Fatigue

A fundamental problem concerning the engineering uses of fiber reinforced plastics (FRP) is the determination of their resistance to combined states of cyclic stress. [4-1] Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. [4-2] Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. There are four basic failure mechanisms in composite materials as a result of fatigue: matrix cracking, delamination, fiber breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall non-linear behavior of composites severely limit our ability to understand the true nature of fatigue. [4-3] Figure 4-1 shows a typical comparison of the fatigue damage of composites and metals over time.

Many aspects of tension-tension and tension-compression fatigue loading have been investigated, such as the effects of heat, frequency, pre-stressing samples, flawing samples, and moisture [4-5 through 4-13]. Mixed views exist as to the effects of these parameters on composite laminates, due to the variation of materials, fiber orientations, and stacking sequences, which make each composite behave differently.

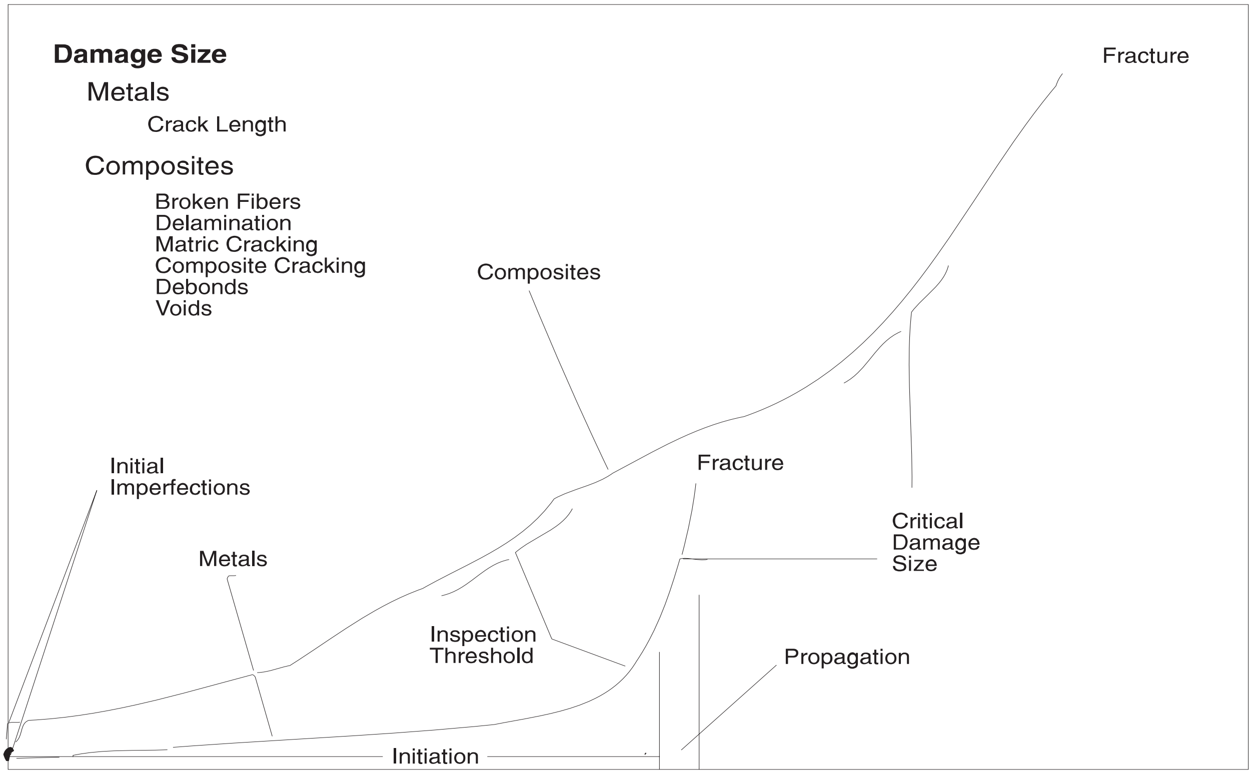

Figure 4-1 Typical Comparison of Metal and Composite Fatigue Damage [Salkind, *Fatigue of Composites*]

Extensive work has been done to establish failure criteria of composites during fatigue loading [4-1, 4-5, 4-14, 4-15]. Fatigue failure can be defined either as a loss of adequate stiffness, or as a loss of adequate strength. There are two approaches to determine fatigue life; constant stress cycling until loss of strength, and constant amplitude cycling until loss of stiffness. The approach to utilize depends on the design requirements for the laminate.

In general, stiffness reduction is an acceptable failure criterion for many components which incorporate composite materials. [4-15] Figure 4-2 shows a typical curve of stiffness reduction for composites and metals. Stiffness change is a precise, easily measured and easily interpreted indicator of damage, which can be directly related to microscopic degradation of composite materials. [4-15]

In a constant amplitude deflection loading situation the degradation rate is related to the stress within the composite sample. Initially, a larger load is required to deflect the sample. This corresponds to a higher stress level. As fatiguing continues, less load is required to deflect the sample, hence a lower stress level can exist in the sample. As the stress within the sample is reduced, the amount of deterioration in the sample decreases. The reduction in load required to deflect the sample corresponds to a reduction in the stiffness of that sample. Therefore, in constant amplitude fatigue, the stiffness reduction is dramatic at first, as substantial matrix degradation occurs, and then quickly tapers off until only small reductions occur.

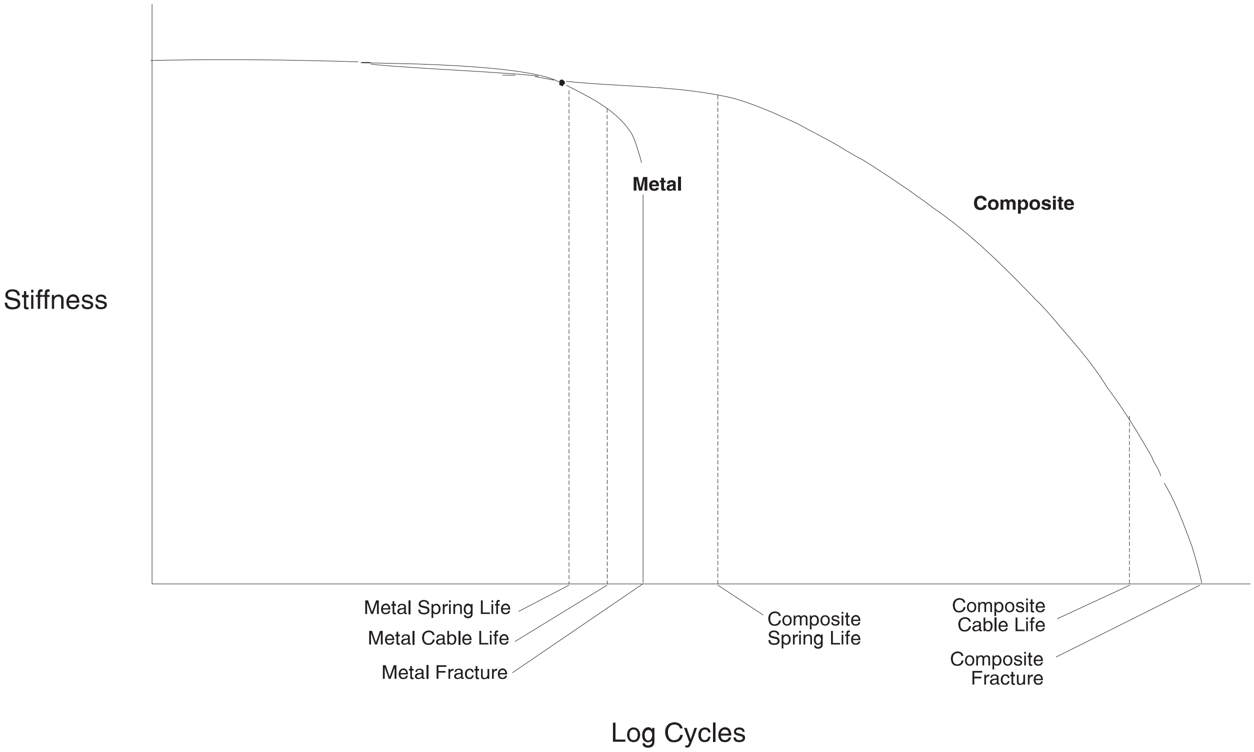

Figure 4-2 Comparison of Metal and Composite Stiffness Reduction [Salkind, *Fatigue of Composites*]

In a unidirectional fiber composite, cracks may occur along the fiber axis, which usually involves matrix cracking. Cracks may also form transverse to the fiber direction, which usually indicates fiber breakage and matrix failure. The accumulation of cracks transverse to fiber direction leads to a reduction of load carrying capacity of the laminate and with further fatigue cycling may lead to a jagged, irregular failure of the composite material. This failure mode is drastically different from the metal fatigue failure mode, which consists of the initiation and propagation of a single crack. [4-1] Hahn [4-16] predicted that cracks in composite materials propagate in four distinct modes. These modes are illustrated in Figure 4-3, where region I corresponds to the fiber and region II corresponds to the matrix.

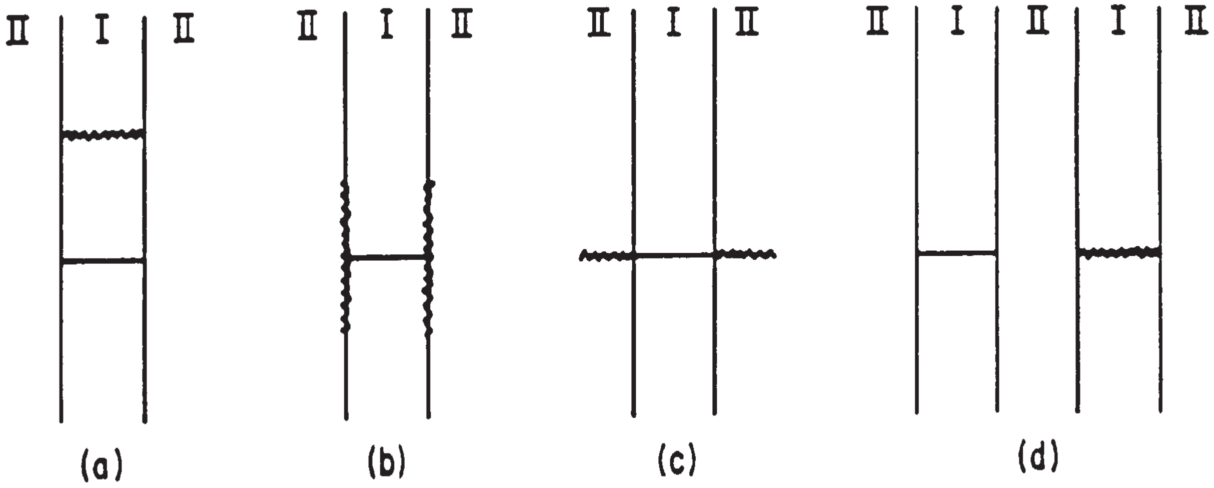

Figure 4-3 Fatigue Failure Modes for Composite Materials - **Mode (a)** represents a tough matrix where the crack is forced to propagate through the fiber. **Mode (b)** occurs when the fiber/matrix interface is weak. This is, in effect, debonding. **Mode (c)** results when the matrix is weak and has relatively little toughness. Finally, **Mode (d)** occurs with a strong fiber/matrix interface and a tough matrix. Here, the stress concentration is large enough to cause a crack to form in a neighboring fiber without cracking of the matrix. **Mode (b)** is not desirable because the laminate acts like a dry fiber bundle and the potential strength of the fibers is not realized. **Mode (c)** is also undesirable because it is similar to crack propagation in brittle materials. The optimum strength is realized in **Mode (a),** as the fiber strengths are fully utilized. [Hahn, *Fatigue of Composites*]

Minor cracks in composite materials may occur suddenly without warning and then propagate at once through the specimen. [4-1] It should be noted that even when many cracks have been formed in the resin, composite materials may still retain respectable strength properties. [4-17] The retention of these strength properties is due to the fact that each fiber in the laminate is a load-carrying member and once a fiber fails the load is redistributed to another fiber.

Composite Fatigue Theory

There are many theories used to describe composite material strength and fatigue life. Since no one analytical model can account for all the possible failure processes in a composite material, statistical methods to describe fatigue life have been adopted. Weibull distribution has proven to be a useful method to describe the material strength and fatigue life. Weibull distribution is based on three parameters; scale, shape and location. Estimating these parameters is based on one of three methods: the maximum likelihood estimation method, the moment estimation method, or the standardized variable method. These methods of estimation are discussed in detail in references [4-18, 4-19]. It has been shown that the moment estimation method and the maximum-likelihood method lead to large errors in estimating the scale and the shape parameters, if the location parameter is taken to be zero. The standardized variable estimation gives accurate and more efficient estimates of all three parameters for low shape boundaries. [4-19]

Another method used to describe fatigue behavior is to extend static strength theory to fatigue strength by replacing static strengths with fatigue functions.

The power law has been used to represent fatigue data for metals when high numbers of cycles are involved. By adding another term into the equation for the ratio of oscillatory-to-mean stress, the power law can be applied to composite materials. [4-20]

Algebraic and linear first-order differential equations can also be used to describe composite fatigue behavior. [4-14]

There are many different theories used to describe fatigue life of composite materials. However, given the broad range of usage and diverse variety of composites in use in the marine industry, theoretical calculations as to the fatigue life of a given composite should only be used as a first-order indicator. Fatigue testing of laminates in an experimental test program is probably the best method of determining the fatigue properties of a candidate laminate. Further testing and development of these theories must be accomplished to enhance their accuracy. Despite the lack of knowledge, empirical data suggest that composite materials perform better than some metals in fatigue situations. Figure 4-4 depicts fatigue strength characteristics for some metal and composite materials. [4-21]

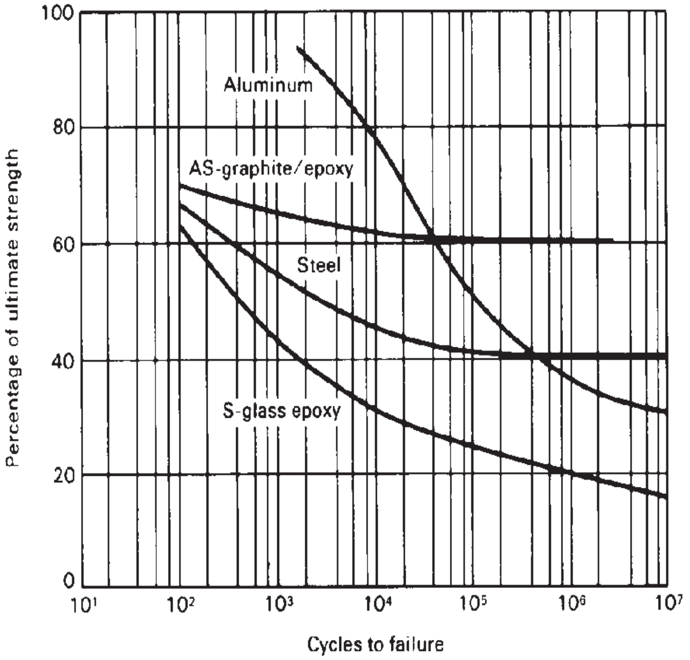

Figure 4-4 Comparison of Fatigue Strengths of Graphite/Epoxy, Steel, Fiberglass/Epoxy and Aluminum [Hercules]

Fatigue Test Data

Although precise predictions of fatigue life expectancies for FRP laminates is currently beyond the state-of-the-art of analytical techniques, some insight into the relative performance of constituent materials can be gained from published test data. The Interplastic Corporation conducted an exhaustive series of fatigue tests on mat/woven roving laminates to compare various polyester and vinyl ester resin formulations. [4-22] The conclusion of those tests is shown in Figure 4-5 and is summarized as follows:

> "Cyclic flexural testing of specific polyester resin types resulted in predictable data that oriented themselves by polymer description, i.e., orthophthalic was exceeded by isophthalic, and both were vastly exceeded by vinyl ester type resins. Little difference was observed between the standard vinyl ester and the new pre-accelerated thixotropic vinyl esters."

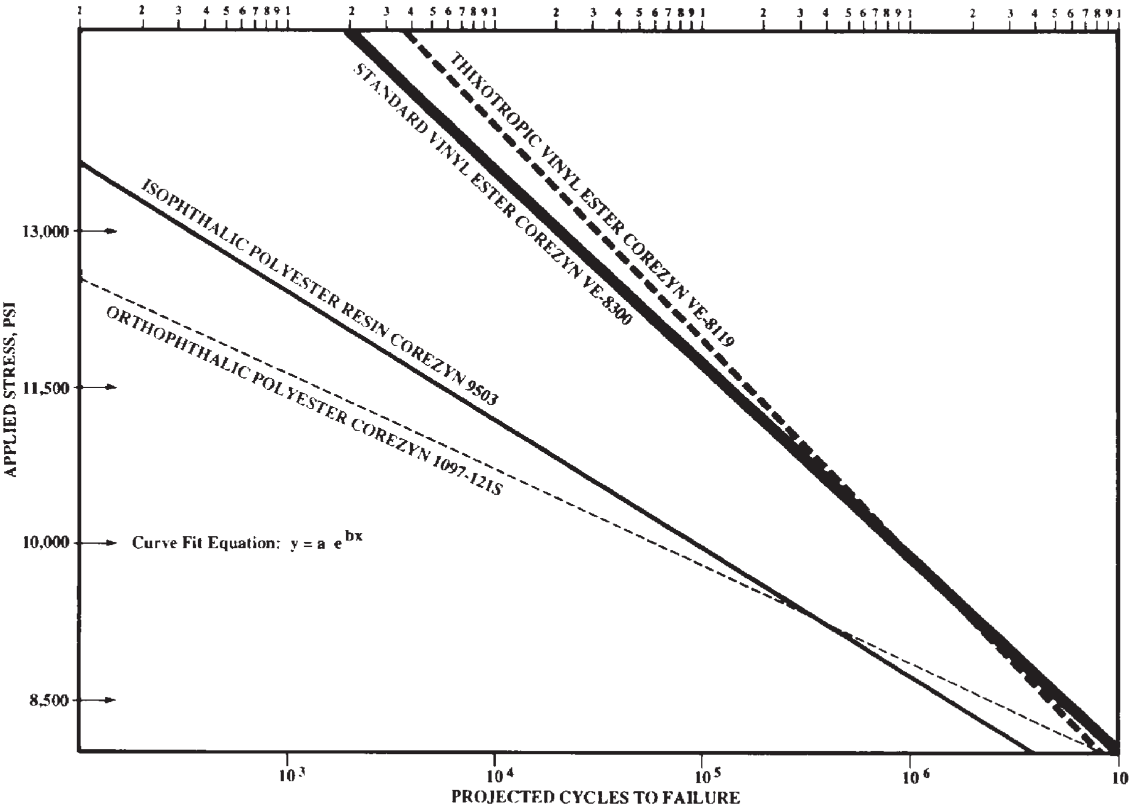

Figure 4-5 Curve Fit of ASTM D671 Data for Various Types of Unsaturated Polyester Resins [Interplastic, *Cycle Test Evaluation of Various Polyester Types and a Mathematical Model for Predicting Flexural Fatigue Endurance*]

With regards to reinforcement materials used in marine laminates, there is not a lot of comparative test data available to illustrate fatigue characteristics. It should be noted that fatigue performance is very dependent on the fiber/resin interface performance. Tests by various investigators [4-23] suggest that a ranking of materials from best to worst would look like:

- High Modulus Carbon Fiber;
- High Strength and Low Modulus Carbon;
- Kevlar®/Carbon Hybrid;
- Kevlar®;
- Glass/Kevlar® Hybrid;
- S-Glass; and
- E-Glass.

The construction and orientation of the reinforcement also plays a critical role in determining fatigue performance. It is generally perceived that larger quantities of thinner plies perform better than a few layers of thick plies. Figure 4-6 shows a comparison of various fabric constructions with regard to fatigue performance.

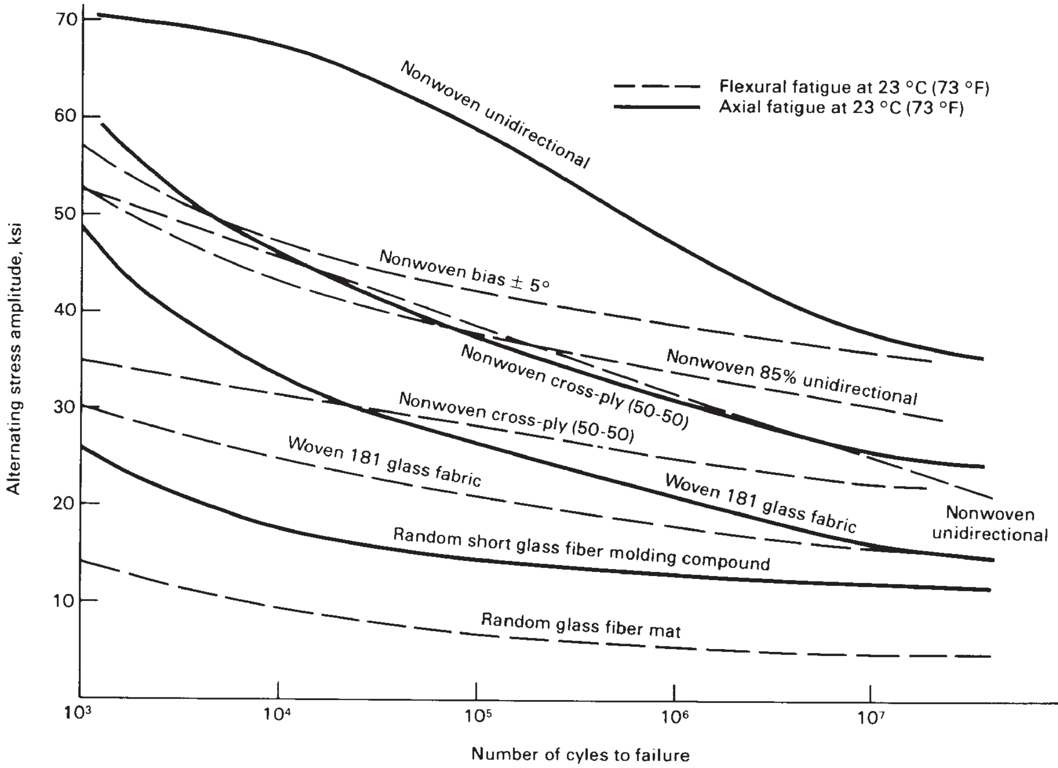

Figure 4-6 Comparative Fatigue Strengths of Nonwoven Unidirectional Glass Fiber Reinforced Plastic Laminates [*ASM Engineers' Guide to Composite Materials*]

Although some guidance has been provided to assist in the preliminary selection of materials to optimize fatigue performance, a thorough test program would be recommended for any large scale production effort that was fatigue performance dependent. This approach has been taken for components such as helicopter and wind turbine rotors, but is generally beyond the means of the average marine fabricator.