N72-29904

FATIGUE OF COMPOSITES*

By Michael J. Salkind

Sikorsky Aircraft Division, United Aircraft Corporation, United States

INTRODUCTION

During the past decade, the extensive development activity in composite structures has indicated the promise of substantial improvements in the performance of aerospace systems. This experience, however, has shown that composite materials are substantially different from our former materials of construction, and new concepts in analysis, design, fabrication, quality assurance, and even systems management will be necessary.

A major difference between composites and metals exists in their respective behavior in a fatigue environment. Whereas metals usually fail by crack initiation and growth in a manner which has come to be predictable through fracture mechanics analysis, composites exhibit several modes of damage including delamination, matrix crazing, fiber failure, void growth, matrix cracking, and composite cracking. A particular structure may exhibit any or all these damage modes, and it is difficult to predict, a priori, which mode will dominate and cause failure. The selection of fiber and matrix can produce predictable fiber or matrix-dominated failure in simple unidirectional specimens. (See refs. 1 to 4.) In real structures, however, the complex multidirectional loadings and complex reaction of nonsimple laminates precludes easy prediction of failure modes. Also, joints and attachments in composite structures generally result in failure modes which are peculiar to a particular design.

A characteristic of composite materials which differs substantially from metals is the relative difference between low- and high-cycle fatigue behavior. Whereas most metals behave according to the so-called Coffin-Manson relationship (refs. 5 to 7) in low-cycle fatigue, composites have been shown to be more sensitive to strain range (ref. 4). This sensitivity results in the high-cycle fatigue strength of composites being high with respect to static- and low-cycle fatigue strength. Many structures designed for fatigue experience a spectrum of high as well as low stresses, and whereas the more numerous low stresses may be the critical design factor for a metal structure, the same structure made from a composite material may well be critical in low-cycle fatigue.

A problem arises in the design of composite structures for fatigue loading because of the lack of an adequate definition of failure. A large part of the fatigue

*Also published in ASTM STP 497.

9

data in the literature is based on time to fracture. For high-cycle fatigue, metals are generally structurally adequate to the point of crack initiation (and to some extent beyond that), which is usually a large part of the time to fracture. Although it is preferable to use fatigue data based on crack initiation, the error introduced by designing metal structures using fatigue data based on fracture is usually not significant. Using such an approximation for composites, however, could lead to disastrous results. Composites generally begin to exhibit changes in properties very early in the total life to fracture. Such changes in elastic properties could lead to structural failure long before the structure is in danger of fracturing. Rotating airfoils such as helicopter rotor blades or gas turbine blades are subject to aeroelastic instabilities if the fundamental frequency shifts because of early fatigue damage that causes stiffness changes. A composite spring whose spring constant changes beyond an acceptable value would be considered failed even though it was in no danger of fracturing. The same composite used for a tension cable application for which stiffness is not critical might have an acceptable fatigue life to failure several orders of magnitude higher than the stiffness critical spring under the same loading conditions. A further complication to this problem is the fact that composites are anisotropic, and for any number of cycles, the change in stiffness in one direction may be unrelated to the change in stiffness in a second direction.

The requirement for an adequate failure criterion, coupled with the challenge of providing adequate damage detection schemes for multiple damage modes, clearly indicates the requirement for a new approach to the design of fatigue-critical composite structures. This paper includes a review of the fatigue behavior of composite materials and structures and a proposed approach for design of fatigue-critical components.

FATIGUE OF COMPOSITE MATERIALS

A large body of small specimen fatigue data has been generated over the past 10 years. These data are primarily for unidirectional laminates and, as mentioned previously, are based upon fracture as the definition of failure. Hence, much of it is of limited value for use in design. A survey of pertinent observations is included in this section.

Fiber-Reinforced Polymers

The most widely used class of composite materials, glass-fiber-reinforced polymers, has been the subject of extensive fatigue testing (refs. 8 to 23). Although the data in references 8 to 23 are based upon fracture as the failure criterion, they give us an indication of the effect of significant variables, such as resin composition and content and fiber composition and orientation on fatigue. Boller (ref. 11) has evaluated a variety of matrix systems and found epoxides to be superior in fatigue. His data, seen in figure 1, is more than 15 years old, and improved surface treatments and processing have since been developed; however, the relative ranking remains unchanged (ref. 19). As seen in figure 2, varying the resin content between 20 and 37 percent has a negligible effect on fatigue behavior for $\pm 5^{\circ}$ glass-fiber composites. The effect of fiber orientation is rather complex. Although the tensile strength of unidirectional composites is a maximum at 0° to the fibers (ref. 24), in fatigue the unidirectional construction is not optimum, as can be seen in figure 3. The best explanation for this phenomenon is the fact that unidirectional material is subject to splitting and rapid crack propagation in the matrix parallel to the fibers. Fatigue data for $\pm 5^{\circ}$, 67% 0°/33% 90°, and Style 181 satin weave ($0^{\circ}/90^{\circ}$) are compared in figure 4. In general, nonwoven materials are superior to woven materials in fatigue. Note also the low notch sensitivity of these materials. A comparison of the behavior of S-glass and E-glass composites (ref. 15) is seen in figure 5. The higher modulus S-glass is consistently stronger in fatigue than E-glass. The effect of mean stress is seen in figure 6 for tension-compression and tension-tension behavior. There have also been some measurements of the compression-compression fatigue behavior in low-cycle fatigue (ref. 20). These data indicate that the effect of mean stress is similar to that for metals, that is, the Goodman diagram is approximately linear.

In recent years, the realization that fracture was not an adequate design criterion for failure has led to studies of failure mechanisms in fatigue which provide a foundation for design. Broutman (ref. 25) studied the mechanisms of failure in glass-fiber-reinforced polymers subjected to fatigue loading. He noted cracks originating at fiber-matrix debonds propagating through the matrix and being deflected by fibers. Recent studies (refs. 26 to 30) have quantitatively described the changes in elastic and strength properties associated with this type of damage. Smith and Owen (ref. 26) evaluated eleven different composite systems with modulus values ranging from 0.5×10^{6} to 6.5×10^{6} psi and found that the initial damage debonding occurred at 0.3% strain as seen in figure 7. Thus, the limiting factor in fatigue is not the fiber but the interface or the matrix. As described in the following section, studies with metal matrix composites confirm this behavior. The data seen in figure 8 for chopped-strand mat-reinforced polyester laminates confirm that initial damage occurs at stresses well below those required for fracture. The effect of such damage on structural capability will determine whether the part has failed. Based on the observation of a critical strain, Smith and Owen postulated a critical maximum stress independent of mean stress for any material. As seen in figure 9, this postulation was found to be incorrect (ref. 26).

Cessna et al. (ref. 27) performed constant-deflection flexural fatigue tests on glass-reinforced polypropylene and monitored the load decay (proportional to modulus decay) with cycles as seen in figure 10. They also monitored the temperature rise, as seen in figure 10, due to viscoelastic energy dissipation, which is common for polymeric composites. (See refs. 31 to 37.) In addition to indicating progressive fatigue damage, the temperature rise also contributes to weakening the material and shortening its fatigue life. As seen in figure 11, by cooling their specimens to maintain isothermal conditions, Cessna et al. (ref. 27) were able to extend both the cycles to onset of stiffness change and the fracture life by an order of magnitude.

Broutman and Sahu (ref. 28) have related the changes in residual tensile strength and modulus to the development of cracks in $0^o/90^o$ crossplied material as seen in figure 12. Although the decrease in residual strength and primary modulus is expected because of the increasing crack density, the initial increase in secondary modulus remains unexplained. A quantitative relationship between modulus change and crack density (fig. 13) has been developed on the same material. Fujii and Mizukawa (ref. 30) have also determined the change in elastic and strength properties with cycling for laminates consisting of several combinations of roving cloth, chopped mat, and woven cloth.

The higher modulus composite materials, graphite and boron, have exhibited higher fatigue strengths than glass-reinforced polymers, as seen in figure 14 (refs. 15, 38 to 41). This difference is primarily attributed to the higher modulus resulting in less strain in the matrix and interface at the same cyclic stress level. The phenomenon of low fatigue strength at zero mean stress for the high modulus composites as seen in figure 14 was first noted for boron-reinforced aluminum. It is thought to be the result of low transverse strength of unidirectional composites resulting in splitting under cyclic compressive loads. This behavior severely limits the use of unidirectional composites as discussed above.

A major variable which can affect the data obtained in a composite fatigue test is the specimen geometry. This variable is very much a function of the particular laminate orientation being tested, as interlaminar shear can be a primary controlling factor (refs. 42 and 43). Although this problem is negligible for a unidirectional material, it becomes a major factor in fatigue testing of $\pm 45^o$ laminates. Figure 15 compares the axial tension-tension fatigue behavior (based on fracture) for $\pm 45^o$ 1002 E-glass composites for three different specimen configurations (ref. 43). The straight-sided specimen is flat, and each fiber terminates at the edge, thus, high interlaminar shear stresses are created. The x-type specimen has all fibers continuous from grip to grip; thus, interlaminar shear stresses at the edge are precluded. The latter type has the disadvantage of having a vanishingly small gage length and very uniformly loaded fibers, which are not representative of the types of loading experienced in most structures; thus, the resultant data are considered to be too optimistic for design. The tubular specimen has a uniformly loaded gage section and no fiber edges; thus, interlaminar shear is precluded. It is felt that such a specimen comes closest to yielding representative material properties for design. Edges are usually handled as a separate factor in design. Although the difference between the straight-sided and tubular specimens is only 5% for glass, it is approximately 50% for boron, as can be seen in figure 16. The reason for this effect is that the interlaminar shear stresses are higher for high modulus materials.

Fiber-Reinforced Metals

Although fiber-reinforced metals considerably lag reinforced polymers in terms of development and usage, some of the earliest and best fundamental studies of fatigue have been accomplished with metal matrix composites. Forsyth, George, and Ryder (ref. 1) demonstrated that the inclusion of steel wires in an aluminum-alloy sheet reduces the rate of crack propagation substantially (fig. 17), although the improvement in total fatigue life to fracture is small (fig. 18). Baker and Cratchley (refs. 2, 44 to 48) performed extensive studies of the fatigue behavior of silica- and steel-fiber-reinforced aluminum alloys. Although silica-reinforced aluminum did not show promise as a fatigue-resistant material, Baker and Cratchley made important observations concerning failure modes and anelastic behavior. They identified the crack-diverting capability of strong fibers (ref. 2) and made important observations concerning the stress-strain behavior and damping capability of composites as seen in figure 19 (ref. 44). In addition, Baker quantitatively defined the effect of fiber length on fatigue behavior (ref. 46) and evaluated the effects of fiber fatigue behavior and the interface (ref. 47).

Extensive studies have been made of the fatigue behavior of composites made by unidirectional solidification of eutectic alloys (refs. 4, 49 to 52). Because these composites have very regularly distributed fibers and well-bonded interfaces, they serve as excellent systems for studying the mechanical behavior of composites without the variable fabrication effects common to other composites. The Al-Al_3Ni (10% reinforcing Al_3Ni whiskers) and the Al-$CuAl_2$ (50% reinforcing $CuAl_2$ platelets) composite materials exhibit markedly different fatigue behavior as seen in figure 20. A comparison of the stress-strain behavior of the two materials showing fatigue failure at the same stress amplitude (ref. 49) reveals that Al-$CuAl_2$ appears to work-harden more rapidly with narrower hysteresis loops than Al-Al_3Ni. It can be speculated that the wide $CuAl_2$ platelets are more effective at blocking plastic flow than the Al_3Ni whiskers (which have a spacing at least an order of magnitude too large for optimum dispersion hardening). In addition, the greater volume fraction of $CuAl_2$ is more effective at blocking plastic flow in the matrix. If matrix strain is the controlling factor, then the behavior seen in figure 20 would be an expected consequence of the difference in stress-strain behavior.

The fatigue behavior of metals has been found to obey a simple empirical relationship (refs. 5 to 7, 53 and 54)

$$\Delta\epsilon_T = \underset{\text{Plastic}}{MN^z} + \underset{\text{Elastic}}{\frac{G}{E} N^{\gamma}} \tag{1}$$

where

$\Delta\epsilon_T$	total cyclic strain range
E	elastic modulus
N	number of cycles to failure
M, G, z, γ	material constants

This relationship is depicted schematically in figure 21, and it is seen that the plastic component (first term of eq. (1)) dominates at low cycles (high strain amplitudes), and the elastic component dominates at high cycles. Although most metals exhibit values of z of -0.5 to -0.6 (refs. 53 and 54), Al_3Ni whisker-reinforced aluminum exhibits much lower values as seen in figure 22. It has been proposed (ref. 4) that the low-cycle fatigue behavior is not governed entirely by the plastic behavior of the aluminum ($z = -0.5$) but also by the elastic behavior of the Al_3Ni ($\gamma < -0.1$). This type of behavior would be expected for most composites having fibers which behave elastically in the stress range of use (glass, boron, graphite, highly cold-worked steel) and accounts for the relatively flat S-N (that is, stress S – number of cycles to failure N) curves discussed in the Introduction.

As seen in figure 23, the flexural fatigue behavior of Al-Al_3Ni is substantially higher than that for the matrix alone. The mode of failure is matrix cracking, the fibers serving to reduce matrix strain. Testing in a protective atmosphere such as argon results in higher fatigue strength as seen in figure 24, which further verifies the fact that failure is matrix dominated. Although the aluminum is susceptible to attack by moisture in the atmosphere, the Al_3Ni whiskers are not.

The fatigue behavior of boron-reinforced aluminum has been extensively studied (refs. 55 to 59). The very high modulus of the reinforcing fiber keeps the matrix strain low for any given stress level. This factor, coupled with the excellent fatigue resistance of boron fiber itself (ref. 60), provides extremely good fatigue resistance as seen in figure 25. The data by Young and Carlson (ref. 56) is particularly valuable as it records changes in deflection for torsion, tension, and combined-load fatigue testing.

Gates and Wood (ref. 61) performed detailed studies of the microstructural changes which accompanied the torsional fatigue testing of copper reinforced circumferentially by tungsten or molybdenum wire. They noted that work hardening followed by crack initiation occurred in the matrix between fibers.

FATIGUE OF COMPOSITE STRUCTURES

In order to define a design base for structures, it is necessary to determine the full-scale fatigue behavior of composite materials to identify the effects of size, manufacturing variation, and combined loads. A limited amount of experience now exists with full-scale components (refs. 62 and 63); however, much of it relates to specific geometries and constructions and few generalizations may be drawn. Two things which are clear from this experience is the fact that composite structures are very fatigue resistant in aerospace applications relative to metal structures, and joints and attachments remain a major design problem, especially in fatigue.

The most substantial body of structural fatigue data exists for helicopter rotor blades (refs. 62 and 63). Jarosch and Stepan (ref. 62) have done fatigue testing of root end and outboard sections of the BO-105 fiberglass/epoxy rotor blade. The blade construction, seen in figure 26, consists of a C-spar of unidirectional E-glass-reinforced epoxy wound around a pin fitting at the root end, a skin of woven-glass cloth/epoxy oriented at $\pm 45^{\circ}$, and a foam core. Measured values of the spar and skin elastic modulus in the spanwise direction were 6.0×10^6 and 2.6×10^6 psi, respectively. The root end was fatigue tested, as seen in figure 27, with equal flapping and lagging loads of 1900 ± 2600 ft-lb and a steady centrifugal load of 24 000 lb. Fatigue lives varied to 13×10^6 cycles. Failure generally occurred in the unidirectional roving at the root-end pin attachment and was accompanied by considerable heating due to interlaminar friction. Readily visible delamination and gradual changes in stiffness and damping also occurred. Outboard specimens were tested in flapping resonance at a fatigue strain level of $\pm 0.8\%$, which is ten times the maximum strain in flight. Typical fatigue lives were more than 10^6 cycles, and failure was preceded by obvious visible delaminations and accompanying changes in damping and stiffness.

Fatigue tests of boron/epoxy and glass/epoxy CH-47 rotor blades (ref. 63) have also indicated excellent fatigue resistance although failures occurred in the metal root-end fitting. Similarly, fatigue testing of the boron/epoxy F-111 horizontal tail resulted in failure associated with the attachment of the composite to the titanium root end. Spectrum testing of components of a boron/epoxy wing box has shown excellent fatigue resistance, as has sonic fatigue testing of a boron/epoxy C-5A slat component. Both of these items have exhibited failure in fittings of composite bonded to metal.

COMPOSITE FATIGUE DESIGN CONSIDERATIONS

A successful design procedure for composite materials in fatigue applications will not be a simple extrapolation of procedures used for metals. Metal parts exhibit cracks when they begin to fail in fatigue, and the cracks generally propagate in a predictable manner to failure. Thus, the metal part may be inspected at specific intervals and removed from service prior to failure. Composites, on the other hand, do not fail in the same manner.

The difference between fatigue behavior of a composite and that of a metal structure is depicted schematically in figure 28. The primary mode of damage in a metal structure is cracking. Cracks propagate in a relatively well defined manner with respect to the applied stress, and the critical crack size and rate of crack propagation can be related to specimen data through analytical fracture mechanics. In this discussion, the critical damage size is defined as that amount of damage at which the composite will be no longer structurally adequate. In general, the crack initiation time (defined as the time to detecable cracking (inspection threshold)) occupies a large part of the fatigue life of a metal part (ref. 64). It should be noted that all structures have some initial damage in the form of microcracks, surface imperfections, inclusions, and other stress risers and that much of the so-called crack initiation time involves propagation of this damage to detectable size. With composite structures there is no single damage mode which dominates. Matrix cracking, delamination, debonding, voids, fiber fracture, and composite cracking can all occur separately and in combination, and the predominance of one or more is highly dependent on the laminate orientations and loading conditions. In addition, the unique joints and attachments used for composite structures often introduce modes of failure different from those typified by the laminate itself.

The composite damage propagates in a less regular manner and damage modes can change. (See fig. 28.) Present experience with composites, although limited, indicates that the rate of damage propagation in composites does not exhibit the two distinct regions of initiation and propagation. Although, as mentioned previously, the crack initiation range in metals is actually propagation, there is a significant quantitative difference in rate. This quantitative difference appears to be less apparent with composites. This observation is very subjective and apparently dependent upon the observer's definition of initiation. Some investigators have observed matrix crazing and other indications early in their tests but have reported short-time rapid propagation because they define the latter based upon their experience with metals as crack propagation. Indeed, composite cracking may occupy only a small part of the fatigue life at the very end, but we can certainly make use of all the earlier indications which are prevalent.

It is expected that composite materials will be more damage tolerant than metals. Again, this expectation is based upon limited experience and will depend upon the laminate orientation (unidirectional composites are subject to splitting) and loading conditions, but, in general, it can be argued that each fiber is a separate load path and that a composite is therefore highly redundant. Our present analytical fracture mechanics tool must be supplemented for use with composites before we have a better understanding of this behavior. Several investigators have indicated that, in general, composites exhibit good fracture toughness (refs. 65 to 67) and, unlike metals, increase fracture toughness with increasing strength. It is thus reasonable to predict the critical damage size in composites to be greater than that for metals (fig. 28), although the multiple failure modes make this value a band for composites. Similarly, the inspection threshold is depicted as a band in figure 28 because there are multiple failure modes and multiple inspection methods.

The problem then is to determine the critical mode or modes of failure and develop detection schemes in order to insure fail safety in critical components. One such procedure involves the determination of changes in the static or dynamic stiffness properties of the component. A change in the resonant frequency or damping behavior of a part is an indication of damage. Failure criteria can be developed from data such as those seen in figures 10 to 12 as substantial changes occur early enough in the fatigue life to allow safe detection and removal from service. This characteristic may provide excellent fail safety for rotor blades in that the aeroelastic behavior may degrade noticeably long before the part has sustained damage of critical size. Other detection schemes such as temperature rise measurements (fig. 10), embedded conducting wires, radiography, sonics, ultrasonics, holography, infrared inspection, dye penetrant, and visual inspection will probably be used separately or in conjunction with dynamic measurements.

As mentioned earlier, a major consideration for developing a valid design methodology is a definition of failure. A problem exists however, in that a single failure criterion may be inadequate for all applications. This situation is seen schematically in figure 29. The example considers two structures, a spring and a tension cable, and two candidate materials, a metal and a composite, for each application. The failure criterion for the spring is a specified loss in stiffness, whereas that for the cable is fracture. Since metal structures exhibit little change in stiffness until cracking is extensive, the metal spring and metal cable have approximately the same life, and a single criterion based on fracture is probably adequate for design. The composite material spring would lose sufficient stiffness to be considered failed at only a fraction of its fracture life, whereas, the tension cable made of the same material and subject to the same loading would have a much greater useful life. In order to provide for such design considerations, it will be desirable to record fatigue data as depicted schematically in figure 30.

CONCLUDING REMARKS

Composite materials appear to offer excellent resistance to fatigue loading and, as such, will likely find use in dynamic components. A second factor which makes composites attractive for these applications is the opportunity for tailoring of the stiffness in different directions, thus the designer is given the capability of tuning dynamic components. As composites find wider application, it will be necessary to provide more precise definitions of failure and to couple these definitions with proper damage detection schemes. New, sophisticated damage detection methods will probably not be necessary; however, because of the multiple damage modes possible, it will be necessary to utilize multiple detection schemes. The apparent high damage tolerance of composites will allow somewhat relaxed inspection requirements and will provide for improved repairability procedures. At this writing, the cost of high modulus composites is still high and must be further reduced to allow wider usage.

REFERENCES

1. Forsyth, P. J. E.; George, R. W.; and Ryder, D. A.: Some Preliminary Tests on Aluminum Alloy Sheets Reinforced With Strong Wires. Appl. Mater. Res., vol. 3, no. 4, Oct. 1964, pp. 223-228.
2. Baker, A. A.; and Cratchley, D.: Metallographic Observations on the Behaviour of Silica Reinforced Aluminum Under Fatigue Loading. Appl. Mater. Res., vol. 3, no. 4, Oct. 1964, pp. 215-222.
3. Morris, A. W. H.; and Steigerwald, E. A.: An Investigation of the Fatigue Behavior of Tungsten-Reinforced and Steel-Reinforced Silver Composites. Trans. Met. Soc. AIME, vol. 239, 1967, pp. 730-739.
4. Salkind, M. J.; and George, F. D.: Fatigue and Bonding of Al_3Ni Whisker Reinforced Aluminum. Rep. G910583.4 (Contract No. 0019-68-C-0016), United Aircraft Corp., July 31, 1968. (Available from DDC as AD 838 871.)
5. Tavernelli, J. F.; and Coffin, L. F., Jr.: A Compilation and Interpretation of Cyclic Strain Fatigue Tests on Metals. Trans. Amer. Soc. Metals, vol. LI, 1959, pp. 438-453.
6. Manson, S. S.: Behavior of Materials Under Conditions of Thermal Stress. NACA Rep. 1170, 1954. (Supersedes NACA TN 2933.)
7. Sachs, G.; Gerberich, W. W.; Weiss, V.; and Latorre, J. V.: Low-Cycle Fatigue of Pressure-Vessel Materials. Proc. Amer. Soc. Testing Mater., vol. 60, 1960, pp. 512-529.
8. Boller, K. H.: Fatigue Tests of Glass-Fabric-Base Laminates Subjected to Axial Loading. Rep. 1823, Forest Prod. Lab., U.S. Dep. Agr., May 1952.
9. Stevens, G. H.; and Boller, K. H.: Effect of Type of Reinforcement on Fatigue Properties of Plastic Laminates. TR 59-27, U.S. Air Force, May 1959. (Available from DDC as AD 213 835.)
10. Kimball, Kenneth E.: Supplement to Fatigue Tests of Glass-Fabric-Base Laminates Subjected to Axial Loading – Effect of Notches. Rep. No. 1823-C, Forest Prod. Lab., U.S. Dep. Agr., Oct. 1958.
11. Boller, Kenneth H.: Resumé of Fatigue Characteristics of Reinforced Plastic Laminates Subjected to Axial Loading. ASD-TDR-63-768, U.S. Air Force, July 1963.
12. Boller, K. H.: Effect of Pre-Cyclic Stresses on Fatigue Life of RP Laminates. Modern Plastics, vol. 42, no. 8, Apr. 1965, pp. 162, 165-166, 168, 171, 173.

13. Boller, Kenneth H.: Effect of Tensile Mean Stresses on Fatigue Properties of Plastic Laminates Reinforced With Unwoven Glass Fibers. ML-TDR-69-86, U.S. Air Force, Mar. 1964. (Available from DDC as AD 605 412.)

14. Boller, Kenneth H.: Effect of Pre-Cyclic Stresses on Fatigue Life of Plastic Laminates Reinforced With Unwoven Fibers. ML-TDR-64-168, U.S. Air Force, Sept. 1964. (Available from DDC as AD 606 769.)

15. Boller, Kenneth H.: Fatigue Strength of Plastic Laminates Reinforced With Unwoven "S" Glass Fibers. AFML-TR-64-403, U.S. Air Force, Dec. 1964.

16. Boller, Kenneth H.: Fatigue Characteristics of Two New Plastic Laminates Reinforced With Unwoven "S" Glass Fibers Under Cyclic Axial or Shear Loading. AFML-TR-66-54, U.S. Air Force, Mar. 1966.

17. Boller, Kenneth H.: Effect of Notches on Fatigue Strength of Composite Materials. AFML-TR-69-6, U.S. Air Force, Apr. 1969. (Available from DDC as AD 853 045.)

18. Boller, K. H.: Fatigue Fundamentals for Composite Materials. Composite Materials: Testing and Design, Spec. Tech. Publ. No. 460, Amer. Soc. Testing Mater., c.1969, pp. 217-235.

19. Broutman, Lawrence J.: Fiber-Reinforced Plastics. Modern Composite Materials, Lawrence J. Broutman and Richard H. Krock, eds., Addison-Wesley Pub. Co., Inc., c.1967, pp. 337-411.

20. Cornish, R. H.; Nelson, H. R.; and Dally, J. W.: Compressive Fatigue and Stress Rupture Performance of Fiber Reinforced Plastics. Proceedings 19th Annual Technical and Management Conference, sec. 9-E, Soc. Plast. Ind., Inc., Feb. 1964.

21. Mettes, David G.; and Lockwood, Paul A.: The Mechanical Properties of Laminates Reinforced With High Performance Glass Fiber Fabric. Proceedings 21st Annual Technical and Management Conference, sec. 4-G, Soc. Plast. Ind., Inc., Feb. 1966.

22. Davis, J. W.; McCarthy, J. A.; and Schurb, J. N.: The Fatigue Resistance of Reinforced Plastics. Mater. Des. Eng., vol. 60, no. 7, Dec. 1964, pp. 87-91.

23. Cutler, Martin B.; and Pinckney, Robert L.: Static and Fatigue Test Properties for Woven and Nonwoven S-Glass Fibers. USAAVLABS Tech. Rep. 69-9, U.S. Army, Apr. 1969. (Available from DDC as AD 688 971.)

24. Kelly, A.; and Davies, G. J.: The Principles of the Fibre Reinforcement of Metals. Metallurgical Rev., vol. 10, no. 37, 1965, pp. 1-77.

25. Broutman, L. J.: Failure Mechanisms for Filament Reinforced Plastics. Modern Plastics, vol. 42, no. 8, Apr. 1965, pp. 143-145, 148, 150, 153, 214, 216.

26. Smith, T. R.; and Owen, M. J.: Fatigue Properties of RP-1. Modern Plastics, vol. 46, no. 4, Apr. 1969, pp. 124-125, 128-132.

27. Cessna, L. C.; Levens, J. A.; and Thomson, J. B.: Flexural Fatigue of Glass-Reinforced Thermoplastics. Proceedings 24th Annual Technical and Management Conference, sec. 1-C, Soc. Plast. Ind., Inc., Feb. 1969.

28. Broutman, L. J.; and Sahu, S.: Progressive Damage of a Glass Reinforced Plastic During Fatigue. Proceedings 24th Annual Technical and Management Conference, sec. 11-D, Soc. Plast. Ind., Inc., Feb. 1969.

29. Lavengood, R. E.; and Anderson, R. M.: Matrix Properties Controlling Torsional Fatigue Life of Fiber Reinforced Composites. Proceedings 24th Annual Technical and Management Conference, sec. 11-E, Soc. Plast. Ind., Inc., Feb. 1969.

30. Fujii, Taichi; and Mizukawa, Kiyoshi: The Effect of the Combination of Roving Glass Cloth and Mat Upon the Fatigue Strength of Reinforced Polyester Laminates. Proceedings 24th Annual Technical and Management Conference, sec. 14-D, Soc. Plast. Ind., Inc., Feb. 1969.

31. Hagerup, E.: Flexural Fatigue Testing of Polyesters. J. Appl. Polymer Sci., vol. 7, no. 3, May 1963, pp. 1093-1116.

32. Lazan, B. J.: Some Mechanical Properties of Plastics and Metals Under Sustained Vibrations. Trans. ASME, vol. 65, no. 2, Feb. 1943, pp. 87-104.

33. Lazan, B. J.; and Yorgiadis, A.: Behavior of Plastics Under Repeated Stress. Symposium on Plastics, Spec. Tech. Publ. No. 59, Amer. Soc. Testing Mater., Feb. 1944, pp. 66-94.

34. Boller, Kenneth H.: Fatigue Characteristics of RP Laminates Subjected to Axial Loading. Modern Plastics, vol. 41, no. 10, June 1964, pp. 145-150, 188.

35. Thompson, A. W.: Fatigue and Creep Properties of Reinforced Plastics. Plastics Inst.-Trans., vol. 30, no. 85, Feb. 1962, pp. 39-50.

36. Owen, M. J.: New Fatigue Testing Machine for Reinforced Plastics. Plastics Inst.-Trans., vol. 35, no. 115, Feb. 1967, pp. 353-357.

37. Dally, J. W.; and Broutman, L. J.: Frequency Effects on the Fatigue of Glass Reinforced Plastics. J. Compos. Mater., vol. 1, no. 4, Oct. 1967, pp. 424-442.

38. Shockey, P. D.; Anderson, J. D.; and Hofer, K. E.: Structural Airframe Application of Advanced Composite Materials. Vol. V – Mechanical Properties – Fatigue. AFML-TR-69-101, Vol. V, U.S. Air Force, Mar. 1970. (Available from DDC as AD 867 017.)

39. Hayes, R. D.: Flightworthy Graphite Fiber Reinforced Composite Aircraft Primary Structural Assemblies. Vols. 1 and 2. FML-TR-70-207-Vols. 1 & 2, U.S. Air Force, 1970. (Available from DDC as AD-877 234 and AD-877 235.)

40. Holmes, R. D.; and Wright, D. W.: Creep and Fatigue Characteristics of Graphite/Epoxy Composites. ASME Paper 70-DE-32, Amer. Soc. Mech. Eng., May 1970.

41. Owen, M. J.; and Morris, S.: An Assessment of the Potential of Carbon Fibre Reinforced Plastics as Fatigue Resistant Materials. Proceedings 25th Annual Technical and Management Conference, sec. 8-E, Soc. Plast. Ind., Inc., Feb. 1970.

42. Puppo, A. H.; and Evensen, H. A.: Interlaminar Shear in Laminated Composites Under Generalized Plane Stress. J. Compos. Mater., vol. 4, Apr. 1970, pp. 204-223.

43. Pipes, R. Byron; and Pagano, N. J.: Interlaminar Stresses in Composite Laminates Under Uniform Axial Extension. J. Compos. Mater., vol. 4, Oct. 1970, pp. 538-548.

44. Baker, A. A.; and Cratchley, D.: Stress-Strain Behaviour and Toughness of a Fibre-Reinforced Metal. Appl. Mater. Res., vol. 5, no. 2, Apr. 1966, pp. 92-103.

45. Baker, A. A.: The Effect of Fibre Volume Fraction and Interfacial Bond on the Fatigue of Aluminum Reinforced With Stainless Steel Wires. Appl. Mater. Res., vol. 5, no. 3, July 1966, pp. 143-153.

46. Baker, A. A.: The Effect of Fibre Diameter and Discontinuous Fibres on the Fatigue of a Fibre-Reinforced Metal. Appl. Mater. Res., vol. 5, no. 4, Oct. 1966, pp. 210-217.

47. Baker, A. A.; Mason, J. E.; and Cratchley, D.: High-Strain Fatigue Studies of a Composite Material. J. Mater. Sci., vol. 1, no. 3, Aug. 1966, pp. 229-237.

48. Baker, A. A.: The Fatigue of Fibre-Reinforced Aluminum. J. Mater. Sci., vol. 3, no. 4, July 1968, pp. 412-423.

49. Salkind, M. J.; George, F. D.; Lemkey, F. D.; and Bayles, B. J.: Investigation of the Creep, Fatigue, and Transverse Properties of Al_3Ni Whisker and $CuAl_2$ Platelet Reinforced Aluminum. E910344-4 (Contract NOw-65-0384d), United Aircraft Corp., May 11, 1966. (Available from DDC as AD 633 241.)

50. Salkind, M. J.; Lemkey, F. D.; and George, F. D.: Whisker Composites by Eutectic Solidification. Whisker Technology, Albert P. Levitt, ed., Wiley-Interscience, c.1970, pp. 343-401.

51. Thompson, E. R.; George, F. D.; and Kraft, E. H.: Investigation To Develop a High Strength Eutectic Alloy With Controlled Microstructure. Rep. J910868-4 (Contract No. 0019-70-C-0052), United Aircraft Corp., July 31, 1970. (Available from DDC as AD 873 832.)

52. Hoover, W. R.; and Hertzberg, R. W.: The Fatigue Characteristics of Unidirectionally Solidified Al-Al_3Ni Eutectic Alloy. Trans. Amer. Soc. Metals, vol. LXI, 1968, pp. 769-776.

53. Manson, S. Stanford; and Hirschberg, Marvin H.: Fatigue Behavior in Strain Cycling in the Low- and Intermediate-Cycle Range. Fatigue – An Interdisciplinary Approach, John J. Burke, Norman L. Reed, and Volker Weiss, eds., Syracuse Univ. Press, 1964, pp. 133-178.

54. Coffin, L. F.: A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal. Trans. ASME, vol. 76, no. 6, Aug. 1954, pp. 931-950.

55. Forest, J. D.; and Christian, J. L.: Development and Application of Aluminum-Boron Composite Material. AIAA Paper No. 68-975, Oct. 1968.

56. Young, J. R.; and Carlson, R. G.: Advanced Composite Material Structural Hardware Development & Testing Program. AFML-TR-70-140-Vol. I, U.S. Air Force, July 1970. (Available from DDC as AD 872 264.)

57. Shimizu, H.; and Dolowy, J. F., Jr.: Fatigue Testing and Thermal-Mechanical Treatment Effects on Aluminum-Boron Composites. Composite Materials: Testing and Design, Spec. Tech. Publ. No. 460, Amer. Soc. Testing Mater., c.1969, pp. 192-202.

58. Kreider, K. G.: Mechanical Testing of Metal Matrix Composites. Composite Materials: Testing and Design, Spec. Tech. Publ. No. 460, Amer. Soc. Testing Mater., c.1969, pp. 203-214.

59. Toth, I. J.: Creep and Fatigue Behavior of Unidirectional and Cross-Plied Composites. Composite Materials: Testing and Design, Spec. Tech. Publ. No. 460, Amer. Soc. Testing Mater., c.1969, pp. 236-253.

60. Salkind, M.; and Patarini, V.: Fatigue of Boron Filament. Trans. Met. Soc. AIME, vol. 239, 1967, pp. 1268-1270.

61. Gates, R. G.; and Wood, W. A.: Evaluating Potential Fatigue Performance of Composites (Cu/W and Cu/Mo) From Microstructural Behavior. Metal Matrix Composites, Spec. Tech. Publ. No. 438, Amer. Soc. Testing Mater., c.1968, pp. 218-228.

62. Jarosch, E.; and Stepan, A.: Fatigue Properties and Test Procedures of Glass Reinforced Plastic Rotor Blades. J. Amer. Helicopter Soc., vol. 15, no. 1, Jan. 1970, pp. 33-41.

63. Stratton, Warren: The Potential of Advanced Composites for V/STOL Propellers. Proceedings of the V/STOL Technology and Planning Conference, U.S. Air Force, Sept. 23-25, 1969.

64. Manson, S. S.: Fatigue: A Complex Subject – Some Simple Approximations. Exp. Mech., vol. 5, no. 7, July 1965, pp. 193-226.

65. Salkind, M. J.; and George, F. D.: The Charpy Impact Behavior of Al_3Ni Whisker-Reinforced Aluminum. Trans. Met. Soc. AIME, vol. 242, 1968, pp. 1237-1247.

66. Cooper, G. A.; and Kelly, A.: Tensile Properties of Fibre-Reinforced Metals: Fracture Mechanics. J. Mech. Phys. Solids, vol. 15, no. 4, July 1967, pp. 279-297.

67. Tetelman, A. S.: Fracture Processes in Fiber Composite Materials. Composite Materials: Testing and Design, Spec. Tech. Publ. No. 460, Amer. Soc. Testing Mater., c.1969, pp. 473-502.

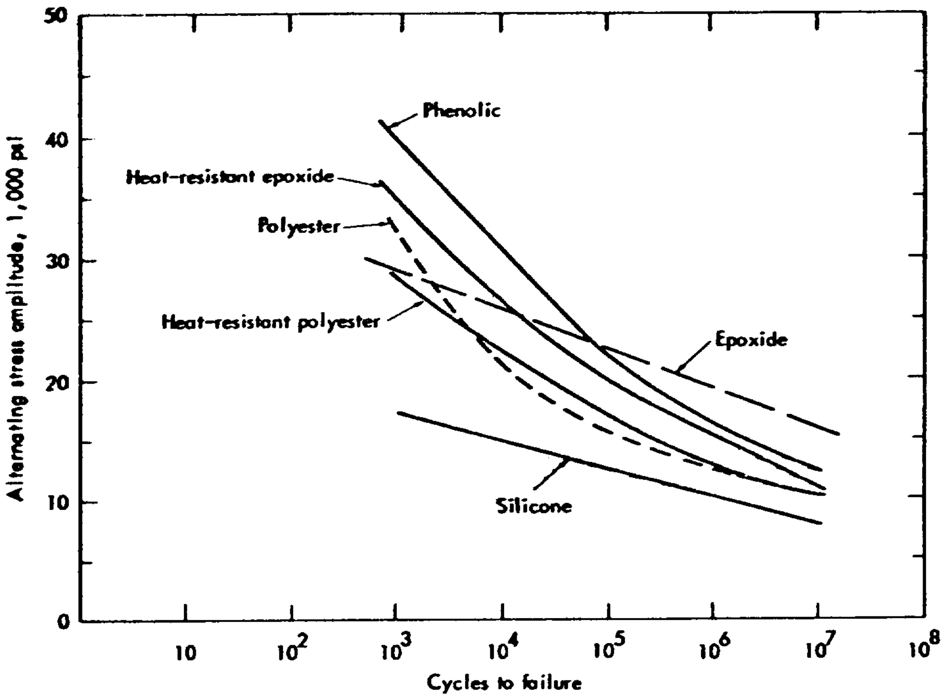


Figure 1.- Effect of matrix material on fatigue of glass fabric composites (from ref. 18).

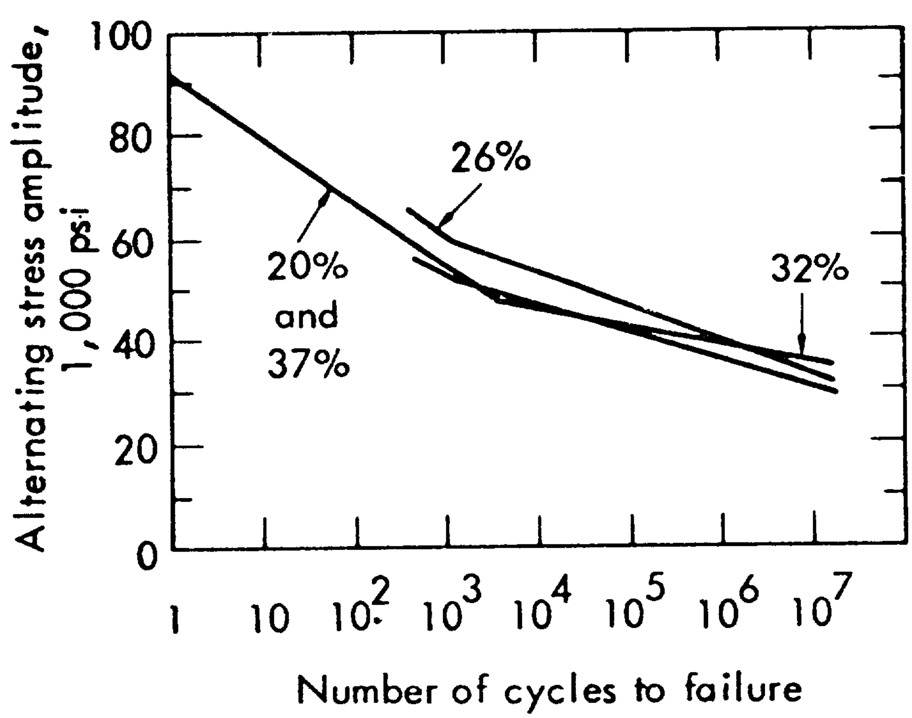


Figure 2.- Effect of matrix content on fatigue of $\pm 5^0$ glass-fiber-reinforced epoxy (from ref. 13).

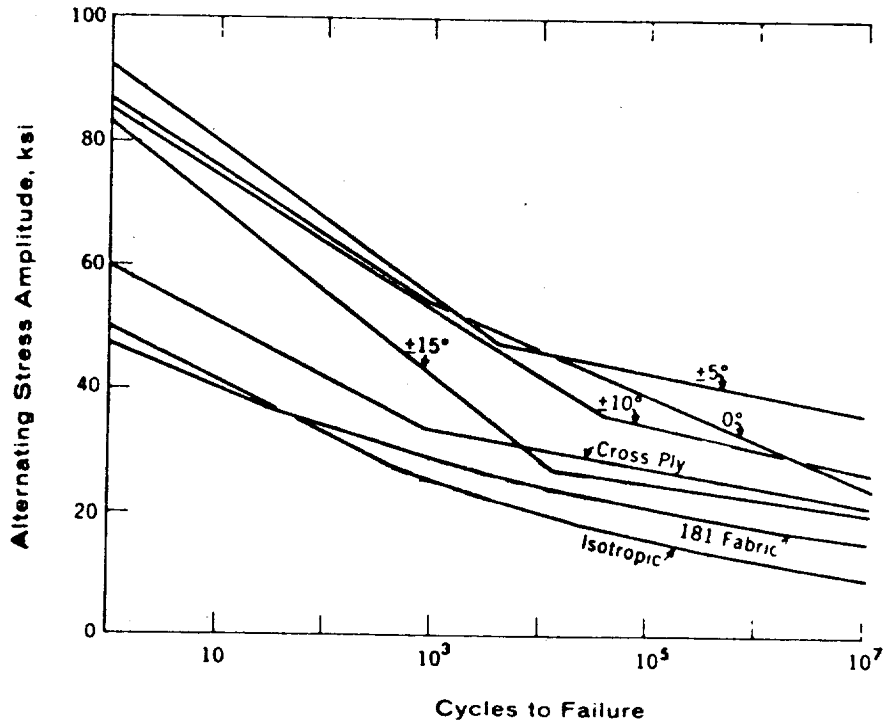


Figure 3.- Effect of fiber orientation (from ref. 18).

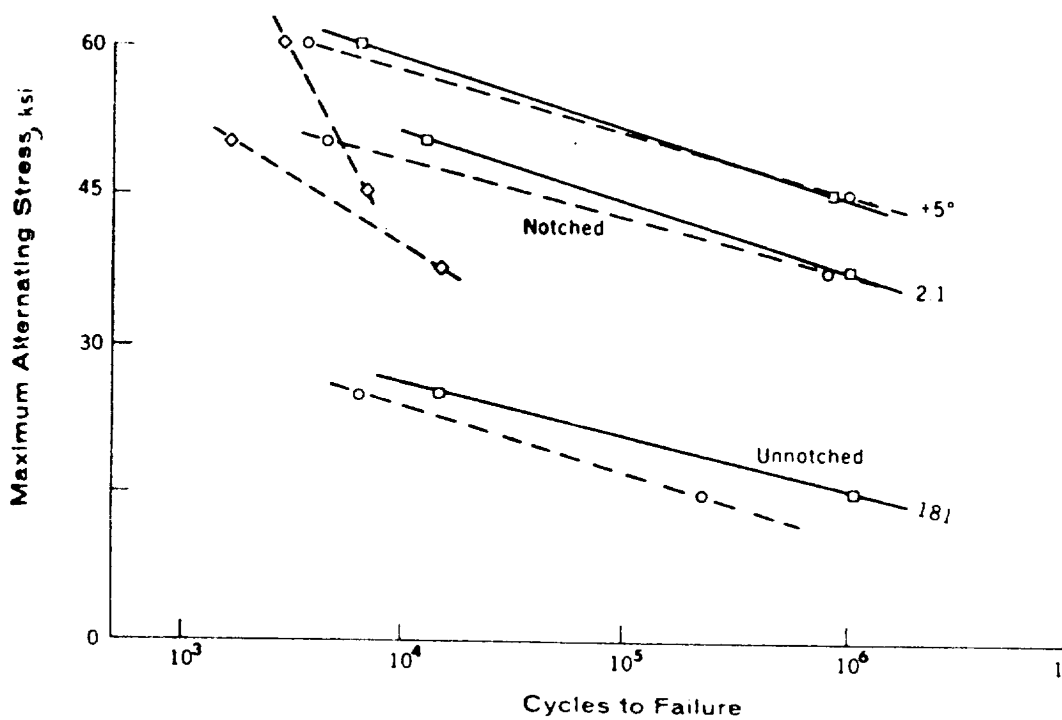


Figure 4.- Fatigue of woven and nonwoven materials (from ref. 18).

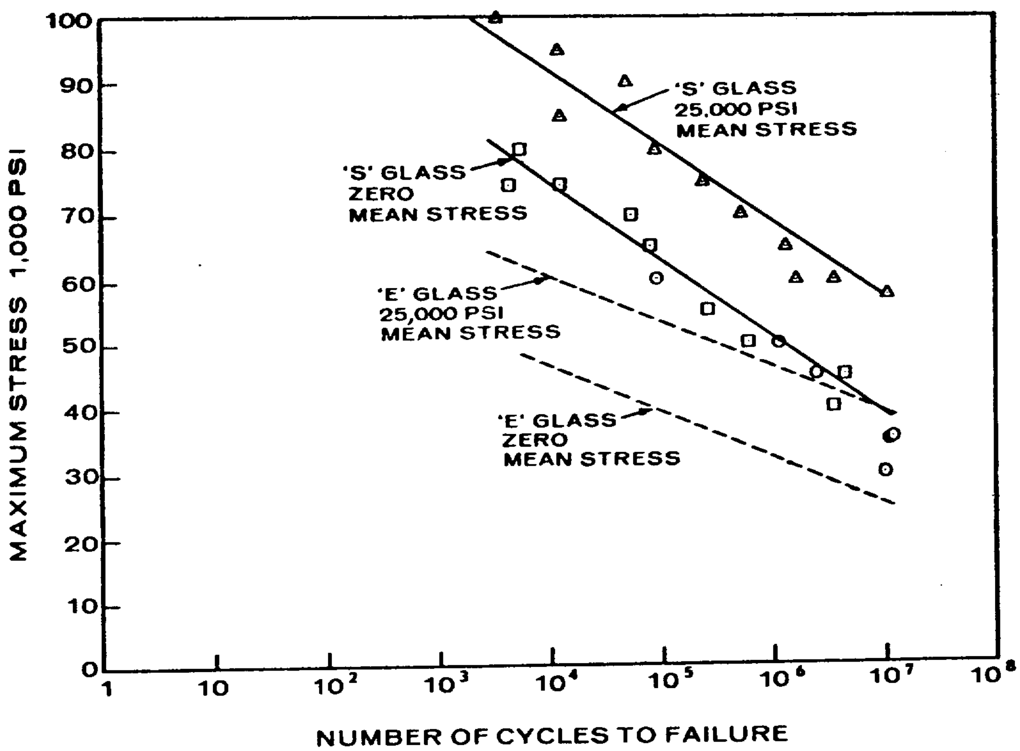


Figure 5.- Fatigue of E- and S-glass composites (from ref. 15).

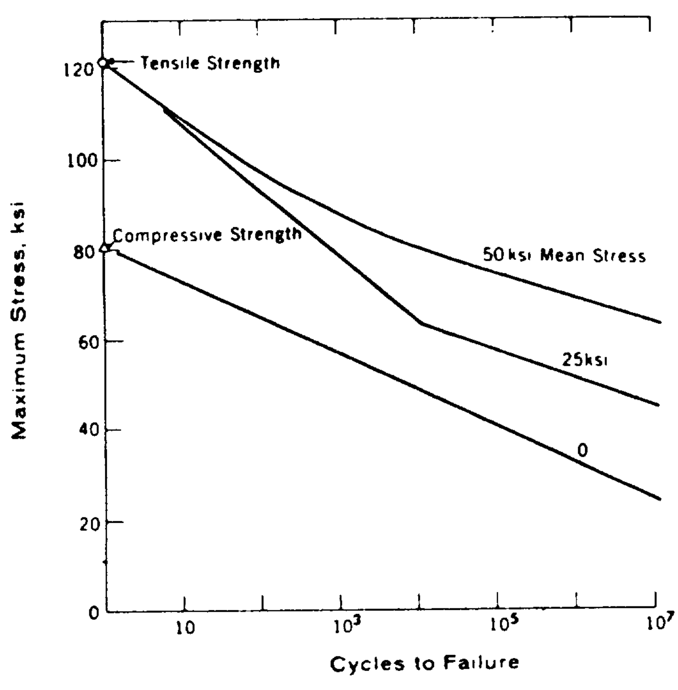


Figure 6.- Effect of mean stress level (from ref. 18).

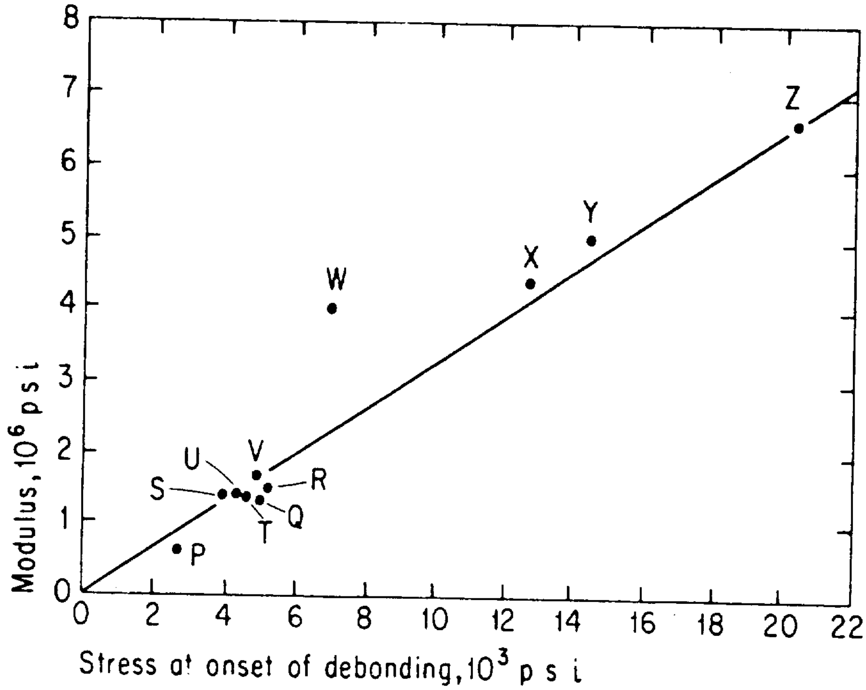


Figure 7.- Composite modulus as a function of stress at onset of debonding (from ref. 26).

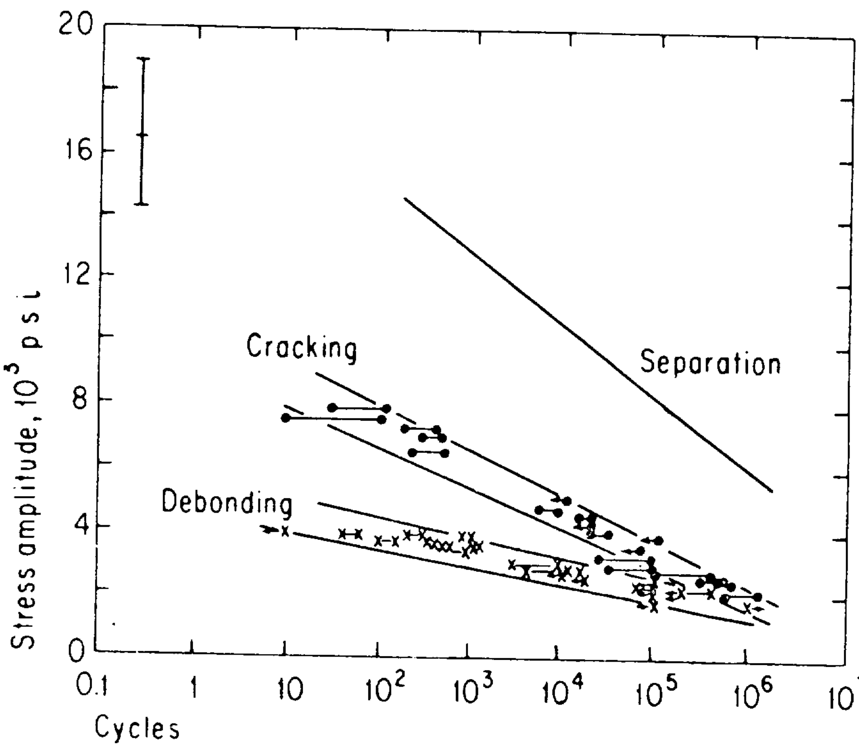


Figure 8.- Fatigue behavior of glass-mat-reinforced polyester (from ref. 26).

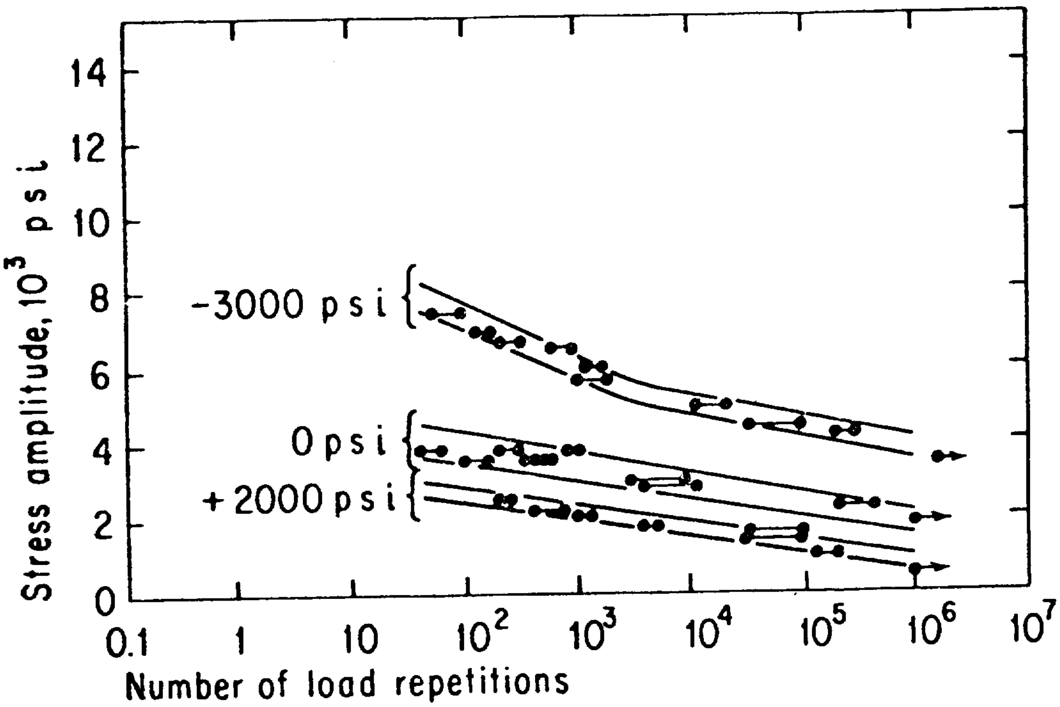


Figure 9.- Effect of mean stress on debonding of glass-mat-reinforced polyester (from ref. 26).

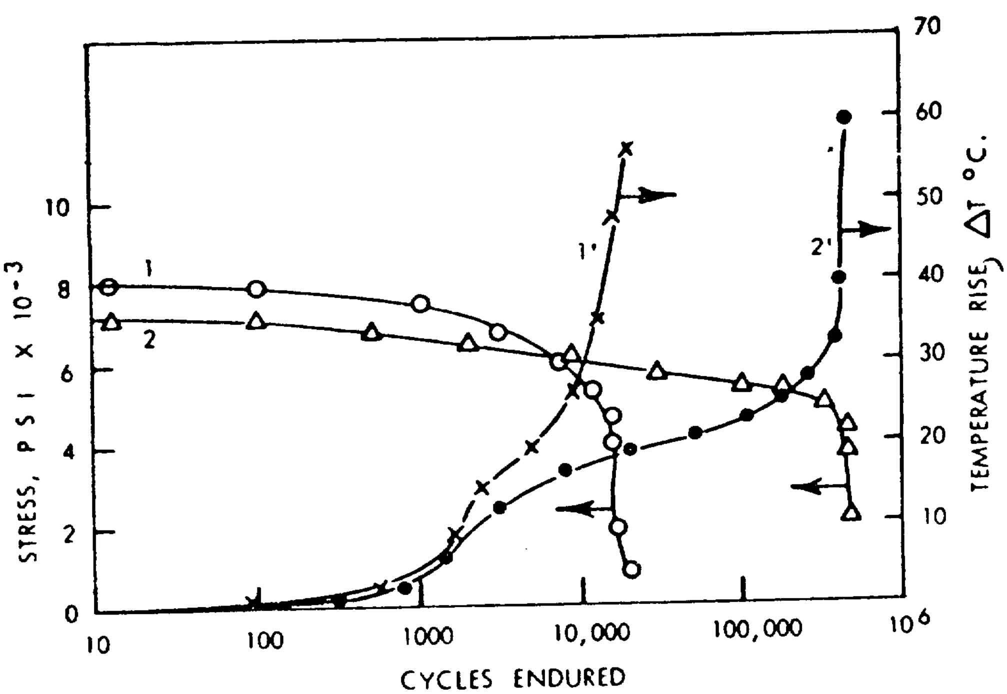


Figure 10.- Apparent stress and temperature rise in glass-reinforced polypropylene (from ref. 27).

C.7

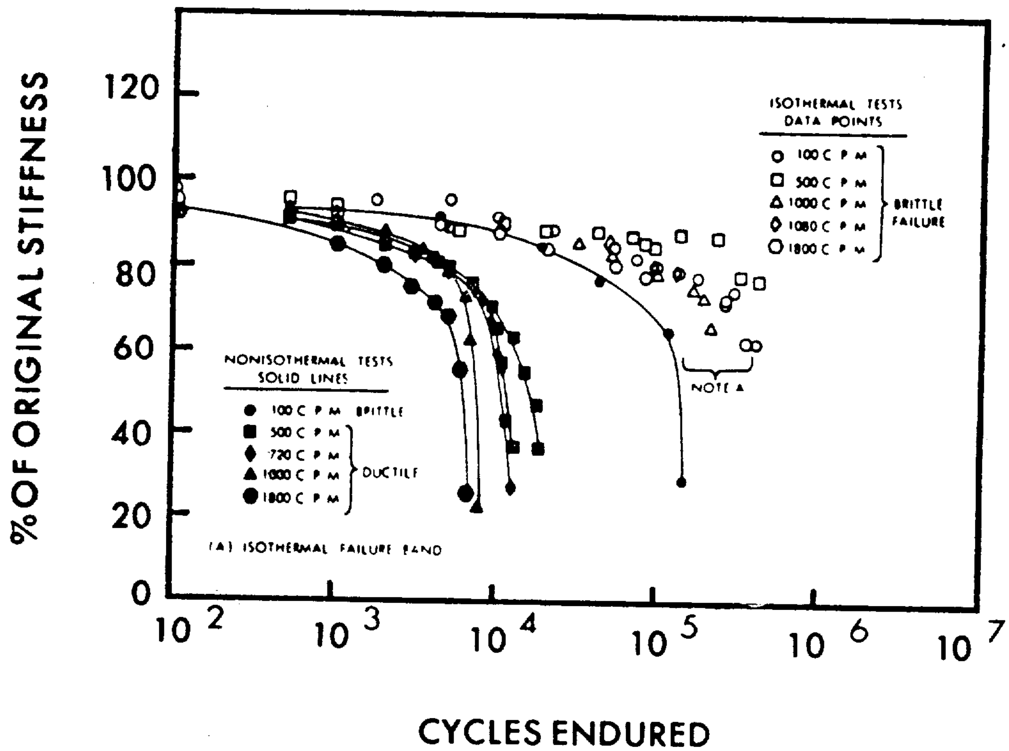


Figure 11.- Stiffness decay during fatigue of glass-reinforced polypropylene (from ref. 27).

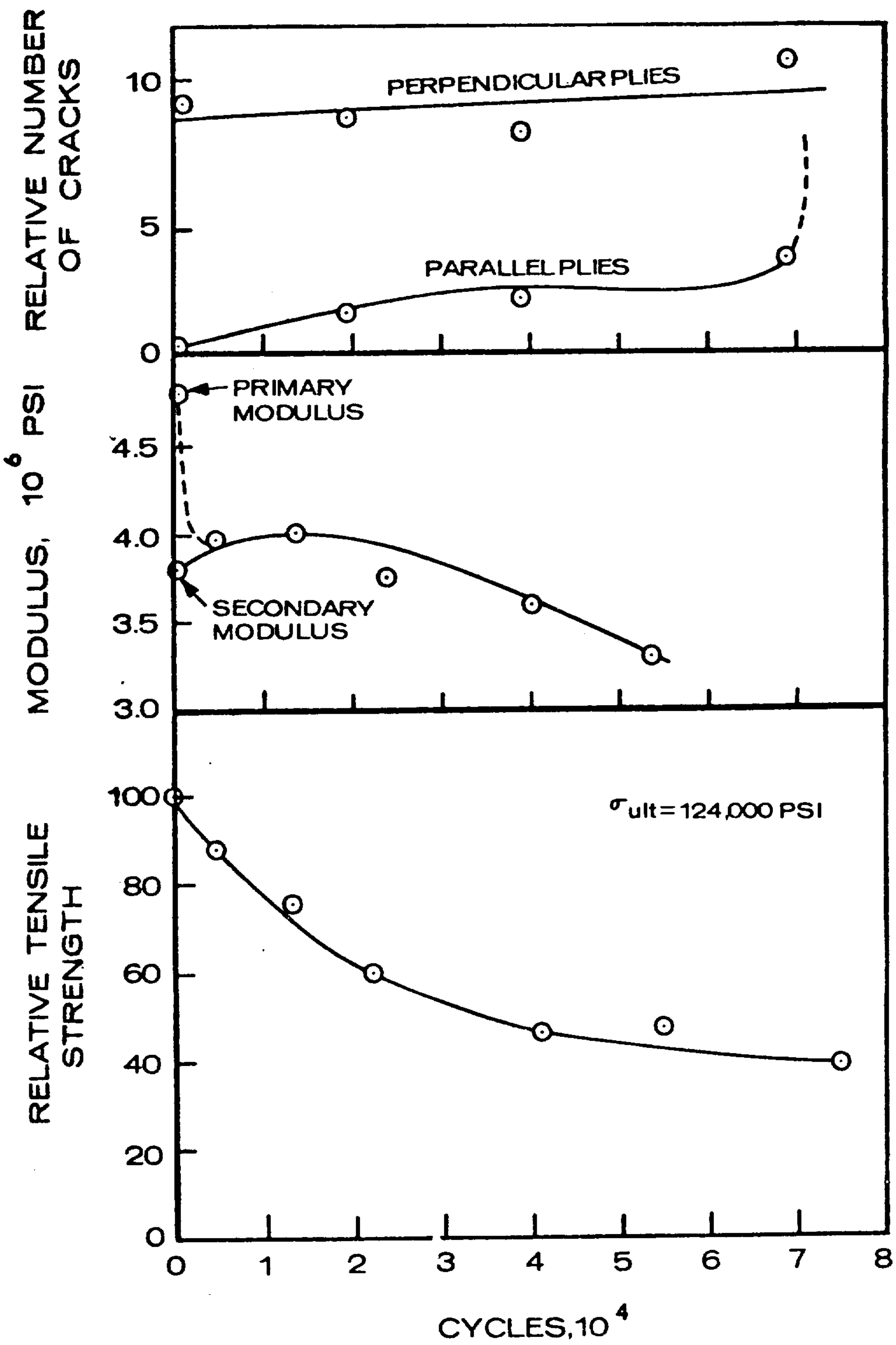


Figure 12.- Changes in strength, modulus, and cracking of $0^0/90^0$ glass-reinforced epoxy (from ref. 28).

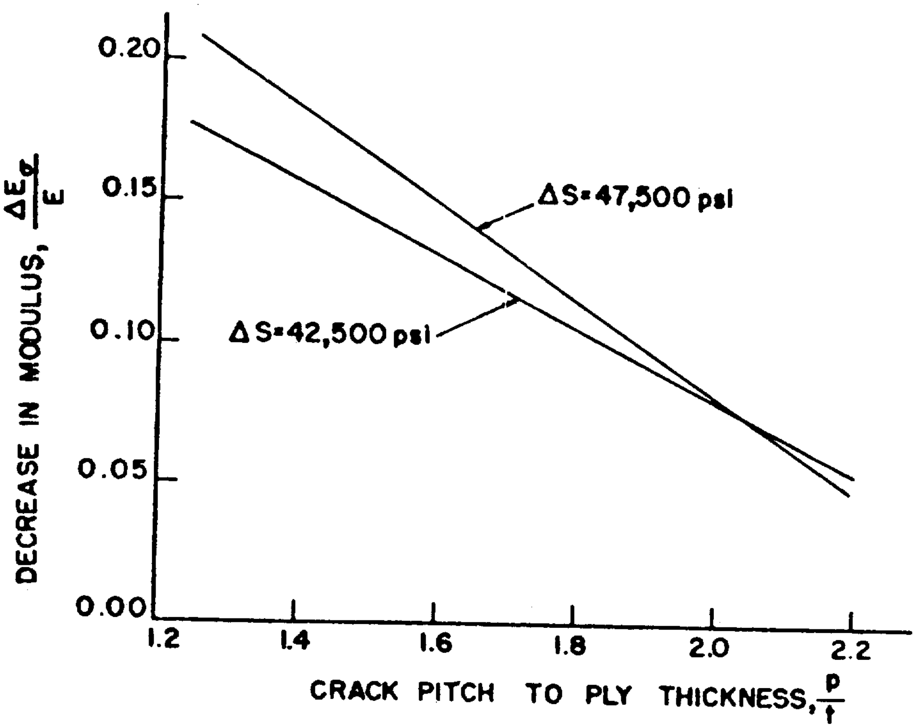


Figure 13.- Change in modulus with density of cracking for 0°/90° glass-reinforced epoxy.

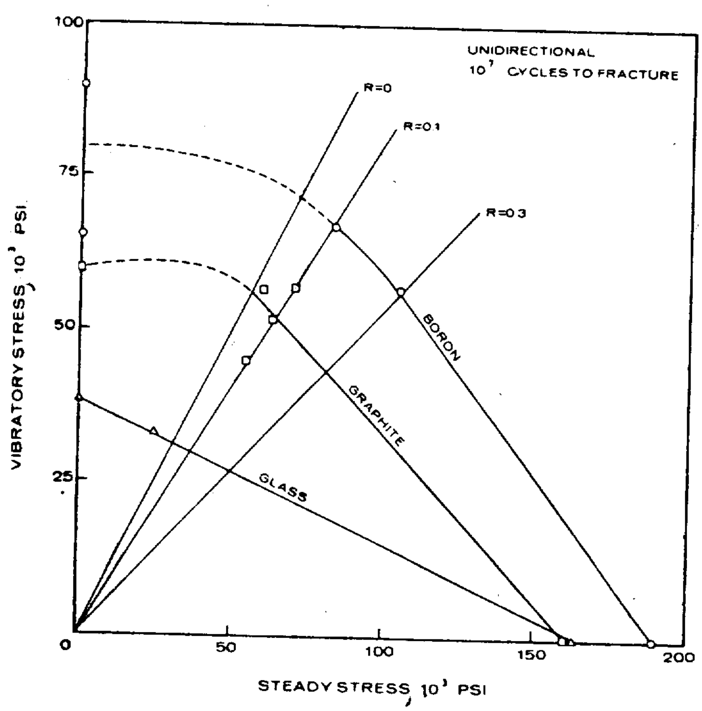


Figure 14.- Comparison of fatigue behavior of unidirectional boron, graphite, and glass-reinforced polymers.

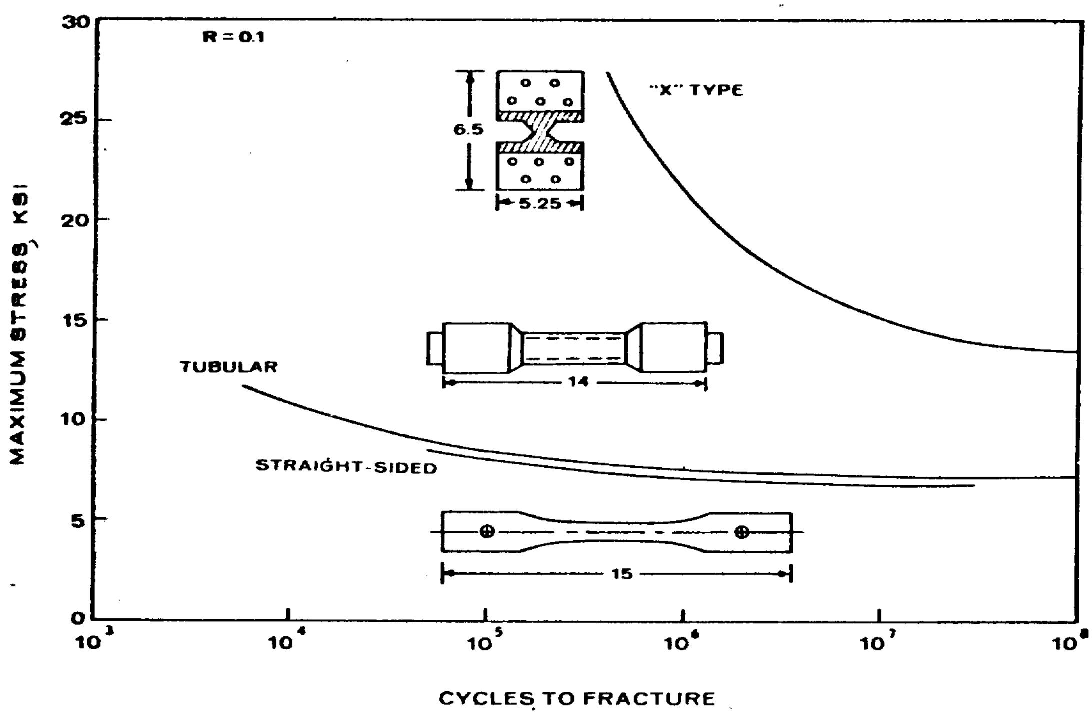


Figure 15.- Effect of specimen configuration on axial fatigue behavior of ±45° 1002 E-glass/epoxy.

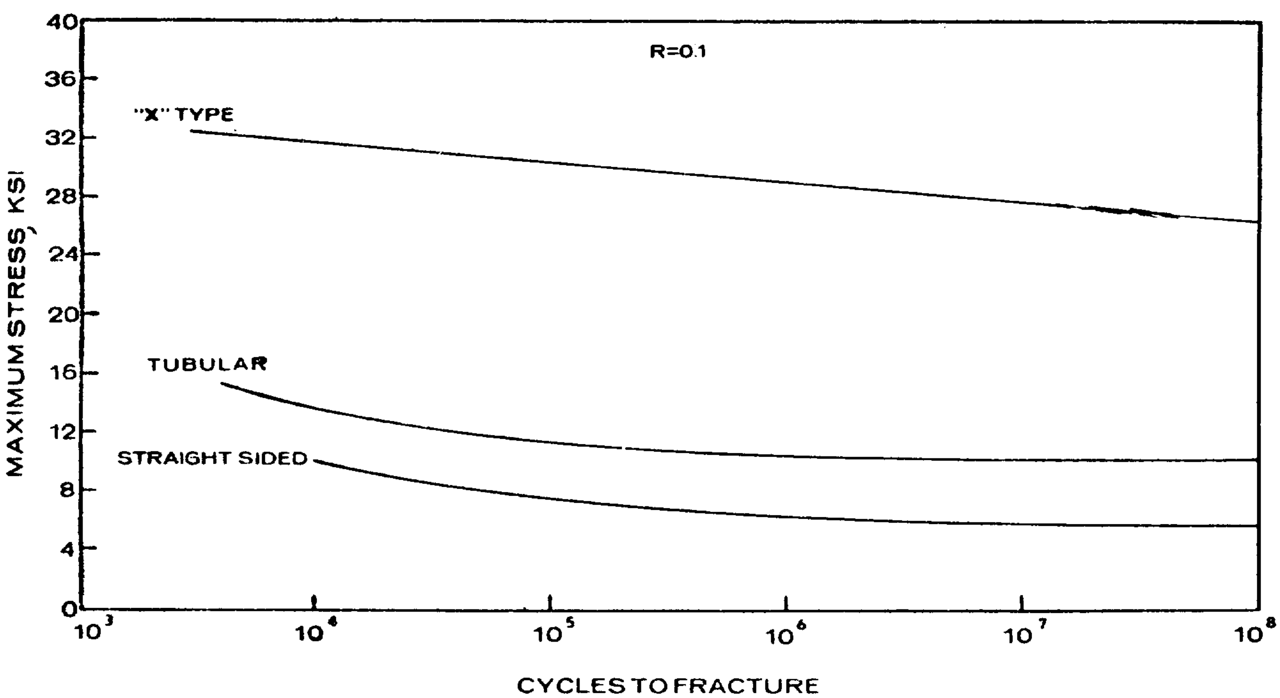


Figure 16.- Effect of specimen configuration on axial fatigue behavior of ±45° boron/epoxy.

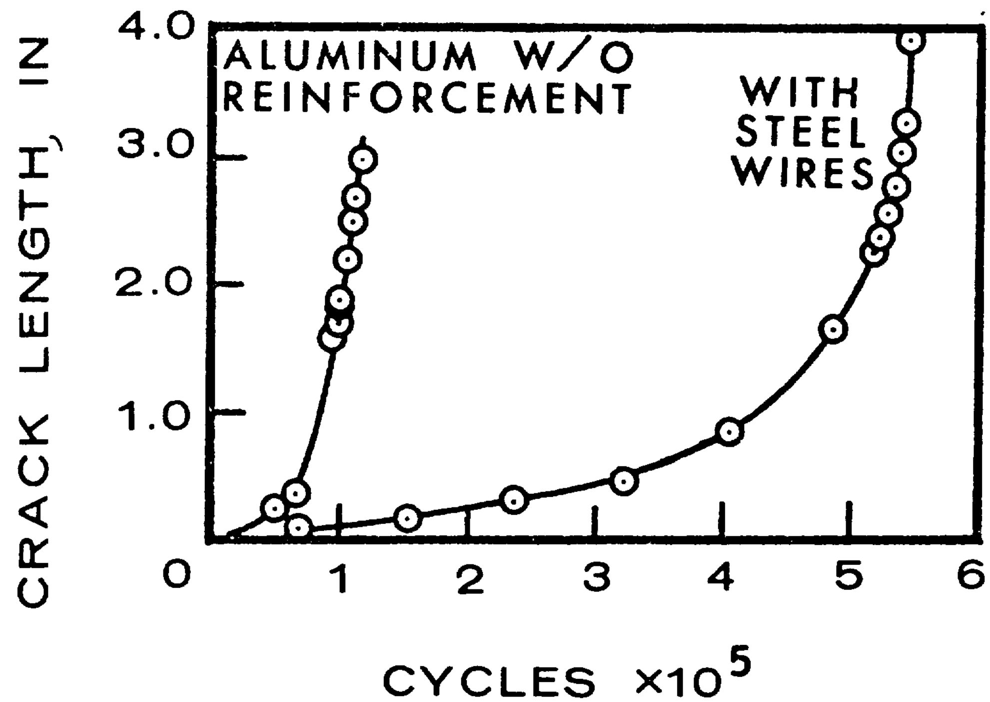


Figure 17.- Effect of steel wire mesh on the crack growth behavior of aluminum alloy sheet (from ref. 1).

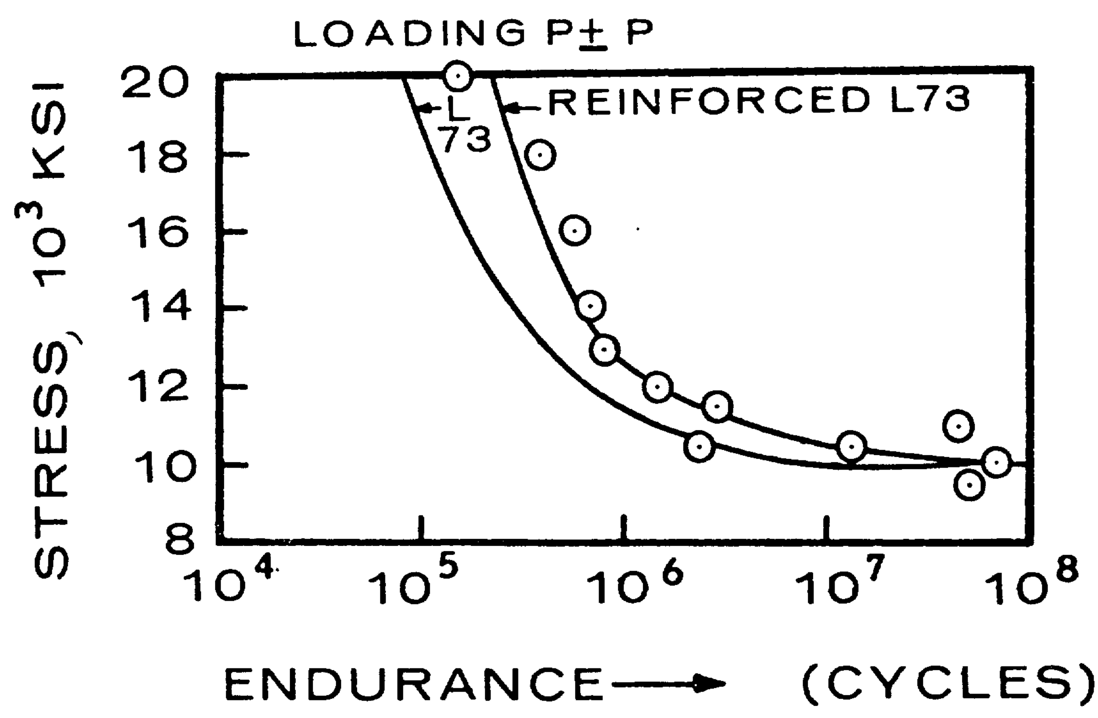


Figure 18.- Fatigue behavior of aluminum alloy with and without 13.5 volume percent steel wire (from ref. 1).

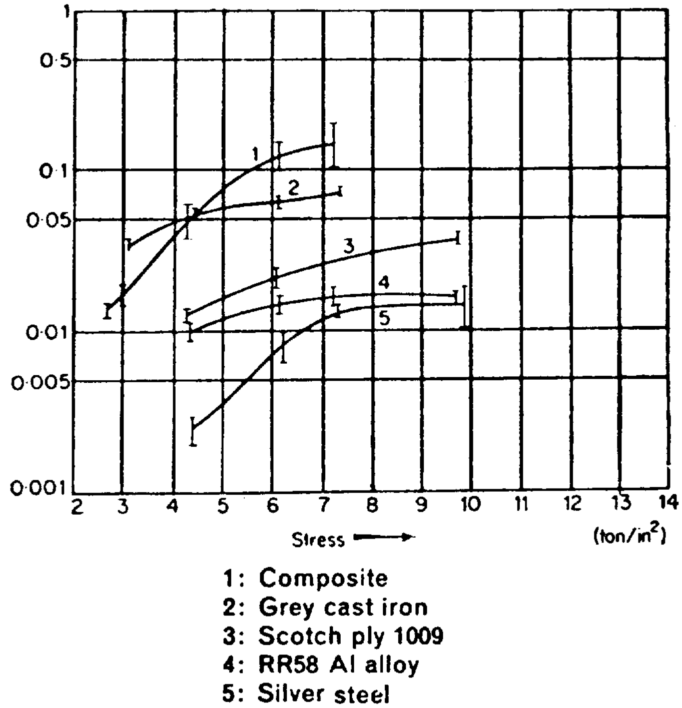


Figure 19.- Vibrational damping capacity (δ) as a function of stress for silica-reinforced aluminum compared with conventional engineering materials (from ref. 44).

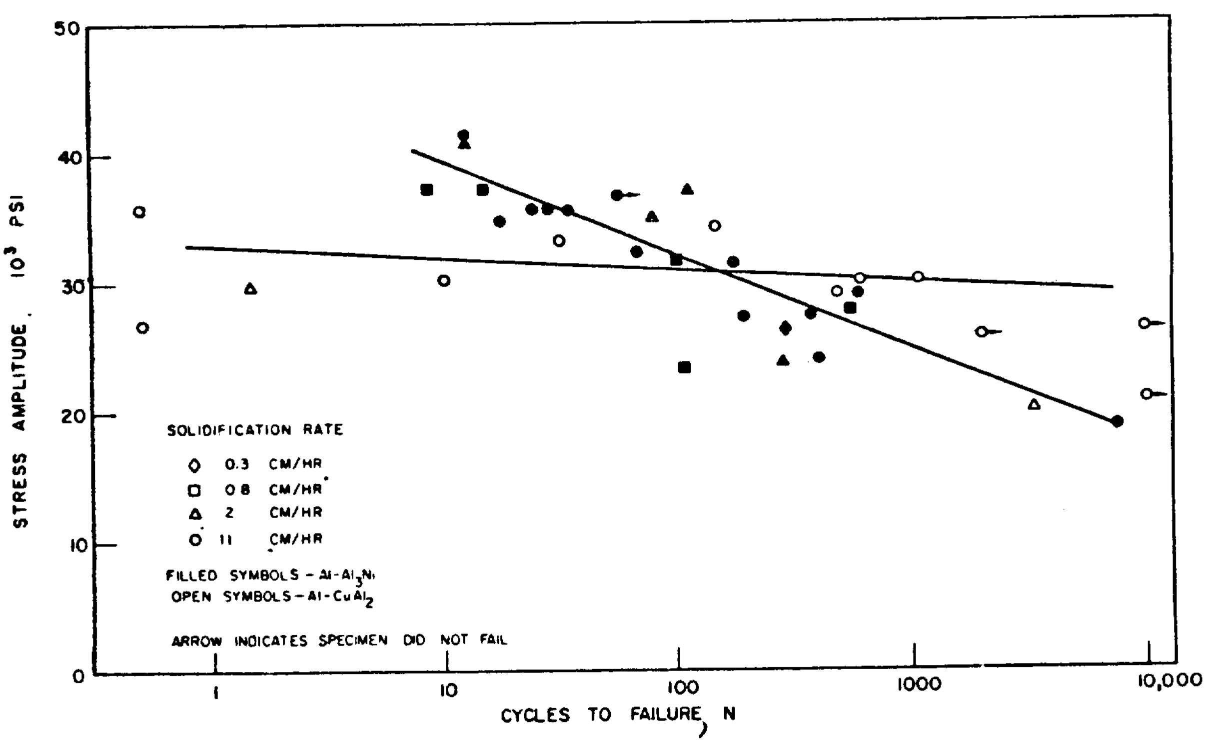


Figure 20.- Comparison of fatigue behavior of lamellar ($Al-CuAl_2$) and fiber ($Al-Al_3Ni$) composites (from ref. 49).

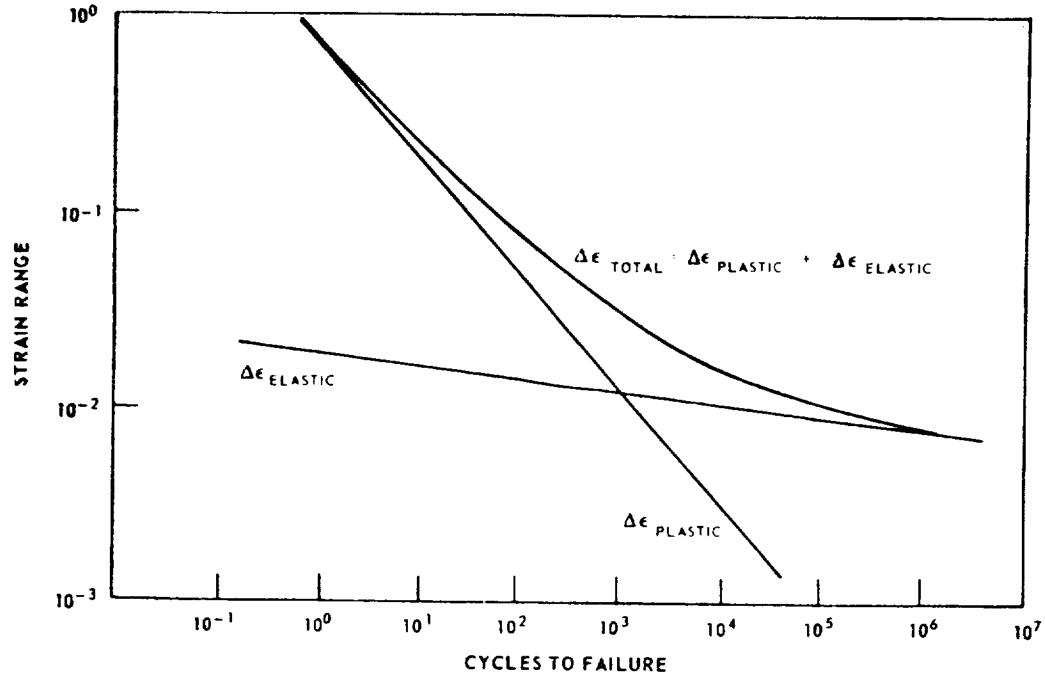


Figure 21.- Schematic behavior of metals in strain cycling (from ref. 57).

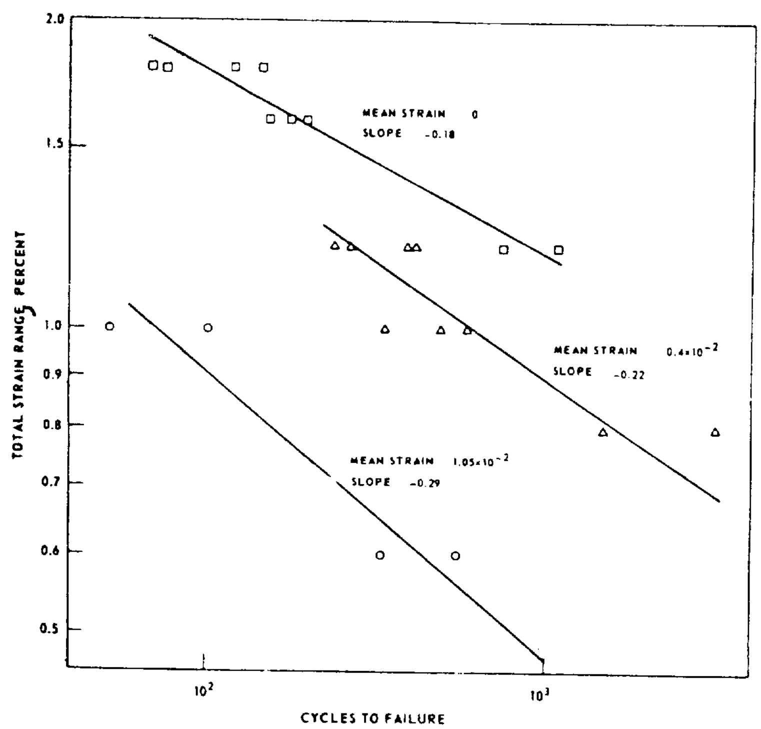


Figure 22.- Low-cycle axial fatigue of Al_3Ni whisker-reinforced aluminum (from ref. 4).

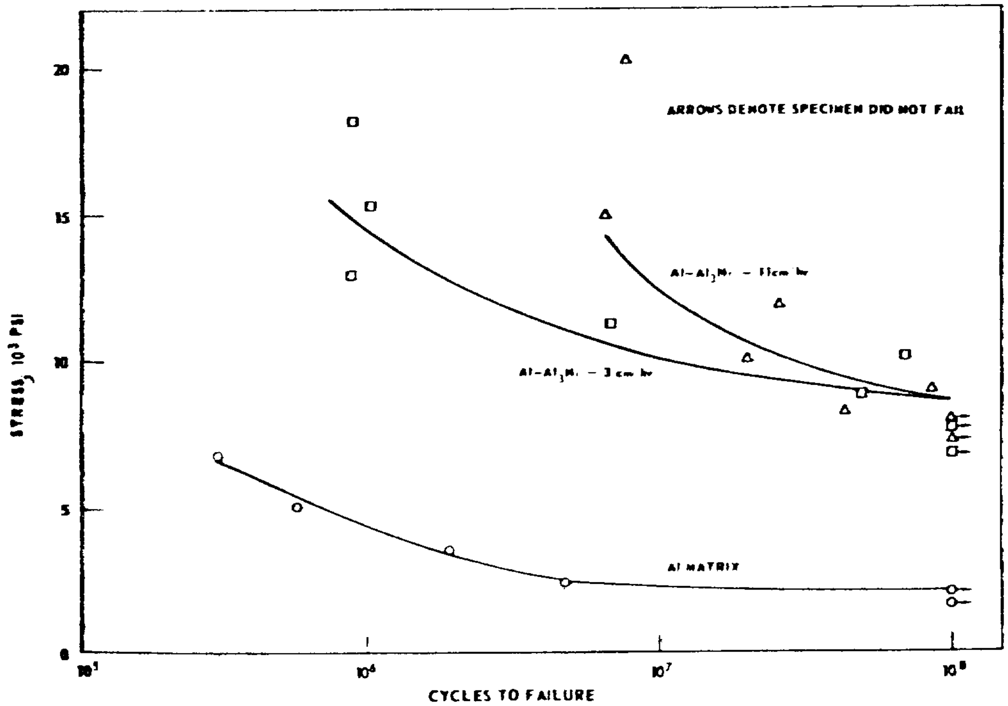


Figure 23.- Flexural fatigue behavior of Al-Al_3Ni in air (from ref. 4).

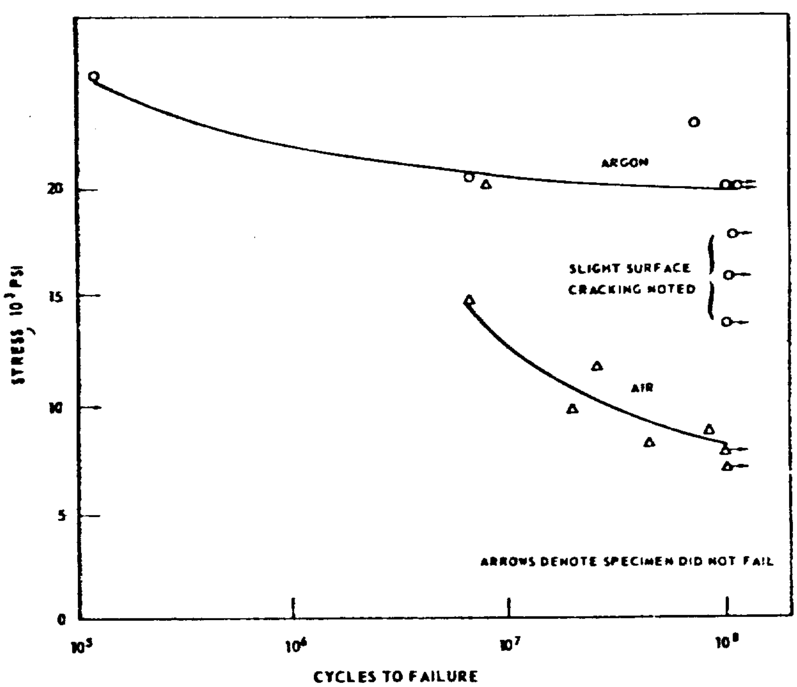


Figure 24.- Effect of environment on the flexural fatigue behavior of Al-Al_3Ni (from ref. 4).

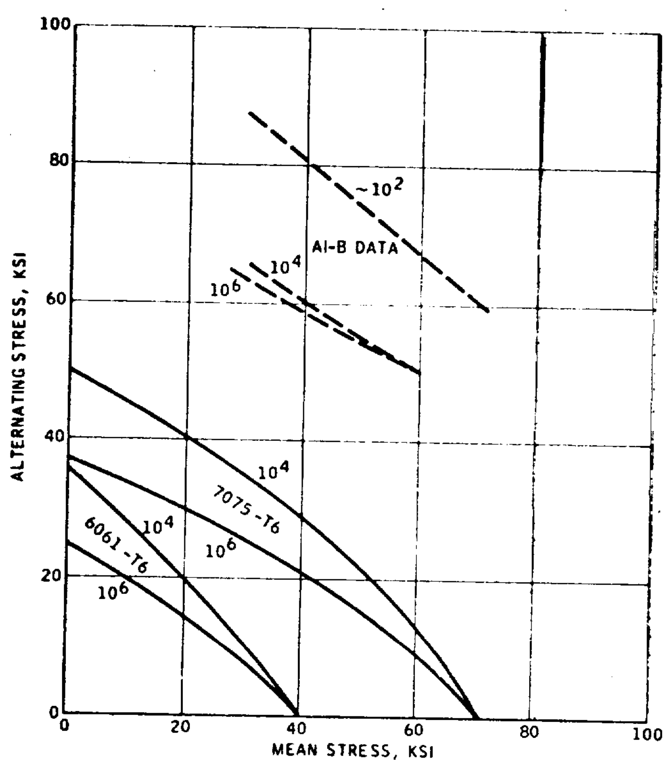


Figure 25.- Fatigue behavior of 40 volume percent boron-reinforced 6061 aluminum, compared with unreinforced aluminum alloys (from ref. 57).

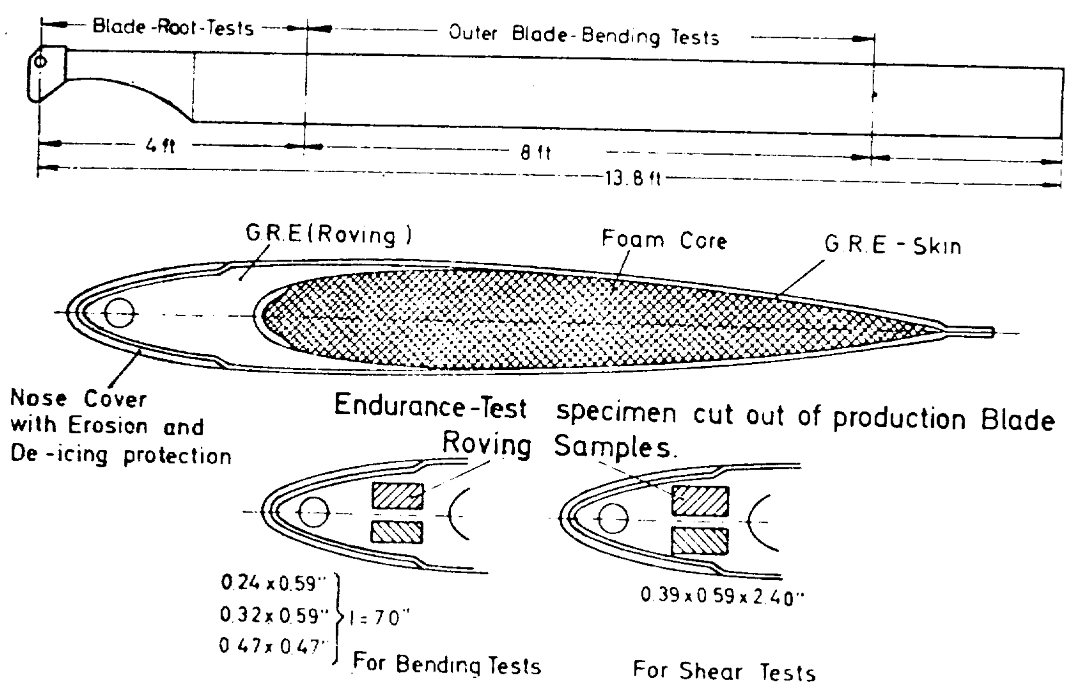
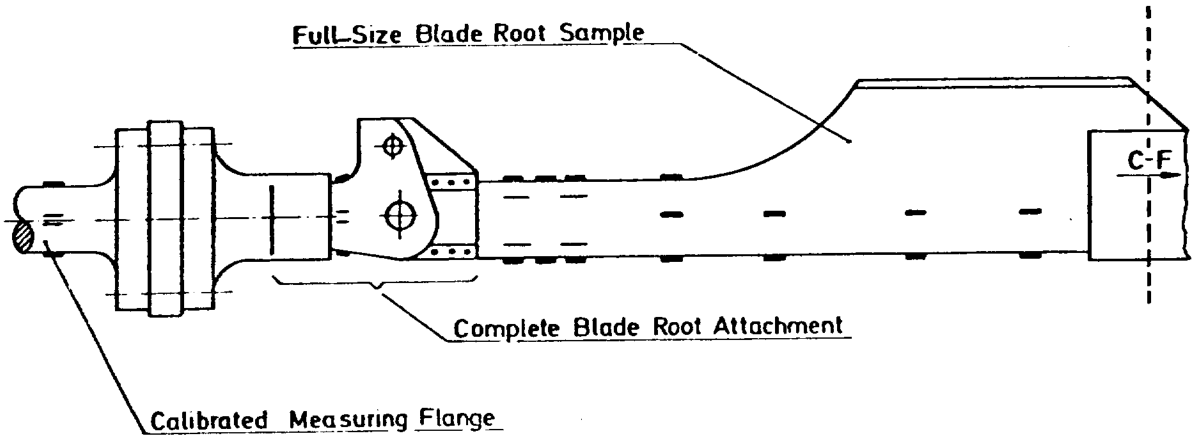


Figure 26.- Glass/epoxy BO-105 rotor blade (from ref. 62).



$M_{flap} = M_{lag} \cong 1900 \div 2600$ ft-lbs
Tension (C.F.) $\cong$ 12 t

Figure 27.- Root-end fatigue test specimen of BO-105 rotor blade (from ref. 62).

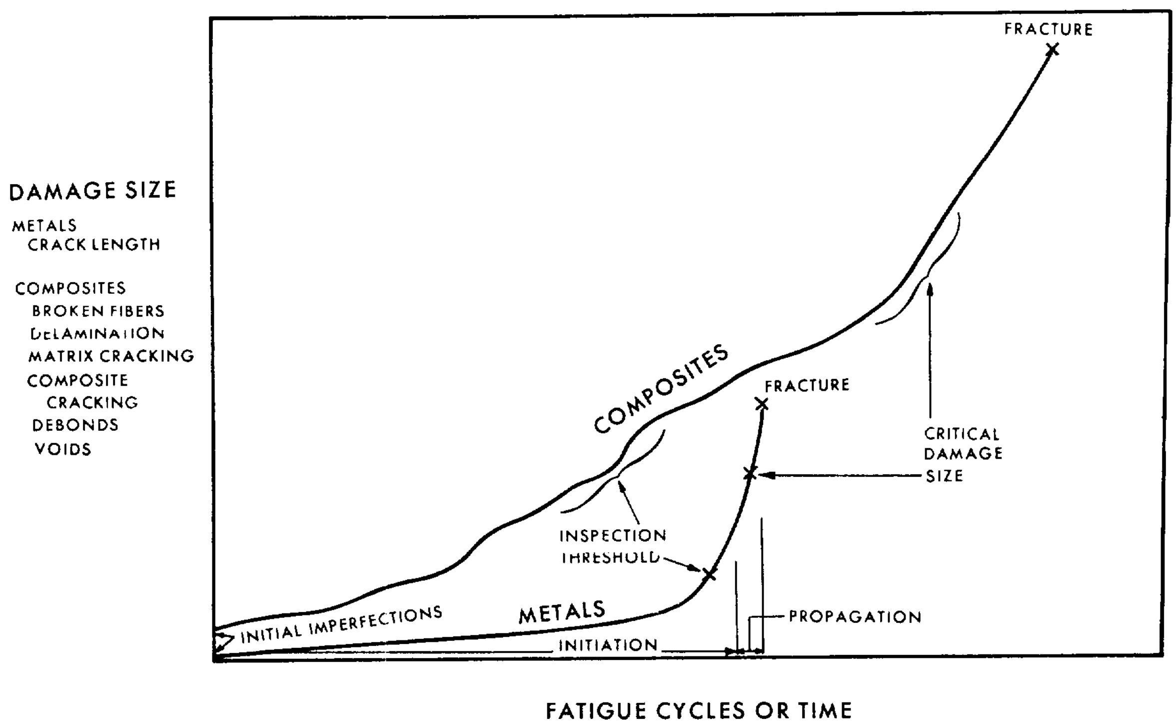


Figure 28.- Comparison of fatigue behavior in metals and composites.

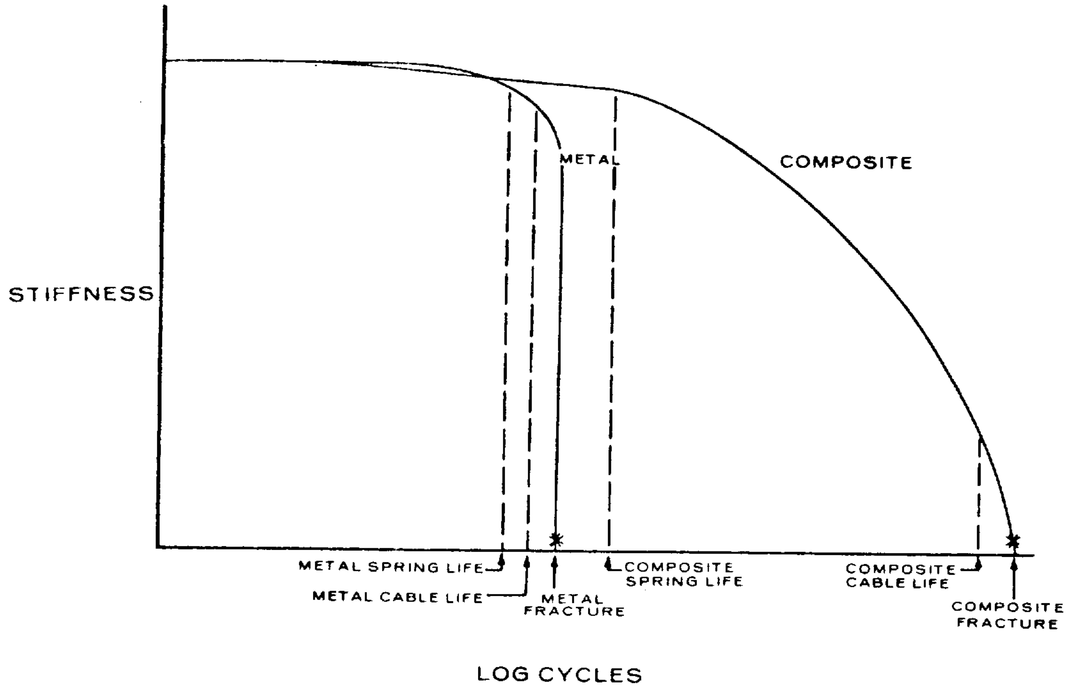


Figure 29.- Schematic fatigue behavior comparison of spring and tension cable made of metal or composite.

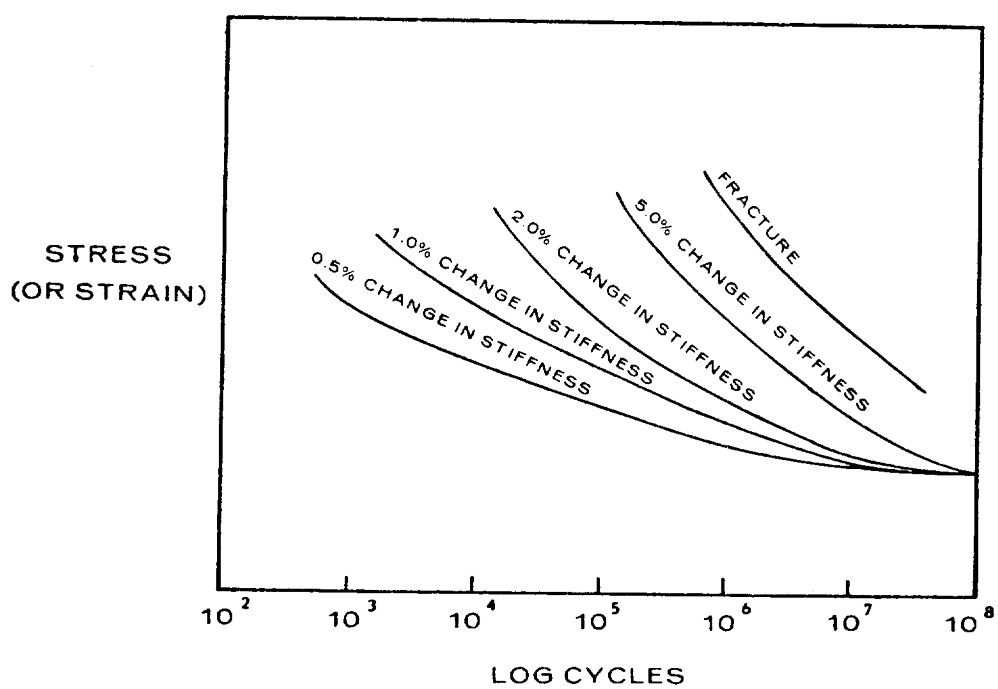


Figure 30.- Proposed method for reporting composite fatigue data.