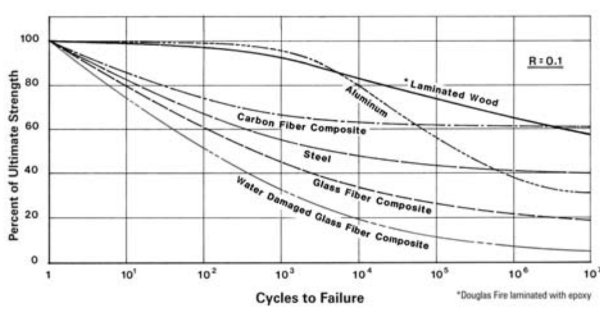

Figure C-1 Tensile Fatigue Comparison.

This theoretical endurance limit is reached with most steel materials at around ten million cycles (10^7) at a load of approximately 40% of its one-time static capability. Carbon fiber is one of the more fatigue-resistant materials, with a fatigue endurance limit of approximately 60% of its one-time load capability. But this is only in the exact direction of the fiber itself; in comparison, steel has a structural advantage in that it exhibits the same properties in all directions.

Some materials either have not revealed an endurance fatigue limit or that endurance limit is reached at such high cycles no one has been able to test far enough out on the curve to find the limit. Aluminum degrades very quickly from 10^3 to 10^6 cycles, but then displays a flattening of its curve at 10^7 cycles. Although aluminum continues to degrade, it does so at an extremely slow rate over the next 100 million cycles (10^8), permitting a long-term material reserve of 15% to 20% for aircraft use. Wood retains an extremely high percentage of its capability at 10^7 cycles, making it a remarkably fatigue-resistant material. Because little testing has taken place with wood beyond 10^7 cycles, it is not known where its endurance fatigue limit is reached. Very old trees indicate this endurance limit is quite high. Glass fiber-reinforced composites exhibit the sharpest drop in fatigue resistance, retaining only 20% of original capability at 10^7 cycles. Leading researchers in the glass fiber materials area believe there is no well-defined fatigue endurance limit for glass fiber composite, and that it suffers a steady degradation of approximately 10% of its initial strength per decade of fatigue cycles.[1] There are data which suggest that the long-term durability of glass fiber-reinforced composites may be further compromised when attempts to reduce structural weight result in local resin insufficiency. Unfortunately, the fatigue life of glass-fiber composite structures often depends upon process and construction details, which are not reproduceable in small-volume test specimens.

The relevancy of one million fatigue cycles (10^6) might be put in perspective with the following analysis: In a controlled experiment, wave frequency was monitored on a sailboat hull with an associated increase and decrease in load once every three seconds.[2] Assuming this to be a typical cyclic loading rate on a yacht at sea, it would take 833 hours of continuous sailing to achieve one million fatigue cycles. In a typically-used sailboat, it may take several years to reach this number of hours, but a cruising boat making an around-the-world passage could easily acquire this many hours in one voyage. Powerboats operating at high speeds are subjected to a greater wave frequency, causing their materials to fatigue more rapidly, with 10 cycles per second possible. At this rate, one million fatigue cycles could be accumulated in fewer than thirty hours.

Understanding the response of materials to cyclic fatigue loads is a complex science practiced by only a handful of researchers. Developing reliable fatigue data is time-consuming and expensive. A data point at 10^7cycles with plastic materials can require weeks of continual test machine cycling of a single test sample at a cost of several thousand dollars.

A complication of fatigue research is the effect of flaws on a material's behavior. In any manufacturing effort, it is impossible to achieve consistently perfect material. Thus, there is always variability in the test data, which generally indicates how much the material in each test sample is flawed. A major goal of the research effort is to understand the statistical impact of the flaw phenomenon on test results. In any test series, some low-performing test sample results must be dealt with when interpreting data to achieve proper design allowables.

Metals, being homogeneous materials (having the same strength and stiffness in all directions), are much easier to test and understand than composites. Metals can also be tested at faster cyclic loading rates because heat buildup within samples does not degrade test sample performance as it does with composites. Because metals have been studied more extensively, there is a good understanding of how they behave under a variety of long-term fatigue conditions. A good correlation has also been developed between static capability and probable endurance fatigue limit with a given metal alloy material. With this large bank of knowledge with a homogeneous material, the job of designing with metals is much easier than designing with directionally-oriented wood or synthetic fiber-reinforced composite materials, especially when trying to guarantee a specific life span.

Epoxy

In wood/epoxy composites, epoxy is the "glue" that holds reinforcing wood or synthetic fibers together to form a true composite material. Epoxy is also used as an adhesive to bond laminate parts together to form completed structures. Knowledge of how an epoxy resin system performs these functions over a long period of time is essential to the design engineer. Unfortunately, very little information has been developed in this area. Typical static stress/strain properties that are given for plastics can only be useful as a general guide when comparing one plastic material with another; no inferences should be drawn from static data about endurance fatigue life or other longevity issues. Developing comprehensive data on fatigue life is expensive and time-consuming. Because of this, even the largest resin manufacturers have been reluctant to support the expense of gathering this data.

The work we have done with resin testing has been limited to room temperature cure (R.T.C.) epoxy-based systems. Most of Gougeon research and development work with R.T.C. epoxy has been in support of wind turbine blade manufacturing efforts. The goal was to develop epoxy that could bond wood, glass fiber, and steel together to yield structures that could survive in a high-fatigue environment with temperature variation between -30°F to 120°F (-34°C to 49°C). The epoxy also needed to be resilient (tough) enough to resist the stress concentrations inevitable when bonding dissimilar materials. Fortunately, this same set of design requirements also suits the marine industry.

Avoiding the limitations of temperature effects when testing R.T.C. epoxy systems has been very difficult. Room temperature cure epoxies are viscoelastic materials that display properties intermediate between crystalline metals and viscous fluids. Temperature very much affects which personality is favored in determining epoxy performance and behavior. ***Creep*** is descriptive of a material's tendency to flow and deform under continuous, steady loading, and is both temperature and time dependent. This kind of failure mode can occur at stresses that are a small fraction of an immediate static load to failure, especially in higher temperatures. To some degree, creep has always been a problem with wooden boats; but fortunately, wood is less affected by temperature than are R.T.C. epoxies.

One cause of temperature buildup in a material is ***hysteretic heating***, i.e., heating due to stretching or compressing. Hysteretic heating and its adverse effects on performance are a crucial factor when testing epoxy and wood. The severity of hysteretic heating is dependent on loading frequency and strain magnitude. ***Strain*** is the term that quantifies the stretching and/or compressing of a material. Strain is usually expressed as a percentage change in length, due to a tensile or compressive force. Under strain, all materials develop internal heat. Metals quickly dissipate this heat, but plastics and wood are good insulators. The result is a buildup of internal heat that contributes to the failure process by allowing a subtle creep-flow process to enter into the fatigue failure as the materials soften with heat. Thus failure in neat epoxy can occur with a lesser degree of crack propagation than is typically found in wood. Epoxy failures in fatigue are usually directly preceded by a sudden rise in sample temperature, which can be followed by a "flow out" of resin around the high-stress area. Only in high-cycle tests with lower loads do we see the more normal crack propagation mode dominant over viscoelastic flow in the failure process.

Hysteretic heat buildup with any plastic increases as a square function of the cyclic strain magnitude. Thus, epoxy that is strained at 1% rather than ½% will generate four times the internal heat buildup and be a candidate for an early viscoelastic flow kind of failure.

White	128°F
Yellow	134°F
Light blue/aluminum	143°F
Purple/silver	148°F
Red/green	178°F
Brown	191°F
Black	198°F

Figure C-2 Measured surface temperature of various colored surfaces when exposed to direct sunlight at 80°F ambient temperature.

Because of the adverse effects of heat on epoxy, designers should be aware that laminates under high cyclic stress will generate internal heat that will degrade performance, and a more conservative use of material allowables is necessary. The designer should also take steps to protect epoxy from heat. Ambient temperatures are rarely over 100°F (38°C), but topsides of marine craft exposed to sunlight can be subject to temperatures that approach 200°F (93°C). Figure C-2 shows the effect of heating by sunlight on various colored surfaces at 80°F (38°C) ambient temperature in a summer sun.

Fatigue Testing of Neat Epoxies

Fatigue can occur in a variety of stress modes. It is not practical nor even possible to test for all conditions. With varying results, we have tried a number of fatigue test methods to measure the effect of stress on R.T.C. epoxies. Because of their low modulus and potential for large distortion, epoxies are difficult to test in fatigue. Hysteretic heat generated within the sample as it is cycled must be controlled or a heat-dominated early failure will result.

The earliest repeated load tests on GBI neat epoxy were torsional (twisting) tests. Torsional fatigue tests were originally developed by the Air Force[3] to address shearing loads considered to be major contributors to failure of a laminate or a bonded joint. Rectangular samples of 105/206 WEST SYSTEM® epoxy measuring 1½" × 1½" × 8" were cast and allowed to cure two weeks at room temperature. These samples were twisted in opposite directions at varying loads and number of cycles until failure occurred. The resulting data plotted in Figure C-3 shows a definite trend line that pegs a maximum working load level at 10^7 cycles in shear and about 1,600 psi. The results of this test did not indicate an endurance limit had been reached, and an extrapolation of the trend line suggests a 10^8 material shear capability of around 1,300 psi. It is not clear if any of the thermoset plastics develop a fatigue endurance capability. This means designs for structures that are subject to high cycles should be very conservative.

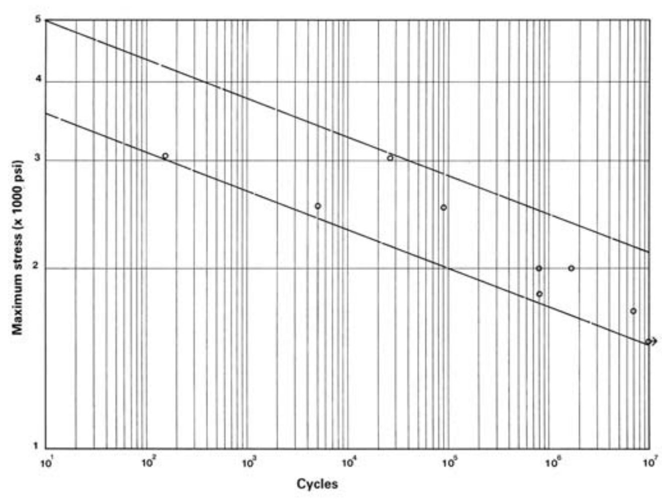

Figure C-3 Torsional Shear Fatigue.

We have conducted other tests to evaluate epoxy, some in conjunction with a wood interface (discussed in the wood section of this paper). These tests contribute to an overall picture of what we can expect from WEST SYSTEM epoxy in structures over long time periods. A particularly accurate multimode screening test has been developed to evaluate shear, compression, and tension forces at substantial stress levels in large material volumes. This

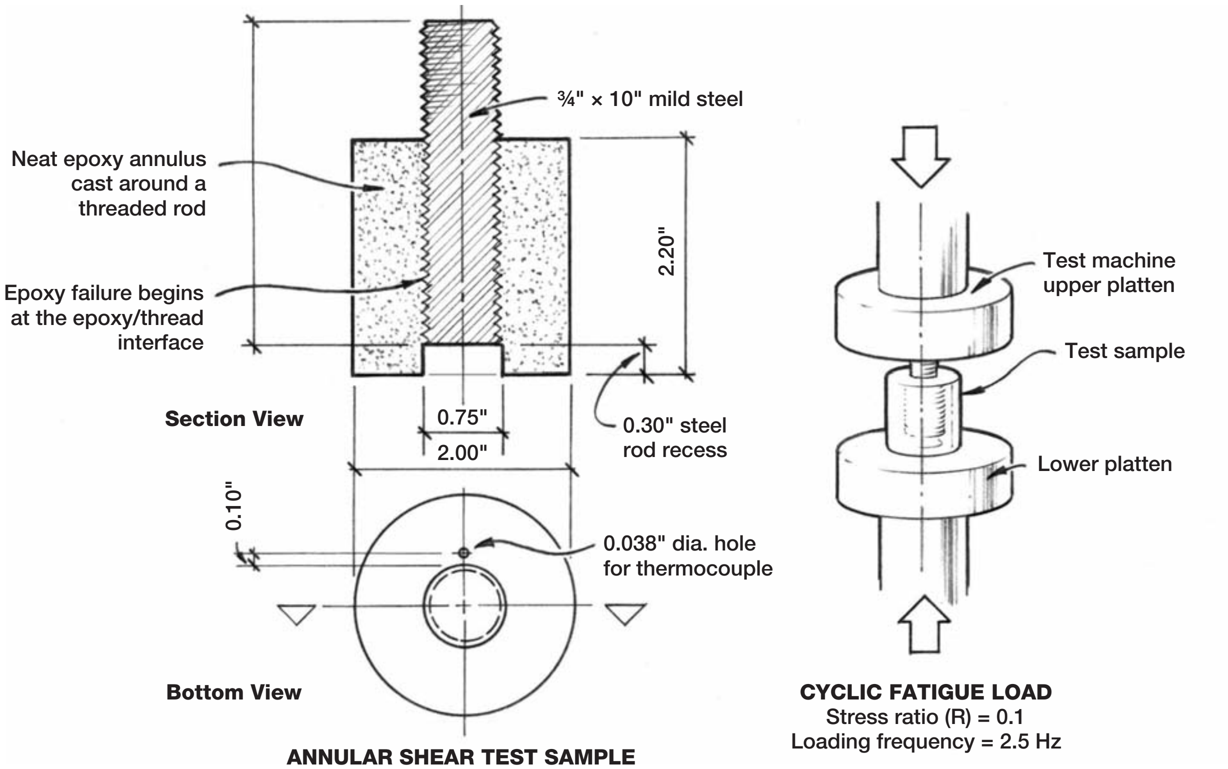

Figure C-4 Annular shear test—A threaded rod is subjected to repeated end loads while supported solely by a thick epoxy casing (annulus) that engages the threads. During each fatigue load cycle, the epoxy must endure a multiplicity of acute stress concentrations at the thread peaks. These concentrations of stress become increasingly severe towards the recessed end of the rod near the annulus base. After some number of cycles, the epoxy test material either deforms or cracks until it can no longer sustain the steel post in its original position. The test is over when the post is displaced downward one-tenth of an inch. Various epoxy formulations can thus be ranked on the basis of how many cycles they can withstand at the standard peak load level, or on the basis of the magnitude of the peak load which is required to produce failure after a standard number of cycles.

annular shear (see Figure C-4) testing approach was originally targeted toward understanding the wood/epoxy interface in bonded steel stud load take-off mechanisms for wind turbine blades. Analysis of test results, however, has shown much wider applicability than anticipated. Very small data scatter and accurate reproducibility have lent credibility to this testing approach. Figure C-5 shows how the magnitude of the peak cyclic load determines the lifetime of several types of epoxy in annular shear fatigue testing.

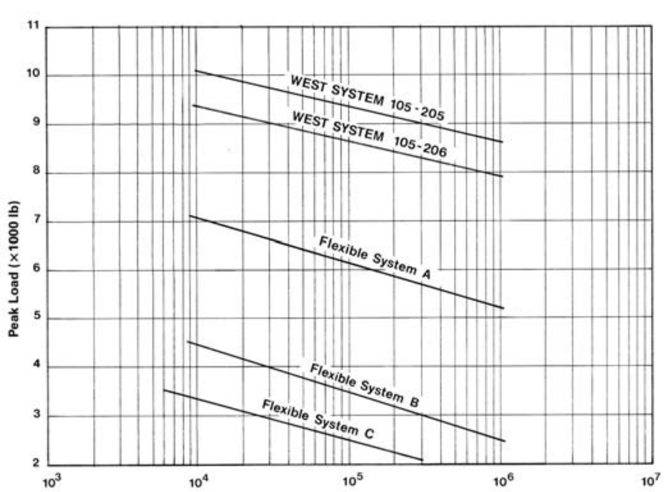

Figure C-5 Annular shear fatigue life of flexible epoxy systems. All samples were cured for two weeks at room temperature.

The annular shear test also evaluates a toughness capability that indicates an epoxy's comparative ability to resist crack propagation. This is done by introducing a stress concentration into the test sample that begins the failure process, usually with visible cracks beginning at the tips of the sharp steel threads. As the test continues, an epoxy's ability to resist crack growth under cyclic load can be assessed.

The annular shear test has allowed us to evaluate the effect of subtle formulation changes on epoxy performance. We have found that epoxy can only be flexed or stretched within narrow limits when subjected to continual fatigue loads without permanent deformation. Flexible epoxy systems with large, one-time strain-to-failure capability (6% to 14%) suffer from low fatigue performance.

Overly flexible systems can carry ony a portion of the load a less flexible system can carry. The difference in this load carrying ability can easily be a factor of two or more. Thus, the epoxy formulator must carefully weigh the pros and cons before sacrificing fatigue strength for increased flexibility.

Wood

Wood exhibits unusually good fatigue resistance. Although its static one-time load strength is not particularly high in comparison to other materials (see Figure C-6), a considerably high percentage of this capability is fortunately available for a long-term fatigue life. This is not surprising when one considers that nature spent millions of years evolving trees in a dynamic, adverse environment. Some trees are more than 2,000 years old and stand 300' (91m) tall, which shows their inherent ability to withstand high cyclic wind loads year after year.

Test direction	Test type	Max stess @ 8% m.c. (psi)	Max stess @ 8% m.c. (Mpa)
Longitudinal	Compression	9,000	62.05
	Tension	10,000	68.95
	Shear-Type 4	1,500	10.34
	Shear-Type 5	1,500	10.34
	Elastic Modulus	$2.0x10^6$	$13.79x10^3$
Tangential	Compression	2,000	13.79
	Tension	500	3.45
Radial	Compression	800	5.51
	Tension	300	2.07

Figure C-6 Typical static strength, Type 110 Douglas Fir Laminate. Laminate augmentation: None; Typical density: .023 lb/cu in (.637 g/cc); Nominal test temperature: 66°F–73°F (19°C–23°C); Veneer specification: GMS-003, BG-2+, Traverse butt joints, 3" stagger; Test method: 5 minute ramp-to-failure, per ASTM standard D198-76.

Wood testing programs began in 1980 and focused on eight different physical property issues. Gougeon Brothers developed a unique dogbone testing specimen (see Figure C-7) that made it possible to test wood laminates in tension fatigue as well as in reverse axial fatigue (cycling from a complete tension load to a complete compression load and back again). Prior to this, wood fatigue testing was conducted using a bending beam approach where a secured cantilever was loaded repeatedly until failure occurred. This work was done during the Second World War with unsophisticated test machines of limited capability. Therefore, much of this early data was flawed. While the overall results showed wood to exhibit excellent fatigue behavior, these tests did not provide quantitative results that could be used to develop safe design allowables.

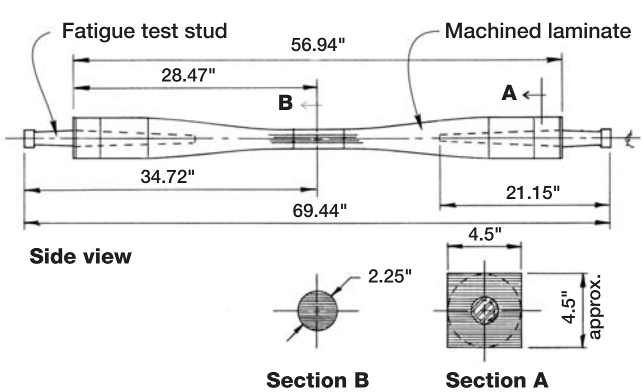

Figure C-7 Detail of "dogbone" type fatigue test specimen.

The Gougeon test program centered on the Douglas fir species because of its excellent strength-to-weight capability and ready market availability. Early on, we established a standard of commercially available 1⁄10" (2.5mm) thick clear veneers, which we thoroughly inspected with a high-speed ultrasonic grading machine. This machine uses a sound wave timer to measure the apparent modulus (or related strength) of each veneer, rejecting all those below an established grade level. This single step has allowed us to eliminate defective veneer in a laminate, guaranteeing a high, consistent material capability.

Primary properties

All testing assumed built-in manufacturing defects. Since veneer sheets are only 8' (2400 mm) long, any structure longer than 8' must be composed of multiple pieces of veneer. The exact effect of veneer joints on performance must be understood. In one group of tests, we characterized a simple butting of veneers laid end to end (see Figure C-8); and in a second series, we used a 12:1 slope scarf joint in place of the butt joints.

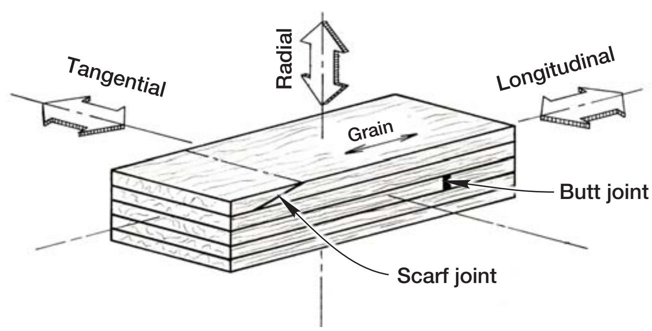

Figure C-8 Reference Axes for Laminate Strength Measurements.

As one would expect, scarfed veneer joints show an increase in tension fatigue capability. Figure C-9 shows the improved fatigue trend line for the scarf jointed laminate compared to that of the butt-jointed laminate. While the difference is great, it is not nearly as outstanding as one should expect. This kind of induced defect in competing materials, such as aluminum or fiberglass, would cause a much greater reduction in fatigue capability and indicates wood's ability to tolerate serious defects in fatigue.

Figure C-10 shows the primary fatigue properties of wood in ***tension***, ***compression***, and ***reverse axial tension-compression***. These data were developed using the 57" test specimen illustrated in Figure C-7. Note that at lower cycles, the tension capability of the laminate is considerably better than its compression capability.

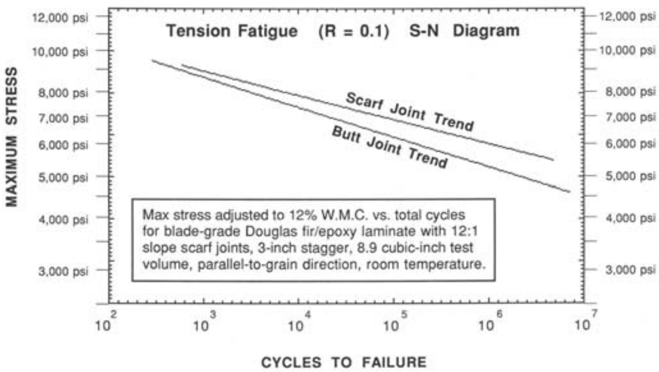

Figure C-9 Scarf joint and butt joint trend lines.

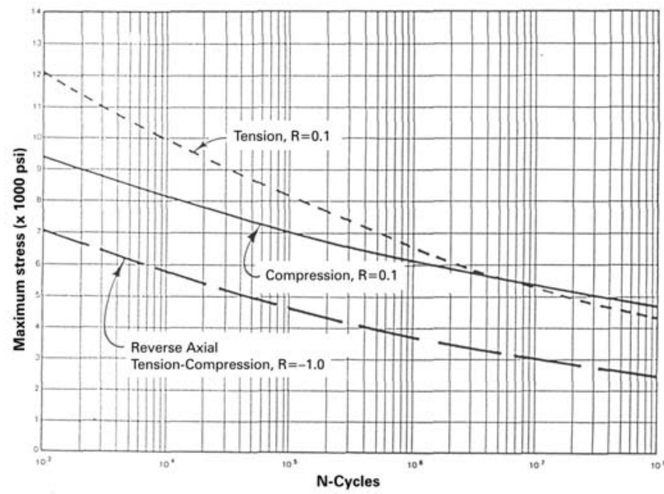

Figure C-10 Primary fatigue properties of wood.

Nature appears to understand that defects compromise tensile strength far more than compressive strength, and adjusts the tensile strength upward accordingly to allow for a larger loss of fatigue capability in tension. At the high number of stress cycles which a tree operates, the two capabilities end up being about equal, producing an ideally balanced material for cantilever structures at 4×10^7 cycles and beyond.

Reverse axial cyclic loading is a far more demanding load condition than either tension or compression fatigue alone. While the tension and compression fatigue trend lines tend to have the same strength value near 10^7 cycles, material capability is substantially reduced when subjected to equivalent cycles of reverse axial loading. Small defects very quickly began to dominate material behavior, and failure modes could be observed for days and even weeks before total sample failure. Fortunately, this demanding fatigue load condition is not the norm in most boat applications; however, when anticipated, a more conservative design allowable is necessary.

Secondary properties

Trees have very simple load paths with most loads aligned parallel to the wood grain. However, a tree must also provide for loads that occur in directions other than that of the wood grain. We call these secondary physical properties, which include shear as well as cross-grain tension and compression strengths. The most important of the secondary properties to a tree is interlaminar shearing, nature's invention to allow trees to bend a long way to shed load in high winds. Wood has the unique capability to distort itself in shearing to a considerable degree without permanent damage; this is a most important but unrecognized factor in wood's success as an engineering material. Douglas fir has a very low shear modulus of about 125,000 psi, which allows significant distortion in adjusting for differing local strains due to

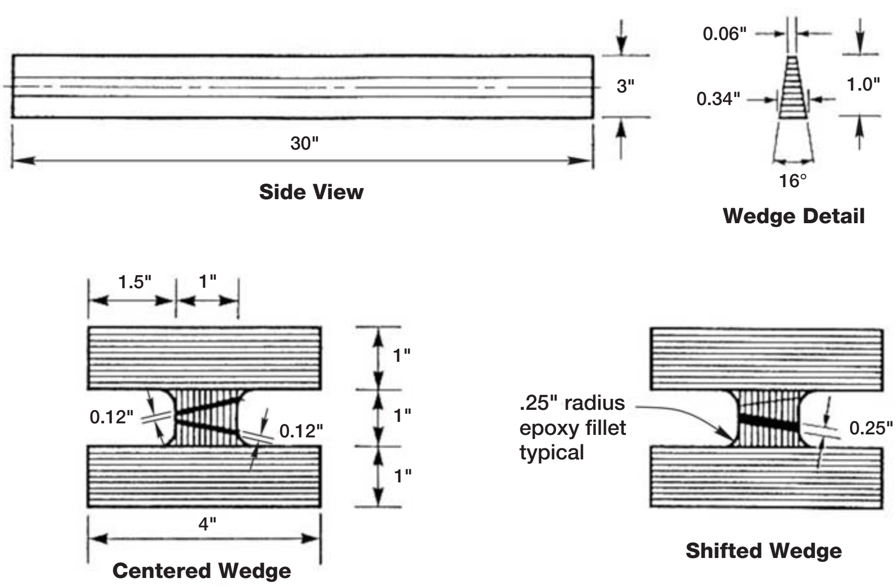

Figure C-11 Longitudinal wedge joint test specimen details.

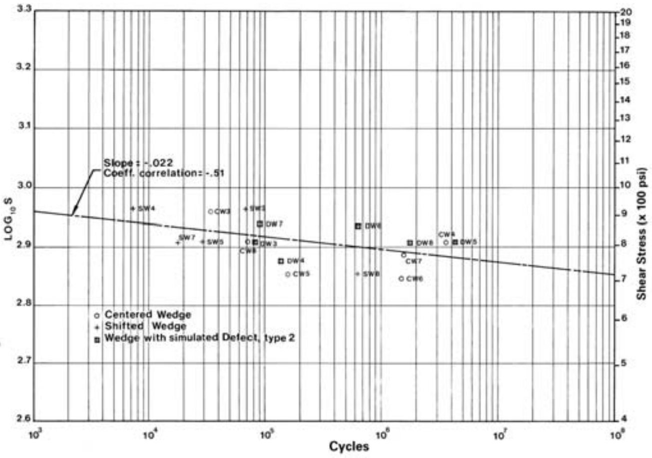

Figure C-12 S-N Diagram. Longitudinal wedge joint, shear stress, three-point bending tests with Douglas fir/epoxy laminate at room temperature. R = 0.1. 12% M.C.

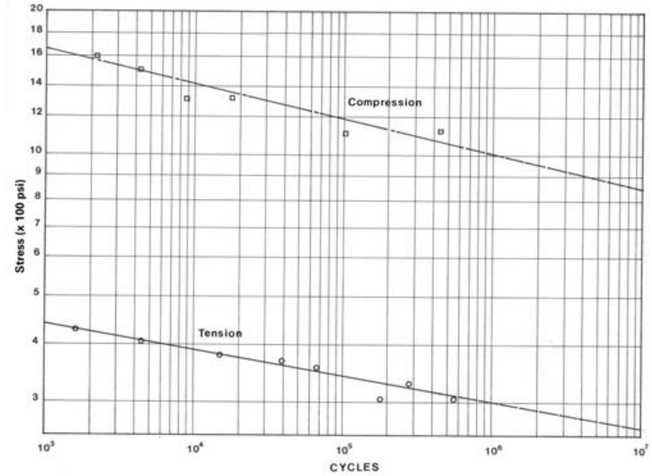

Figure C-13 Tangential Fatigue.

discontinuities or defects. Test results show we can take advantage of this unusual shearing mechanism to reduce stress concentrations and defect problems in structures.

Shearing loads can be very high in wind turbine blades. Because of this, the shearing capability of wood/epoxy laminates was carefully evaluated. Of special concern were bonded joints with defects and gaps up to .25" (6mm) that were filled with a thickened 105/206 WEST SYSTEM adhesive. This kind of joint will have some stress concentrations because of the difference in shear modulus between wood and adhesive. (Douglas fir is 125,000 psi, and 105/206 epoxy is 375,000 psi.) It is also difficult to make this kind of joint without small voids or air bubbles in the adhesive. The cost of these defects to design allowables needed to be evaluated. Figure C-11 shows three different kinds of joint defects that were tested in fatigue. The object of this program was to simulate worst-case results that could occur under typical manufacturing conditions.

All of the I-beam samples were tested in shear, using a three-point bending fixture that supported the 30"-long sample between two points 24" apart. Load was then applied at the center of the 24" dimension. Eighteen specimens were tested, with six representing each joint category. All testing was performed at a stress ratio of R = 0.1 at varying load levels to develop S-N curves.

The combined results of this test series are plotted in Figure C-12 and, even with a limited sample population, some remarkable results were produced. The notably shallow trend line suggests the shear fatigue capability of wood composite with defects is unusually good, especially when compared to the already excellent trend lines of the primary fatigue properties of tension and compression.

Most important is the apparent insensitivity of the bonded joints, which are defects themselves, to major defects. The "Type 2 Defect" test samples (half-inch square nylon chips placed at two-inch intervals), in particular, performed better on average than the ideal "centered wedge" series test sample.

All test specimens displayed shear failure in the wood veneer area adjacent to the bond line. The induced defects (nylon squares) within the bond line only occasionally acted as crack initiators, with cracks developing in the test sample well before failure occurred. This initial crack generation, however, did not appear to be related to performance, for samples with defect-generated cracks performed just as well as regular samples with no cracks, further illustrating the ability of wood to live in fatigue with serious defects.

No failure occurred in the bond lines or within the WEST SYSTEM epoxy adhesive itself, even at the .25"-thick gap joints. This was reassuring evidence that thick bond lines can be trusted in high cycle fatigue conditions. This feature results from the ability of the epoxy itself to withstand long-term fatigue loading.

Another important secondary failure mode within wood structures is perpendicular-to-grain tension fatigue. When wood structures are created by laminating rotary-peeled veneers, with all wood fiber aiming the same direction, two cross-grain dimensions result: (1) through-the-thickness (radial) cross-grain, perpendicular to the plane of the laminations, and (2) edge-to-edge (tangential) cross-grain, parallel to the plane of the laminations. (See again Figure C-8).

The static, tangential cross-grain tension capability of Douglas fir laminate is only 500 psi, and Figure C-13 shows this capability degrading to about 300 psi when approaching one million (10^6) fatigue cycles.

This was the first time cross-grain tension had ever been tested in fatigue. The limited data that was generated, when extrapolated to 10^7 cycles, suggests that only about 75 psi is available for long-term use. While this may be a conservative interpretation, legitimate concern is raised over this "physical property" weakness. Designers should be extra cautious when dealing with cross-grain tension loads in their structures.

Tangential cross-grain compression strength was also tested, and results suggest a typical material degradation with increasing cycles (see Figure C-13). In our experience, this mode of failure would be unusual for most marine structures.

A more critical concern is the radial cross-grain tensile fatigue strength. It is nearly impossible to design large wood structures that do not incur at least some radial cross-grain tensile stress. Until recently, the potential for through-the-thickness failures of plywood due to tensile fatigue was little understood. A significant advance took place in the late 1980s as a result of a dedicated GBI research program underwritten by the U.S. Department of Energy (DOE). The study was a breakthrough, since innovative specimen design and testing techniques made it possible to associate tensile strengths not only with varying numbers of fatigue cycles, but also with varying specimen sizes, i.e., ***size effect***. Size effect is the name for the phenomenon where small test specimens exhibit unrealistically high strengths (per unit cross-sectional area) compared to larger-volume specimens, including actual structures. DOE support allowed a large number of specimens to be built in order to compare static and fatigue data from populations that differed in stressed volume by a factor of 200.

In terms of one-time ultimate tensile strength, the smaller (1.45 in^3) specimens averaged 393 psi. The larger (295 in^3) specimens averaged just 281 psi. Laminate moisture content was on the order of 6% for this series. The tension fatigue results for the two groups is summarized in the graph of Figure C-14.

Note that the slope is steeper for the larger volume specimen group. One could use this trend to estimate what peak stress value would give a typical 295 in^3 specimen a chance of surviving 400 million cycles. Doing so returns a value of only 78 psi. Size effect needs to be respected in establishing safe working loads for wood structures in general. The GBI/DOE study showed that size effect is particularly severe for secondary properties such as radial cross-grain tension.

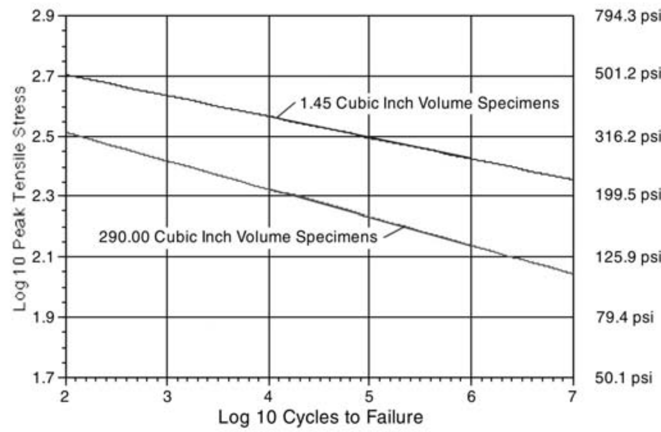

Figure C-14 Classical fatigue trends for radial cross-grain tension fatigue of blade grade douglas fir laminate. (R = 0.1)

There is another secondary wood loading mode that is often overlooked in design exercises. That is the ***rolling shear*** loading mode. Rolling shear is so-called because it represents the tendency of individual wood fibers to twist and roll over each other when opposing forces arise in adjacent plies of a laminate. This situation is illustrated in item #6 in Figure C-15.

Since rolling shear resistance ranks as the least of the shear strengths cataloged in Figure C-15, it was singled out for inclusion in the GBI/DOE fatigue research of the late 1980s. Once again, the test matrix was structured to gauge size effect. It featured two populations of specimens, one group having a test volume of 2.5 in^3 and

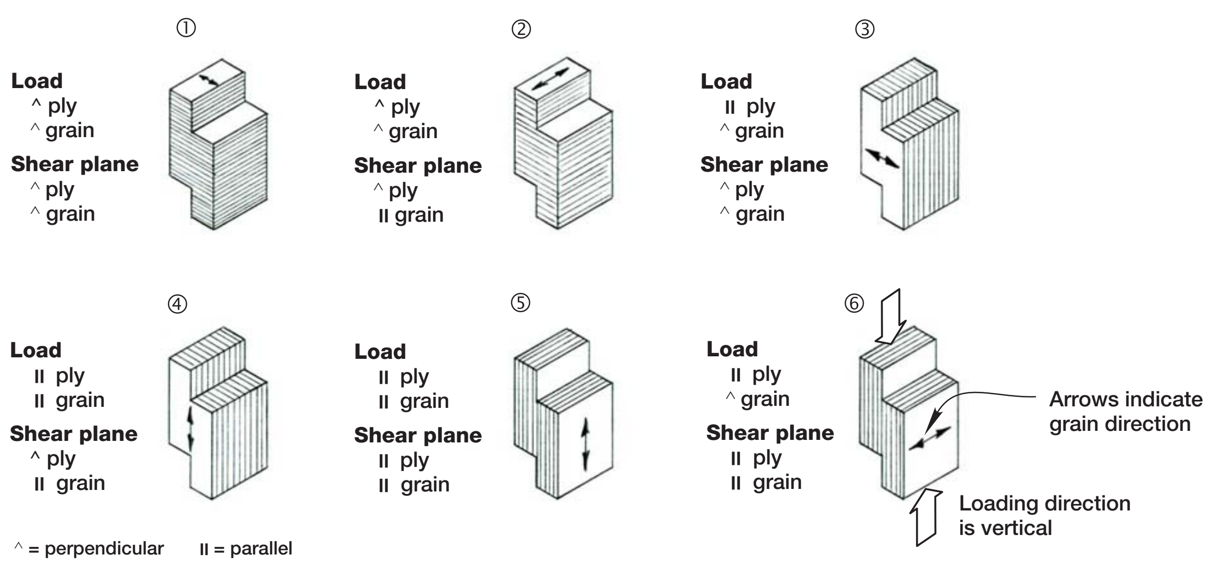

Figure C-15 Various Shear Loading Possibilities for Blade Laminate. Loading direction is vertical in all six cases.

a second group having a test volume of 160 in^3. In terms of static (one-time) strength measurements, the groups averaged 275.9 psi and 268.1 psi, respectively. Laminate moisture content was on the order of 5%-6%. The fatigue results are presented in Figure C-16.

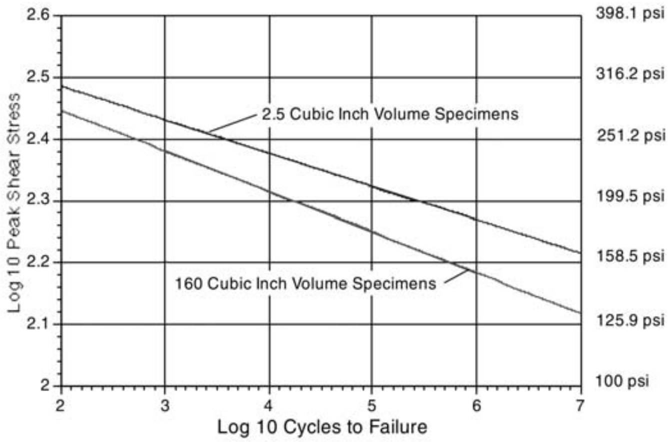

Figure C-16 Rolling Shear Fatigue Trends for Blade Laminate.

While the size effect for rolling shear is less pronounced than that for radial cross-grain tension, note that the effect still intensifies as the cycles to failure increase. Therefore, the peak rolling shear stress must be restricted to 102 psi before a typical 160 in^3 specimen could be expected to have a lifetime of 400 million cycles.

Bonded Finger Joints

Bonded finger joining of wood pieces has been practiced for many years, but no reliable fatigue testing of this joint geometry had been completed to quantify joint efficiency as a percentage of downstream material load carrying capability.

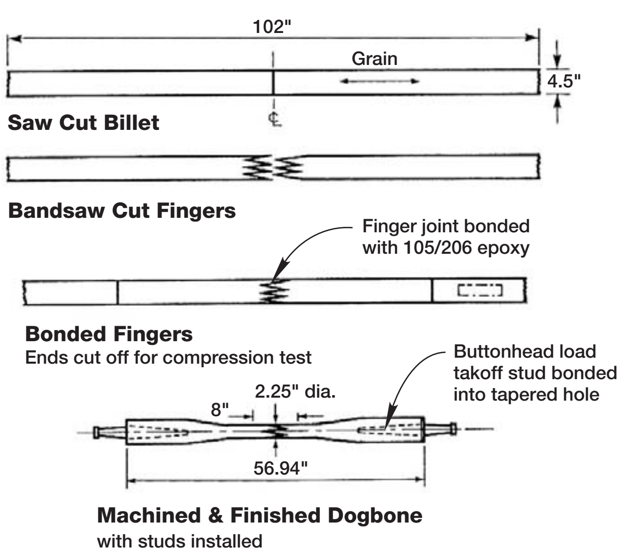

Figure C-17 Detail of finger joint dogbone-type fatigue test specimen.

A comprehensive program was developed to define this efficiency factor using a 10:1 slope finger joint for splicing sections of large wind blades. All joints were bonded with a thickened 105/206 WEST SYSTEM epoxy using 5 psi pressure for finger engagement (see Figure C-17).

The trend line for finger joints can be compared directly with that of standard unjointed laminate in tension fatigue because both sets of data were developed using the same dogbone test sample design. An unexpected result of this direct comparison was that the finger joint trend line tends to slope at a slightly lower rate than that of a regular laminate. This suggests that a major defect, such as a scarfed finger joint, is well tolerated at higher cycles and no degradation of the trend line is anticipated when extrapolating out to 10^8 cycles (see Figure C-18). One must also observe that at 10^7 cycles, finger joint capability is about 80% of standard laminate in tension. Note that the static one-time load capability for finger joints is almost 100% of the standard laminate, and this would be a very misleading number for design purposes by itself if the fatigue data were not consulted.

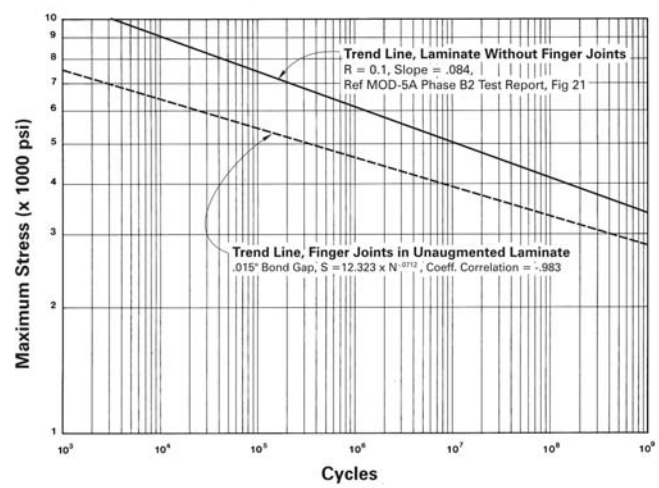

Figure C-18 S-N Diagram, Tension fatigue test of Douglas fir/epoxy laminate with bonded finger joints.

Finger joint test samples with large gaps (up to .062") show that WEST SYSTEM epoxy was capable of carrying high cyclic loads across a finger joint for long time periods. All finger joints suffer from stress concentrations, which can contribute to early failure if the bonding adhesive lacks the necessary toughness, especially if a thick bond line is involved.

Limited fatigue testing of other species of wood besides Douglas fir has been done. Most woods have a similar slope in their fatigue curves, at least with the primary properties. The long-term performance of a wood species is more a function of its density, with strength and density of a species being relatively proportional. The main difference between good and bad wood is in the number and kind of defects. How well a particular wood species can perform with a given kind of defect is a crucial question to answer when choosing design allowables.

There is probably a greater fatigue strength variation among wood species when considering the secondary properties. This is most notable between softwood and hardwood, where static cross-grain properties of hardwood species can be double that of softwood with, perhaps, only a 50% increase in density. This is why hardwood was chosen for framing timber and softwood was chosen for planking in traditional boats of the past.

Conclusion

Epoxy has proven to be a sound solution to the problem of enhancing the use of wood and synthetic fibers by creating effective bonds between these basic materials.

Can wood/epoxy boats last for 50 years? Unfortunately, we can't yet say for sure. Experience in the field over the next 30 years or so will give us sound answers to this question. The oldest all-bonded wood/epoxy structure is the Gougeon Brothers designed and built 35' (10.6m) trimaran *Adagio* that in 2005 is beginning her 35th sailing season. *Adagio* is lightly built (2200 lb or 998 kg total) and has been raced extensively. *Adagio* is expexted to remain competitive for many years to come.

The only other way to get answers to the boat longevity question is to perform accelerated fatigue testing that compresses years into weeks, as described in this paper. The knowledge from this kind of testing is critical to developing even more fatigue-resistant epoxy formulations, and we encourage anyone who is developing bonding adhesives to adopt fatigue testing as a primary criterion for evaluating long-term performance results.

Present test results suggest we can safely predict a life span of 30 years for wind turbine blades built with WEST SYSTEM epoxy. Turbine blades undergo on average more demanding service than do boats, which provides for some optimism that boats built to operate at similar stress levels should last equally long in active service and probably longer in actual years of existence.

Endnotes

[1] "Fatigue Behavior of Fiber Resin Composites,"J. F. Mandell, MIT Department of Materials Science and Engineering, 1981.J. F. Mandell, et al. See Bibliography.

[2] "Dynamic Loading Analysis and Advanced Composites," R. Lazarra and D. E. Jones, Jr., West Lawn Yacht Design Symposium, 1984.

[3] USAF Specifications No. S-133-1140 (22 Nov. 1978)

Bibliography

Bertelsen, W. D. and Zuteck, M. D., “Douglas Fir/Epoxy Laminate Compression Strength, Perpendicular to Grain,” Gougeon Brothers, Inc., May 1984

Bertelsen, W. D., “Cross-grain Tangential Tests of Douglas Fir/Epoxy Laminate,” Gougeon Brothers, Inc., May 1984, (GBI proprietary).

Bertelsen, W. D., “Static Compression Ramps of Laminate Augmented with Unidirectional E-Glass,” GBI Internal Test Report, July 1984.

Bertelsen, W. D., “Fatigue Strength Testing of Douglas Fir/Epoxy Laminates for MOD-5A Wind Turbine Blade Project - Phase B2,” Gougeon Brothers, Inc., March 1984.

Bertelsen, W. D., “Fatigue Strength Testing of Scarf-jointed Douglas Fir/Epoxy Laminates Containing High and Low Levels of Moisture,” Gougeon Brothers, Inc., May 1984.

Bertelsen, W. D., and Zuteck, M. D., “Investigation of Fatigue Failure Initiation and Propagation in Wind-Turbine-Grade Wood/Epoxy Laminate Containing Several Veneer Joint Styles,” Gougeon Brothers, Inc., September 1989.

Forrest, R. C., “Static and Fatigue Tests of Finger Joints in Douglas Fir/Epoxy Laminates for MOD-5A Wind Turbine Blade,” Gougeon Brothers, Inc., May 1984.

Forrest, R. C., “Shear Testing of Longitudinal Bonded Joints in Douglas Fir/Epoxy Laminates for MOD-5A Wind Turbine Blade Project,” Gougeon Brothers, Inc., February 1984.

Forrest, R. C., “Testing of Cross-grain Tension Joint Concepts for Augmented Douglas Fir/Epoxy Laminates, MOD-5A Wind Turbine Blade Project,” Gougeon Brothers, Inc., June 1983.

Forrest, R. C., “Effects of Circular Holes on Strength of Douglas Fir/Epoxy Laminates - MOD-5A Wind Turbine Blade Project,” Gougeon Brothers, Inc., June 1983.

Hofer, K.E. and Bennett, L. C., “Fatigue Testing of Low Cost Fiberglass Composite Wind Turbine Blade Materials,” IIT Research Institute, 1981, DOE-NASA-0182-1, NASA-CR-165566.

Hofer, K.E. and Skaper, G., “Fatigue Endurance of Glass-reinforced Plastic Laminate Material in a Marine Environment,” L. J. Broutman & Associates, Ltd., February 1985.

Kunesh, R., “Tensile Strength of End-jointed Composite Veneer Material for Large Wind Turbine Blades,” K Consulting Company, February 1984.

Kunesh, R., “Tensile Strength Properties Perpendicular to Grain in the Radial and Tangential Directions of Epoxy-laminated Douglas Fir Veneer Composite Material,” K Consulting Company, October 1982.

Kunesh, R., “Strength Properties of Birch Veneer and Fiberglass-reinforced Plastic Composite for Large Wind Turbine Blades,” K Consulting Company, May 1983.

Kunesh, R., “Strength Properties of Rotary-peeled Douglas Fir Veneer Composite Material for use in Wind Turbine Blades,” K Consulting Company, January 1982.

Lazarra, R. and Jones, D. E., Jr., “Dynamic Loading Analysis and Advanced Composites,” West Lawn Yacht Design Symposium, 1984.

Mandell, J. F., “Fatigue Behavior of Fiber Resin Composites,” MIT Department of Materials Science and Engineering, 1981.

Mandell, J. F., “Fatigue Crack Propagation Rates in Woven and Non-woven Fiberglass Laminates,” from Composite Reliability ASTM STP 580, American Society for Testing and Materials, 1975, pp. 515-527.

Mandell, J. F., and Meier, V., “Effect of Stress Ratio Frequency and Loading Time on the Tensile Fatigue of Glass-reinforced Epoxy,” from Long-term behavior of Composites, ASTM STP 813, T. K. O’Brien, Ed., American Society for Testing and Materials, Philadelphia, 1983.

Mandell, J. F., Samborsky, D. D., and Cairns, D. S., “Fatigue of Composite Materials and Substructures for Wind Turbine Blades”, Sandia National Laboratories, Sandia Report SAND2002-0771, March 2002.

Thomas, G., and Forrest, R. C., “Fatigue Strength Testing of Douglas Fir/Epoxy Laminates for MOD-5A Wind Turbine Blade Project - Phase B1,” Gougeon Brothers, Inc., December 1982.