18 FATIGUE OF COMPOSITES

FATIGUE OF COMPOSITES

Fatigue properties of a material are its response to cyclic loading. Fatigue strength is lower than static strength. On a macro-scale fatigue failures appear to occur with little or no gross plastic deformation, however a micro examination of the fatigued surface often reveals evidence of plastic deformation. Fatigue life depends on stress level, state of stress, mode of cycling, process history, and environmental condition.

Fatigue Testing

Fatigue testing is usually performed using sinusoidal loading. Thus the state of fatigue loading can be described a few parameters shown in Fig.18-1. By specifying the maximum and minimum stress the other stress parameters can be easily determined such as stress range, s_r, stress amplitude, s_a, mean stress, s_m, and fatigue stress ratio, *R*.

$$s_r = s_{\max} - s_{\min}$$

$$s_m = \frac{s_{\max} + s_{\min}}{2}$$

$$s_a = \frac{s_{\max} - s_{\min}}{2}$$

$$R = \frac{s_{\min}}{s_{\max}}$$

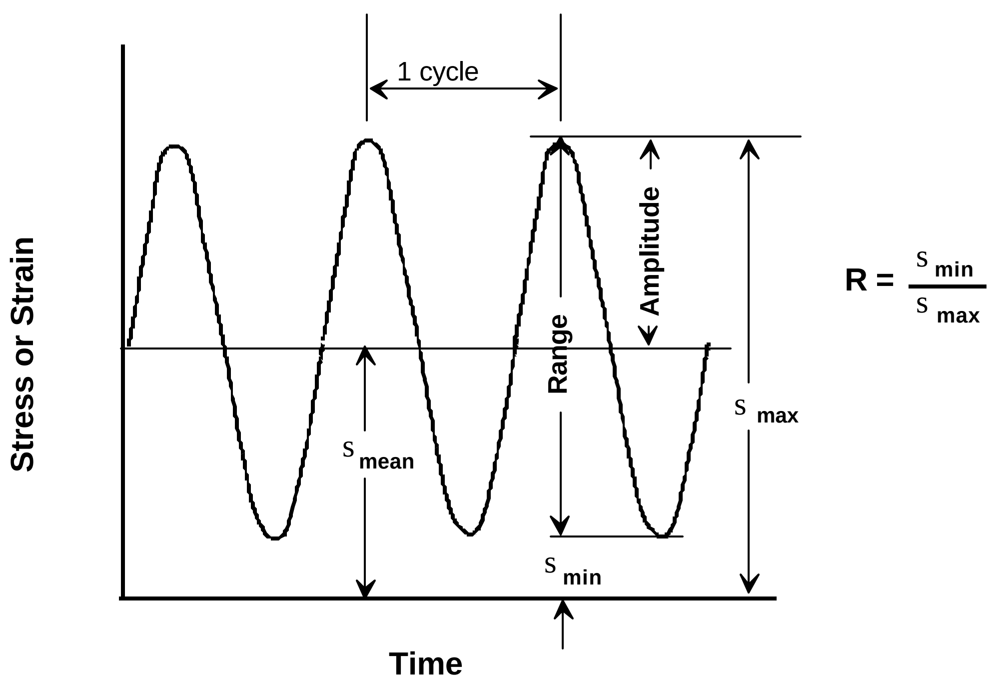


Figure 18-1. Sinusoidal loading for fatigue testing

The R value is an indication of the mode of fatigue loading. Table 18-1 summarized the important loading modes.

Table 18-1 Fatigue loading modes as indicated by R value

Fatigue Stress Ratio	Fatigue Loading Mode
$R=1$	Static loading
$R=0$	Tension-unload
$0<R<1$	Tension-tension
$R=-1$	Tension-compression fully reversed
$-1<R<0$	Tension-compression

The effect of mean stress on fatigue strength

The fatigue strength for a given cyclic life time at any load amplitude depends upon the mean stress, s_m. For the same given fatigue life it is evident that the stress amplitude, s_a (fatigue strength) must be reduced as the mean stress is increased. To avoid having to make fatigue measurements at all possible mean loads, an empirical method called the Goodman plot is commonly employed,. The so-called "Goodman Line" is just a linear reduction in the fatigue strength (the stress amplitude for a given fatigue life) with increasing mean stress at a rate proportional to the ratio of the fatigue strength at zero mean stress, s_a^o (fully reversed loading) to the tensile strength, s_{TU}. The Goodman relation is thus expressed as

$$\frac{s_a}{s_a^o} = 1 - \frac{s_m}{s_{TU}} \qquad (18.1)$$

For metals such as steel there is a stress at which the fatigue life becomes infinite (i.e. material does not fail by fatigue). The fatigue strength for this case is referred to as the endurance limit. Other materials such as aluminum alloy have no endurance limit, so an arbitrary fatigue life must be chosen (eg. 10 million cycles, 1 million cycles, 100,000 cycles or some other relevant life). When the Goodman line is plotted for a number of such life times, the plot is often referred to as a master diagram shown in Fig 18-2. In this plot the "Goodman lines" are plotted for static loading and for fatigue lives of 10^3, 10^5 and 10^7 cycles.

For polymer composites a modification of the Goodman line is needed to more accurately predict the effect of mean stress on fatigue strength. In this modification, the Goodman-Boller line uses the stress rupture strength at the time corresponding to the cyclic life, s_c for the x-axis intercept instead of the tensile strength. The Goodman-Boller relation is thus

$$\frac{s_a}{s_a^o} = 1 - \frac{s_m}{s_c} \qquad (18.2)$$

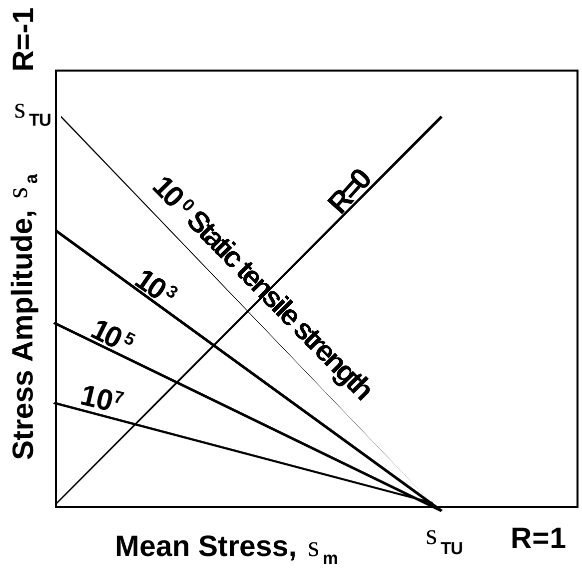


Figure 18-2 Master diagram typical of metal fatigue

The stress rupture strength often can be predicted from the following relationship

$$s_c = s_{TU}\left(A - B\log t\right) \tag{18.3}$$

where t is the time, s_{TU} is static tensile strength and A and B are constants.

Closed loop fatigue testing

Fatigue data used for design is usually obtained by applying a sinusoidal load cycle. This is because originally fatigue machines used rotating mass or rotating specimens that result in sinusoidal loading. Although these machines are still in use, today extensive use is made of electro-hydraulic closed loop fatigue testing machines that can produce a variety of waveforms in addition to sinusoidal loading. Example of such loading cycles are shown in Fig.18-3. Although these machines are capable of load frequencies fatigue testing of composites is usually performed at 10 Hz or less to minimize temperature build-up.

Closed loop fatigue testing permits readily allow for either load or displacement control. In load control the specimen is cycled between specified maximum and minimum loads so constant stress amplitude is maintained. The stress-strain cycle for load control fatigue testing is illustrated in Fig. 18-4a. The solid line represents the cycle s at the start of fatigue loading. As fatigue damage progresses the compliance of the specimen increases and the strain range for the original stress range increases as shown by the broken line. In displacement control the specimen is cycled between specified constant maximum and minimum strains so constant strain amplitude is maintained as shown in Fig. 18-4b.

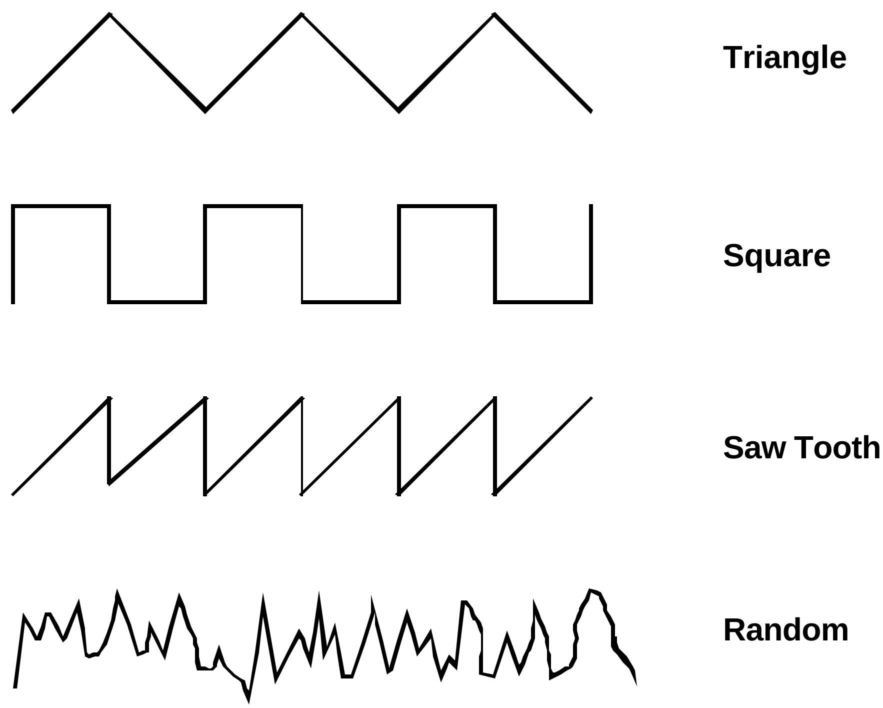
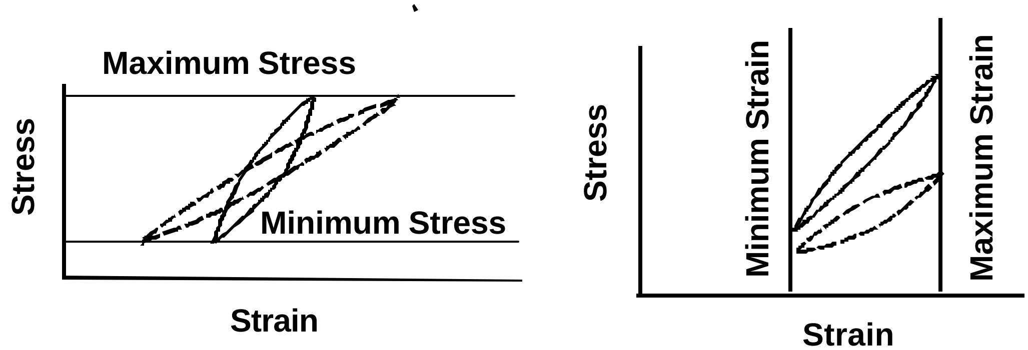


Figure 18-3 Load cycle waveforms applied by closed loop testing.



a) Load control b) Displacement control

Figure 18-4 Comparison of load and strain control modes of fatigue testing on stress-strain behavior.

The S/N Curve

Fatigue performance is often expressed in terms of the number of cycles to failure at a given maximum stress level. A complete description of fatigue performance requires the mean stress or fatigue stress ratio, *R* to also be given. The results of such tests are plotted as maximum fatigue stress versus the cycles to failure on a base 10 logarithmic scale. This plot is referred to as an *S/N curve*. The *S/N* curves for two unidirectional composite materials are shown in Fig. 18-5. The form of the *S/N* curve for E-glass/epoxy is similar to that of most metals. At low stress, often referred to high-cycle-fatigue (HFC) the fatigue life increases significantly, and in some cases

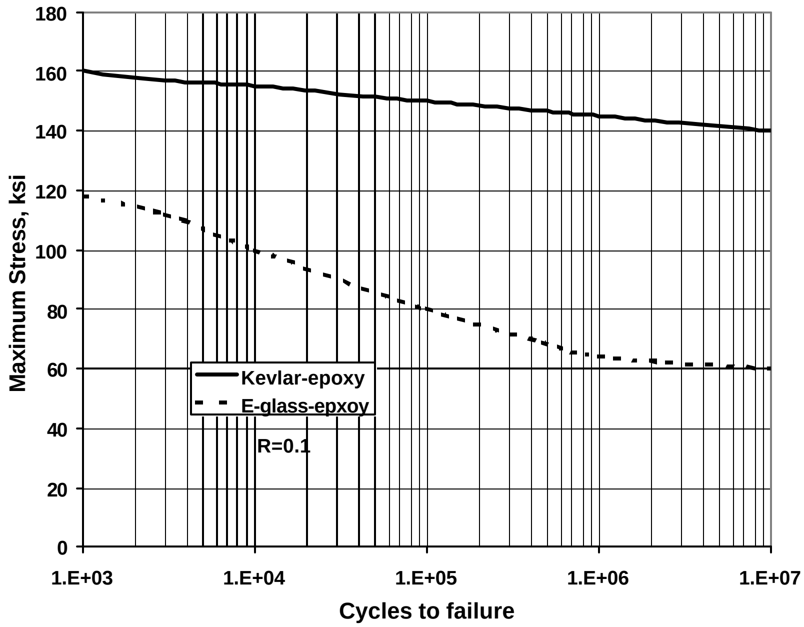


Figure 18-5 *S/N* plots for two unidirectional composites

the fatigue life can become infinite. The stress at which this occurs is called the fatigue endurance limit. The form of the *S/N* curve for Kevlar/epoxy is typical of a material with high fatigue strength.

The S/N curve can be described as

$$S = s_{TU}\left(m\log N + b\right) \tag{18.4}$$

where S is the maximum fatigue stress, N is the number of cycles to failure, s_{TU} is the average static strength, m and b are constants. The constant m describes the slope and the constant b is the stress intercept of the *S/N* curve. Low values of m and high values of b indicate high fatigue strength. Typical values for constants m and b are given in Table 18-2 for some common composites. Comparing the values of m and b for carbon fiber and E-glass fiber composites at the same R ratio, it can be seen that the carbon fiber composites have the better fatigue strength. The coefficient b is strongly influenced by the static strength.

The *S/N* curve can also be described by the power law

$$\frac{S}{s_{TU}} N^{d} = c \tag{18.5}$$

where d and c are constants.

Table 18-2. Typical values for *m* and *b*

Material	*R*	*m*	*b*
E-glass/ductile epoxy 0E	0.1	-0.1573	1.3743
T300 carbon/ductile epoxy 0E	0.1	-0.0542	1.0420
E-glass/brittle epoxy 0E	0.1	-0.1110	1.0935
T300 carbon/brittle epoxy 0E	0.1	-0.0873	1.2103
E-glass/epoxy $[0/90]_s$	0.05	-0.0815	0.934

THE STATISTICAL NATURE OF STRENGTH AND FATIGUE DATA

Inhomogeneity of all materials, as well as variations in the strengths of composite constituents can result in large variations in strength or fatigue life from specimen to specimen. The statistical properties used are often based on a normal distribution where average strength is given as

$$\bar{s} = \sum \frac{s_i}{n} \tag{18.6}$$

The standard deviation is

$$d = \sqrt{\frac{\left(\sum s_i^2\right) - n\bar{s}^2}{(n-1)}} \tag{18.7}$$

and the coefficient of variation is

$$r = \frac{100d}{\bar{s}} \tag{18.8}$$

The Weibull distribution is a more realistic representation of variations in strength and life parameters where the probability of survival a property level, *s* is

$$F(s) = e^{\left[-\left(\frac{s}{s_o}\right)^a\right]} \tag{18.9}$$

where a is the shape parameter (dimensionless) which is the slope of the Weibull plot and s_o is the location parameter found from the intersection on the axis of the Weibull plot.

The mean value of the property is found as

$$\overline{s} = s_o \Gamma\left(\frac{1-a}{a}\right) \tag{18.10}$$

To produce the Weibull plot to obtain these parameters, do the following:

1) Arrange you data in increasing order
2) Assign $I = 1,2,3,\ldots n$ to each value.
3) Calculate the probability of failure for each value as $P = \dfrac{i}{n+1}$
4) Plot $\ln\left[\ln\left(\dfrac{1}{1-P}\right)\right]$ vs $\ln s$ for each value.

An example of strength data arranged in such a manner is shown in Table 18-3.

Table 18-3 Strength data arrange for a Weibull plot

	Stress, MPa	*i*/(1+*n*)	ln stress	ln(ln(1/1-*P*)))
1	291.2	0.042	5.674	-3.157
2	304.1	0.083	5.717	-2.442
3	327.6	0.125	5.792	-2.013
4	332.3	0.167	5.806	-1.702
5	337.5	0.208	5.822	-1.454
6	347.0	0.250	5.849	-1.246
7	353.8	0.292	5.869	-1.065
8	354.8	0.333	5.872	-0.903
9	355.1	0.375	5.872	-0.755
10	356.8	0.417	5.877	-0.618
11	359.4	0.458	5.884	-0.489
12	360.4	0.500	5.887	-0.367
13	366.7	0.542	5.905	-0.248
14	368.2	0.583	5.909	-0.133
15	369.2	0.625	5.911	-0.019
16	372.3	0.667	5.920	0.094
17	377.9	0.708	5.935	0.209
18	378.7	0.750	5.937	0.327
19	382.5	0.792	5.947	0.450
20	383.7	0.833	5.950	0.583
21	388.0	0.875	5.961	0.732
22	394.4	0.917	5.977	0.910
23	396.8	0.958	5.983	1.156

The Weibull plot for this data is shown in Fig. 18-6. From this plot the parameters $s_o = 372.3\text{MPa}$ $(\ln s_o = 5.9197)$ and $a = 17.15$ were found.

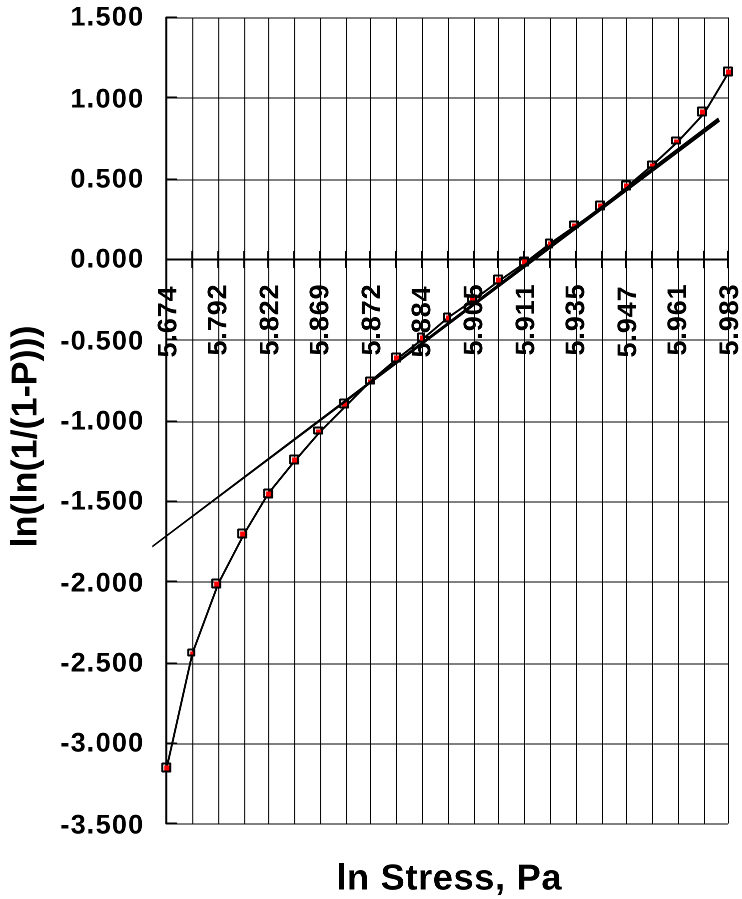


Figure 18-6. Weibull plot for strength.

FATIGUE MODES IN COMPOSITES

In a unidirectional single layer composite three fatigue failure modes can occur: fiber breakage, matrix cracking and fiber-matrix debonding. Fiber Breakage has a strong dependence on fiber strength. Matrix cracking can be postponed if the fibers have high stiffness which limits the amount of strain transferred to the matrix. Debonding if the fiber matrix interface is promoted by weak fiber/matrix bond strength. In multiplayer composites a fourth failure mode, ply delamination, can occur as a result of fatigue loading. An *S/N* curve can then be generated for each of these modes as shown in Fig.18-7. Although significant laminate strength degradation does not occur until fiber fracture, one of the lesser forms of composite degeneration may constitute laminate failure. Even fiber debonding my unacceptable in some applications because of the increased susceptibility to moisture damage once fiber-matrix separation has occurred.

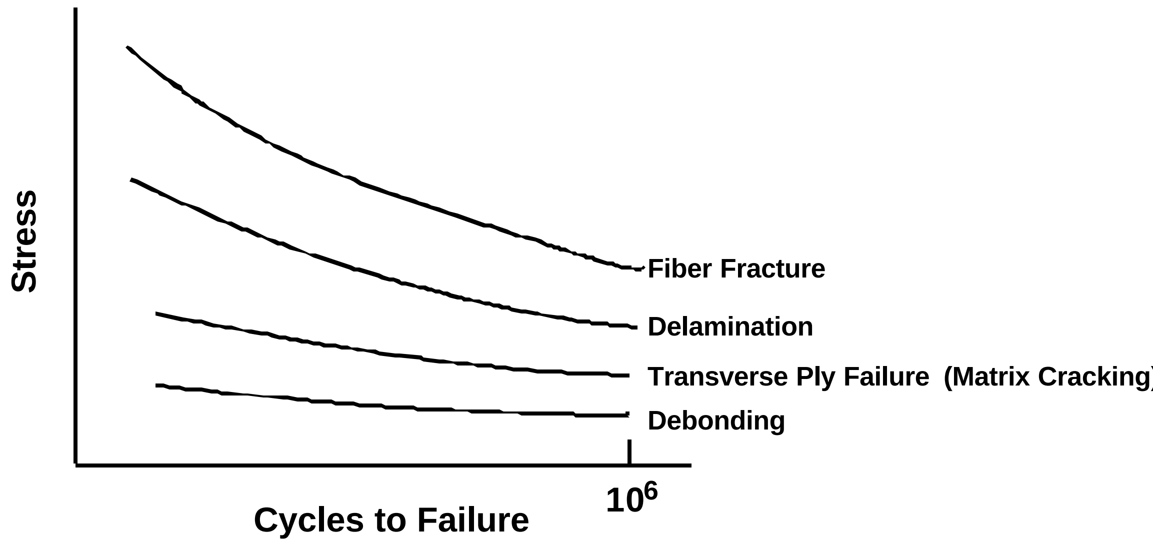
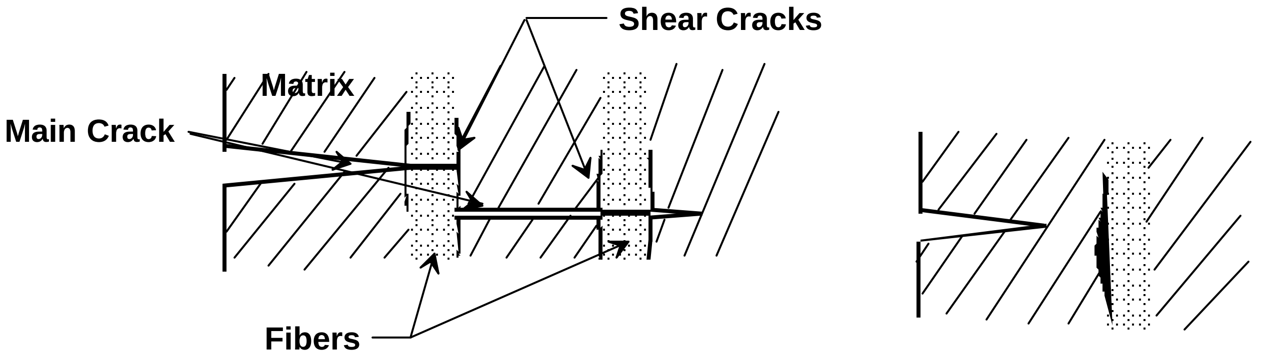


Figure 18-7 Relative *S/N* behavior for various composite fatigue failure modes

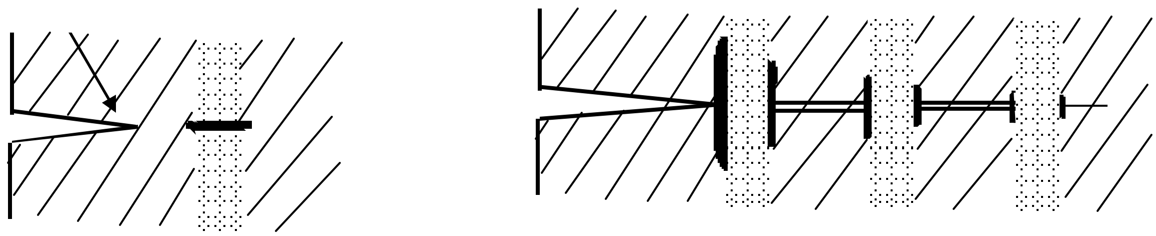
Fatigue is considered to take place in two successive stages; crack initiation and crack propagation. At high fatigue stress levels, usually referred to as low-cycle-fatigue (LCF), the initiation stage occurs very early in the load cycling, and a large portion of the fatigue life is crack propagation. In HCF a large fraction of the total fatigue cycles are required to initiate the fatigue crack. In metal fatigue crack initiation occurs at the surface where the likelihood of finding flaws or stress concentrations is greatest. In composites the fiber/matrix discontinuity of matrix voids are potential flaw sites, hence, it is not uncommon to find subsurface fatigue origins.

A number of possible events can occur during the propagation of a fatigue crack in a composite including the fiber and matrix fracture accompanied by shear cracks, shear cracks alone caused by tensile splitting, fiber rupture ahead of crack with no matrix cracks or shear cracks and matrix cracking with no fiber fracture. These events are illustrated in Fig.18-8. The formation of shear cracks is generally beneficial to fatigue life since they absorb fracture energy by increasing the fracture path, as seen in Fig.18-8a and tend to blunt the fatigue crack. Shear cracks can occur ahead of the fatigue crack, as seen in Fig.18-8b due to differential Poisson's strain between fiber and matrix. When the failure strain of the fiber is small compared to that of the matrix the fibers can fail ahead of the crack as shown in Fig.18-8c. For the case of ductile fibers in a brittle matrix the matrix can fail leaving the fibers in tact as shown in Fig.18-8d.

The events illustrated in Fig.18-8 can occur in both unidirectional and multi-ply laminates. However in multi-ply laminates the fiber angles and ply boundaries can have a significant impact on fatigue crack propagation. Crack propagation generally can progress with little hindrance in the direction parallel to the fibers, thus the transverse plies in a cross-ply composite will fail first under both static and fatigue loading. The cracks in the transverse plies can also be arrested at the interlaminar boundaries to produce crack blunting and shear cracking as seen in Fig.18-9.



a) Fiber and matrix fracture accompanied by shear cracks b) Shear cracks by tensile spitting



c) Fiber fracture ahead of crack d) Matrix cracking without fiber fracture

Figure 18-8 Crack propagation events during fatigue of composites

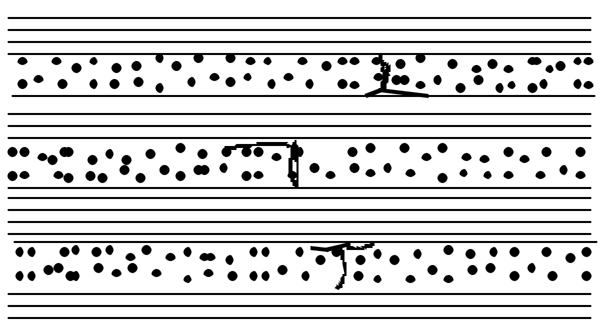


Figure 18-9 Crack propagation through a cross-ply laminate

FACTORS AFFECTING FATIGUE IN COMPOSITES

Fatigue in composites is affected by basic constituent, lamina and ply properties such as fiber properties, matrix properties, ply orientation and fiber fraction.

Fiber property effects

For unidirectional fiber composites high strength and high stiffness composites result in greatest fatigue strength. This can be seen in Fig.18-10. The high stiffness fibers limits strain in matrix preventing the initiation of matrix cracks that can act as stress risers. High static strength of any materials is usually a prerequisite of high fatigue strength as well. In addition to strength abrasion resistant fibers minimized surface flaws.

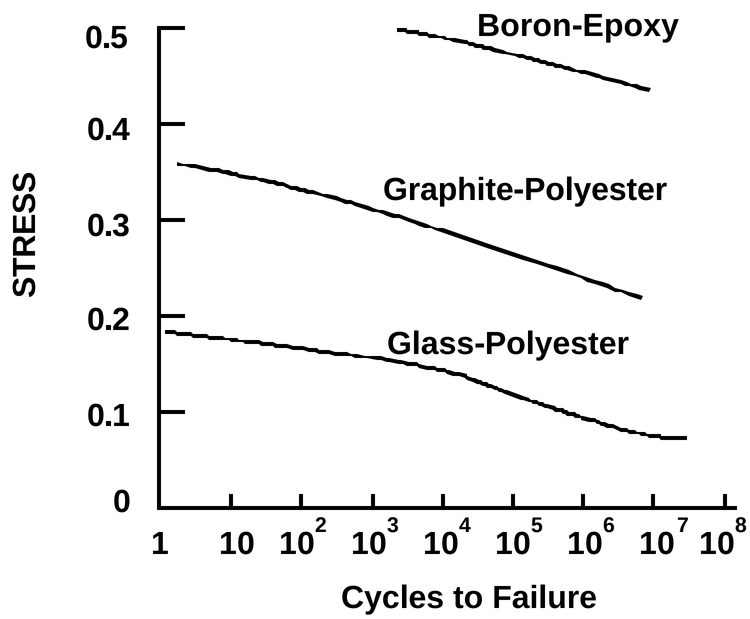


Figure 18-10 Effect of fiber type on composite fatigue

Matrix property effects

Fatigue resistance of composites is improved for matrix materials that are strong and have high failure strains. Resistant to thermal degradation is also important especially in glass fiber composites since the heat of fatigue is not readily dissipated in low thermally conductive materials. The relative strength of E-glass fiber composites with various matrix materials are shown in Fig.18-11. Low strength silicone matrix materials have the lowest fatigue strength. Polyester materials are medium strength polymers and exhibits improved fatigue strength. The high strength epoxies show even greater fatigue resistance. A toughened epoxy has lower strength than the high strength epoxy, which is reflected in lower fatigue strength at high stress levels. At low stress levels, however, the toughened epoxy has significantly improved fatigue strength. Phenolic is both strong and heat resistant hand exhibits very high fatigue resistance for an E-glass composite.

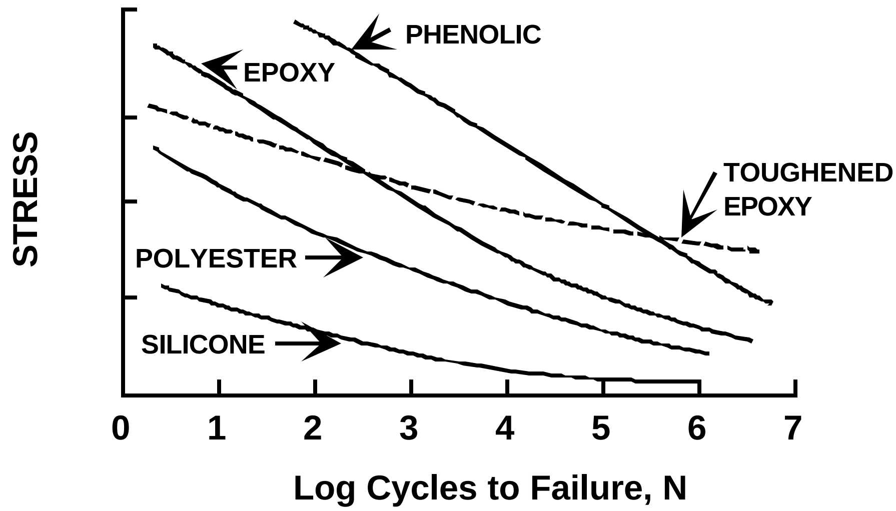


Figure 18-11 Relative fatigue strength of E-glass fiber composites with various matrix materials.

Orientation effects

Various fiber orientation effects on *S/N* behavior of composites are shwn in Fig. 18-12. On-axis loading results in the greatest fatigue strength, especially in LCF. By orienting the fibers at a slight off-axis loading, longitudinal splitting can be induced resulting in reduced crack growth rate and therefore an increase in fatigue life in the high cycle regime. This effect can also be seen for larger off-axis orientations although the overall fatigue strength is lower. Longitudinal

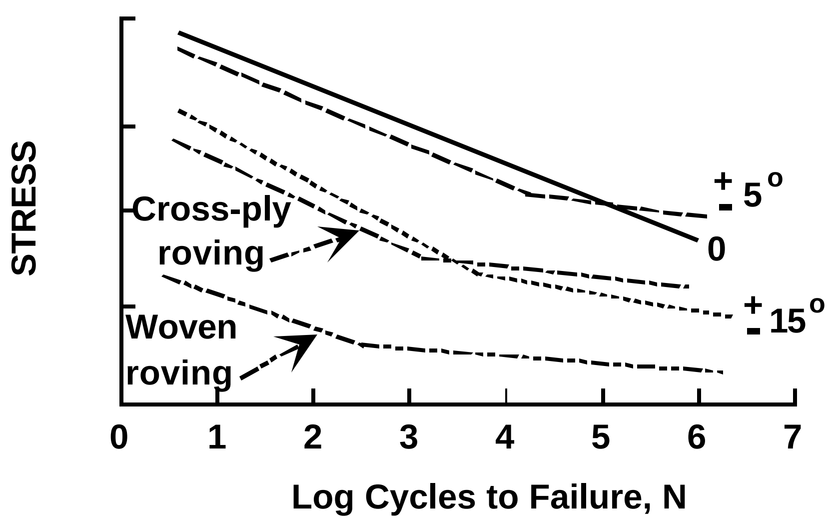


Figure 18-12 Fiber orientation effects on composite fatigue

splitting can also be produced by cross-plying. Notice a significant reduction in fatigue strength if the cross-ply is fabrication from woven roving compared to straight roving.

Fiber fraction effects

The effect of fiber fraction on fatigue strength as expressed in the S/N curve is shown in Fig.18-13.

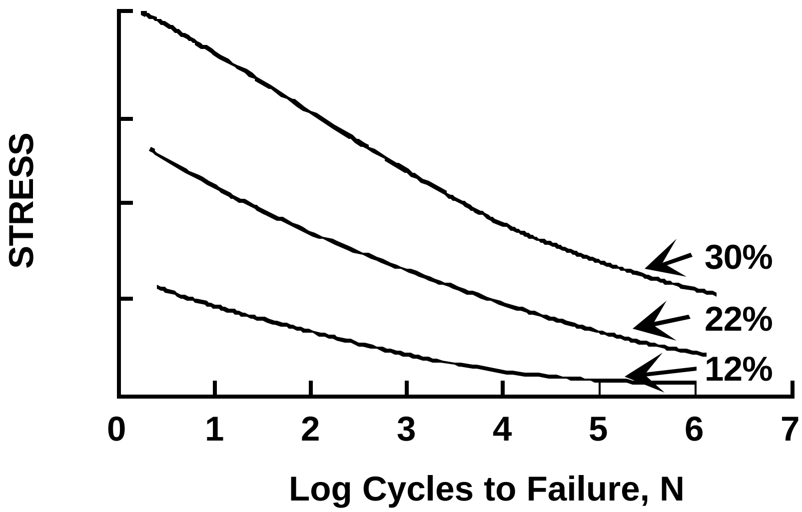


Figure 18-13 Fiber fraction effects on composite fatigue

<u>FATIGUE IN METAL MATRIX COMPOSITES</u>

In metal matrix composites the matrix allows a significant amount of plastic strain to occur at each stress cycle. Fatigue in a material exhibiting a significant amount of plastic deformation can be described by the Coffin relation,

$$N^{1/2}\Delta e_p = C \qquad (18.11)$$

where Δe_p is the plastic strain range shown in Fig. 18-14 and C is a constant.

The plastic strain range for a metal-matrix composite can be found using the Baker relation,

$$\Delta e_p = \frac{2s - 2s_Y\left[\frac{E_f}{E_m}V_f + \left(1 - V_f\right)\right]}{E_f V_f + U\left(1 - V_f\right)} \qquad (18.12)$$

where s is the maximum stress applied to the composite, s_Y is the yield stress in the cyclically hardened matrix and U is the effective modulus of in the yielded matrix. Assumes matrix behavior is unaffected by presence of fibers. This is not usually the case, hence,) ,$_p$ is over-estimated by this relation.

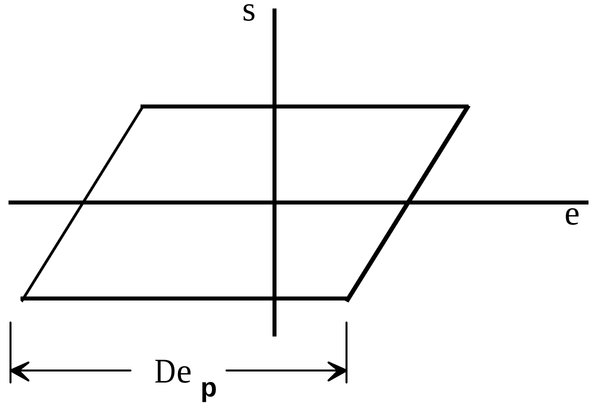


Figure 18-14. Plastic strain range in a metal matrix composite