AIAA JOURNAL
Vol. 31, No. 6, June 1993

Review of Crack Propagation Under Unsteady Loading

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Introduction

STRUCTURES subjected to high-amplitude unsteady pressure fluctuations may suffer from fatigue failure. Narrow-band and broadband random noise, as well as discrete frequency noise, are characterized by unsteady loads and are common sources of fatigue damage. Increasing evidence of this type of failure, commonly referred to as acoustic fatigue failure, has been encountered in high-speed aircraft, nuclear power plants, machine equipment, and buildings subjected to acoustic loads from ground and air traffic. The main source of research on the subject, however, has come from the aerospace industry in response to acoustic fatigue failures of aerospace structures.

Acoustic fatigue failure became a growing concern in the 1950s as increasing engine performance resulted in more intense acoustic pressures on aircraft structures. Decreasing weight requirements contributed to these failures since the thinner structures were less resistant to damage. As a result, numerous investigations of the failures associated with jet engine noise have been conducted.[1–3] Missiles have also suffered acoustic fatigue damage, particularly those launched from silos, where damage was caused by the acoustic energy confined within the silo before launch. The fatigue failure of a Titan II skin panel in an acoustic test simulated by Rader and McGregor[4] is shown in Fig. 1. This fatigue crack propagated along the lines of flexure of the buckled skin as a result of the severe loading. Other reported fatigue failures were induced by the unsteady pressures associated with boundary-layer turbulence,[1,5–10] sonic booms,[11–13] and noise generated close to propeller tips.[14,15] All of these failures demonstrated the need for research in the area of acoustic fatigue.

Since the original theories on fatigue failure could not adequately account for random loading conditions, modified theories that were capable of providing statistical methods of analysis were needed. The First International Conference on Acoustical Fatigue convened in 1959 and brought together scientists and engineers who were studying the acoustic fatigue phenomenon. Since then, numerous investigations of acoustic fatigue have been conducted, but still only a limited amount of research is available on the specific subject of crack propagation under acoustic loading.

This paper presents an overview of the theories and research currently available on crack propagation under unsteady loadings, especially those of acoustic origin. Although all efforts have been taken to provide a thorough review of the subject, inadvertent omissions of relevant material are unavoidable.

Impact of Acoustic Fatigue in the Aerospace Industry

Fatigue associated with fluctuating flows are all too common in high-performance, high-speed aircraft. The need for aeroacoustic loads research for high-speed vehicles can be seen in an excellent report prepared for NASA Langley Research Center by Zorumski.[8] According to Zorumski, exhaust nozzles designed to last 5000 h are failing in 50 h. Numerous incidents of structural fatigue are reported in aircraft such as the F-15, AV-8B, and the B-1 due to combined effects of high temperatures and intense plume loads. The vectored plumes of short take-off vertical landing (STOVL) operations and high-speed maneuvers will generate loads far greater than the parallel streams of the jets of the conventional aircraft of today.

It is anticipated that future high-performance aircraft, transatmospheric vehicles, and orbital vehicles will be considerably constrained by design for intense aeroacoustic loads combined with aerothermal loads.

Hypersonic vehicles are particularly prone to acoustic fatigue. Such acoustic fatigue occurs when fluctuating pressures produced by both the engines and the aerodynamic boundary layer produce vibrations of the external surface (skin) panels at their natural frequencies, thereby inducing stresses in the panels. This results in the

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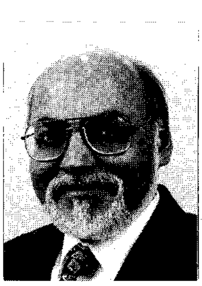

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Received June 21, 1991; revision received Feb. 9, 1992; presented at the DGLR/AIAA 14th Aeroacoustics Conference, Aachen, Germany, May 11–14, 1992; accepted for publication July 1, 1992.

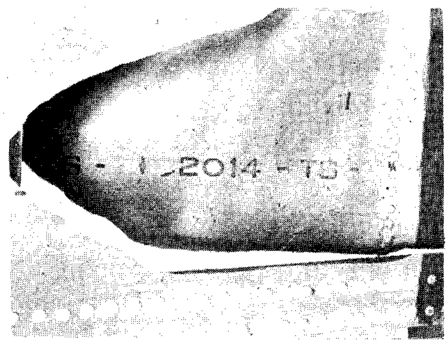

Fig. 1 Acoustic fatigue failure of a Titan II skin panel.[4]

fatigue of the panels, depending on the material characteristics and the severity of the acoustic environment.

Experience with development of the Shuttle showed that these loads are most intense during ascent where large dynamic heats occur at transonic and supersonic speeds. Future Space Transportation Systems are expected to have similar loads. Shock structures in transonic flow oscillate around an average surface position due to disturbances such as atmospheric turbulence.[8] These oscillations result in low-frequency random loads on the vehicle surface. Additionally, the turbulent boundary layer generates higher frequency random surface loads. Turbulence within the attached boundary layer is thus a major source of aeroacoustic loading. Aeroacoustic loads are particularly intense along lines where an attached shock interacts with the boundary layer. Often the pressure increase across the shock causes boundary-layer separation. Vorticity generated in these separation regions is a common loading source.

Transatmospheric vehicles are likely to be subjected to rather high temperatures. This will reduce material strength, fatigue resistance, and stiffness and develop internal strains due to thermal gradients and the restraint of material growth. These factors render a study of the role of acoustic fatigue for the structural integrity of transatmospheric vehicles particularly important.

High-performance aircraft also cause acoustic fatigue in structures located on the ground when they fly at supersonic speeds and create a sonic boom. Window breakage is the most commonly reported damage since brittle materials (e.g., glass, plaster, etc.) are extremely sensitive to the impulsive load generated by a sonic boom. The failure mode of brittle materials is abrupt (no yielding), and the damage can be assumed to occur when the peak stress response exceeds the material strength.

Two examples of window damage by sonic boom are now given.

1) Damage to Air Terminal Building,[11] Ottawa, Canada: This incident relates to the flight of an F-104 that made a clear pass over the runway followed by a slight left turn and pullout over a new five-story metal frame terminal building under construction near the end of the runway. The aircraft approach was at a 500-ft altitude. This supersonic flight broke all of the glass in the nearby temporary control tower. In addition, all 3/8-in. thick glass in the tower on the side of the old tower facing the approaching aircraft broke.

2) Window damage in Caliente, Nevada due to a nearby supersonic aircraft maneuver[12]: Substantial cracks developed in a number of windows in the city of Caliente, Nevada, on February 28, 1990. Two F-16 aircraft were flying at Mach 1.05, at 3300 ft above ground level. The original heading based on eyewitness accounts was roughly northwest. Before they passed to the south of Caliente, it appears that the pilots, in their attempt to turn away from the town, performed a maneuver to the right executing an 83-deg bank, with a total directional change of 140 deg. The initial part of the turn was toward Caliente. Calculations[12] indicate that this turn must have produced a focus of sonic boom along the damage line, thus producing a major breakage of windows in the city.

Much remains to be understood about the effect of sonic boom on cracks. The available data on window damage by sonic boom find window orientation to be critical and pre-existing stress to be more important in controlling crack development than panel strength. Thus prestressed windows will crack first.

A new issue for the aviation community concerns the advanced age of many aircraft that are currently in service. The 1988 Aloha Airlines accident, in which a section of the B-737's aircraft canopy was lost during flight, brought the "aging aircraft" issue to public attention. Multisite Damage (MSD) was detected along rows of rivet holes in the fuselage skin. This incident found MSD to be a key issue in the structural integrity of aging airplanes.

The Federal Aviation Administration held a symposium in 1990 in response to the growing concerns about aging aircraft.[16] Scientists and engineers from across the world addressed the problems related to the structural integrity of aging airplanes, including MSD. Their research focused on the life enhancement and safety assurance of these airplanes.

Basic Principles

Material strengths may be significantly reduced by the presence of cracks. A fundamental understanding of crack formation and growth is therefore needed to assess material strengths as accurately as possible. A physical description of a crack is best understood on a molecular scale (see Fig. 2).[17] A continuous chain of atoms in tension should carry its full theoretical stress, as shown in Fig. 2a. Several chains, arranged side by side to represent a crystal (Fig. 2b), should also achieve their individual theoretical strengths under tension. A crack is represented by cutting several adjacent bonds in the crystal, shown in Fig. 2c. By breaking the chains, the flow of stress is interrupted, and the load is transferred around the end of the opening (Fig. 2d). The single bond located at the tip of the crack is therefore weakened considerably. Once this weak bond is broken, the next bond at the crack tip must bear the original load as well as the load in the newly broken chain. The crack will continue to grow in this manner until total fracture occurs.

When considering the model of a fatigue crack, it is necessary to distinguish between the opening, tearing, and edge-sliding modes of failure. Although cracking occurs in mixed modes in actual practice, this discussion is limited to the opening mode of failure.

Fatigue Crack Initiation

Fatigue is the fracture of a material under repeated stresses. Under any loading condition two types of cracks exist: ductile cracks and brittle cracks. If a material yields (suffers plastic deformation) before cracking, the crack is considered a ductile crack. In contrast, if a material cracks without prior plastic deformation, the crack is considered a brittle crack. Materials are capable of either type of cracking; however, the makeup of most materials renders

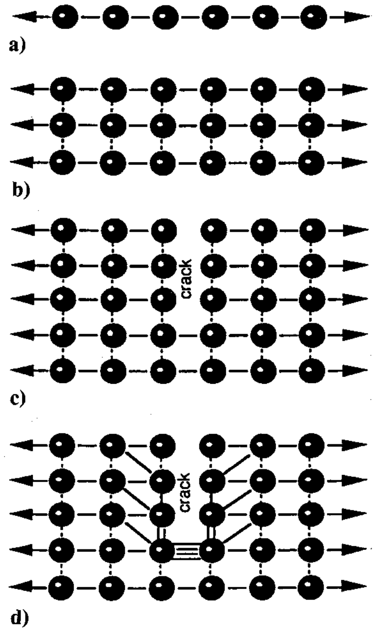

Fig. 2 Initiation of a stress concentration at a crack tip.[17]

them more susceptible to one type than the other. For example, glass, pottery, cement, bricks, ceramics, and some plastics generally crack in a brittle manner. Metals and metal alloys are alternately considered ductile materials, since they typically suffer plastic deformation before and during crack formation. Gordon[17] provides an extensive review of both types of cracks.

Cracking in brittle materials, such as glass, has been found almost always to be initiated on the surface of the material. When glass comes into even the lightest contact with any other solid, elaborate crack patterns are created. Cracks may also be initiated when glass hardens from a molten state, during the cooling process. As glass is cooled, the viscosity of the molecules prevents them from sorting into crystals before the cooling process is complete. There is a tendency, however, for these materials to crystallize, involving shrinkages capable of initiating external cracks that can spread to the interior of the material.

Many ductile materials, such as metals and metal alloys, are composed of randomly oriented and shaped crystalline grains. Under cyclic or random loading, "slip bands" consisting of localized plastic deformations can form within crystals or along grain boundaries. These bands, formed at an angle approximately 45 deg from the loading direction, are most commonly initiated at free surfaces. They are also found internally, however, where material imperfections such as inclusions or other stress concentration sites exist. The slip bands may gradually widen into "striations." Ryder[18] and Forsyth[19] determined that striations are alternate bands of dark plastic and silver brittle fracture and that each cycle of stress produces a pair of these ductile and brittle bands. The striation pattern of an aluminum alloy subjected to a random tensile load is shown (under two different magnifications) in Fig 3.[6] The cleavage lines and river markings are unevenly spaced, and this irregularity is attributed to the nature of the random load. Load reversals cause the striations to multiply, producing large numbers of dislocations. After the material undergoes a sufficient number of load reversals, the dislocations nucleate, and microscopic cracks may be formed. Several detailed studies have been conducted on the initiation and growth of microscopic cracks.[20–25]

Fatigue Crack Propagation

Microscopic cracks may continue to propagate until they are large enough to be considered macroscopic cracks. The crack growth is a process consisting of the transition of the crack from one subequilibrium state to the next. When the crack is in a subequilibrium state, microdamage accumulates at the arrested crack tip. The crack will grow after its transition into a nonequilibrium state, which occurs at maximum loading levels. It is assumed that the stresses at the crack tip are bounded, and damage is the result of the stress state and the environmental prehistory in the crack tip vicinity.[26]

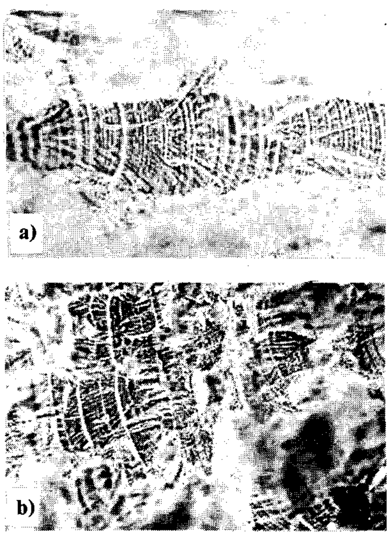

Fig. 3 Microscopic details of the striation patterns on the fracture surface: a) ×870, and (b) ×1200.[6]

Table 1 Various equations for predicting crack propagation rates

Eq. (1) Paris-Erdogan equation[31]

$$\frac{da}{dN} = c(\Delta K)^n$$

Eq. (2) Walker equation[37]

$$\frac{da}{dN} = c[(1-R)^m K_{max}]^n$$

Eq. (3) Forman equation[38]

$$\frac{da}{dN} = \frac{c(\Delta K)^n}{(1-R)K_{IC} - \Delta K}$$

Eq. (4) Two modified Forman equations

a) Ref. 38

$$\frac{da}{dN} = \frac{c\Delta K^p (1-R)^m (\Delta K - \Delta K_{th})^n}{[(1-R)K_{IC} - \Delta K]^q}$$

b) Ref. 45

$$\frac{da}{dN} = cK_{rms}^n \left[\frac{K_{mean} + K_{rms}}{K_{IC} - (K_{mean} + K_{rms})}\right]$$

where

a = crack length
c, n, m, p, q = material constants (available in Ref. 163)
K_{IC} = fracture toughness
K_{mean} = $K_{max} - K_{rms}$
K_{rms} = stress intensity factor range, rms value
N = number of cycles
R = stress ratio, K_{min}/K_{max}
ΔK = stress intensity factor range
ΔK_{th} = threshold stress intensity factor

Crack propagation is a stochastic process depending largely on the chance orientation and distribution of weak and strong crystals or the molecular arrangement of noncrystalline materials. Propagation paths and rates are, therefore, difficult to determine analytically, and many theories have been proposed to predict such variables.

Griffith's Theory

Griffith[27] studied the stability of cracks in glass extensively. In 1920, he proposed a crack propagation theory based on an energy concept. According to his theory, a crack is in equilibrium when its strain and surface energies are in balance. When a crack grows, it releases a greater amount of energy as strain energy than it consumes as surface energy. At a critical crack length (there is a characteristic critical crack length for each material stress), the onset of rapid fracturing or crack instability occurs. Once failure has begun, the brittle fracture may appear to occur instantaneously, with propagation rates up to several thousand miles an hour.

Irwin[28,29] later extended Griffith's theory to account for the brittle fracture of ductile materials. His modifications incorporated the energy dissipation associated with plastic deformation. The Griffith theory (also referred to as the Griffith-Irwin theory) is widely accepted and serves as a foundation for many other crack propagation theories.

Crack Propagation Rates

There are many methods of approaching the problem of crack propagation under unsteady loading. According to the classical "stress intensity factor" approach, the elastic stress field near the crack tip is governed by the stress intensity factor K given by

$$K = \sigma f(2a)$$

where σ is the applied stress and $f(2a)$ is a function of the crack length. Research conducted by Paris[30] and Paris and Erdogan[31] has

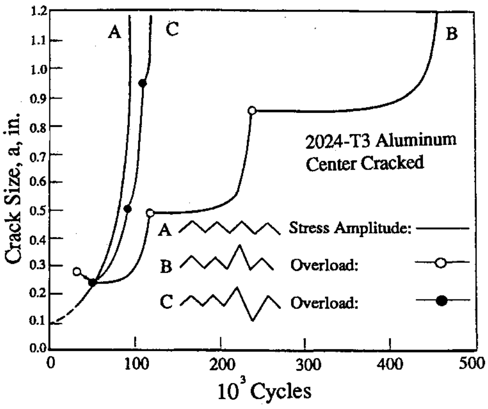

Fig. 4 Crack growth retardation effects in an aluminum plate subject to various overloads.[52]

shown that the rate of crack extension caused by constant amplitude cyclic loading is dependent on the magnitudes of crack tip stress intensities. They found the crack extension rate to be otherwise independent of the method of loading, crack length, and geometry of the specimen.

The Paris-Erdogan equation, given by Eq. (1) in Table 1, predicts the rate of fatigue crack growth for constant amplitude loading and through-the-thickness cracks. The change in crack length per loading cycle, da/dN, is proportionate to some power n (an experimentally determined constant) of the stress intensity range $\Delta K = K_{max} - K_{min}$, where K_{max} and K_{min} correspond to the maximum and minimum cyclic loads. (All symbols are defined in Table 1.)

Even under constant amplitude loadings, fatigue crack growth rates are variable due to the inhomogeneous nature of materials. Several studies[32–36] have attempted to account for material variability by randomizing the material parameters in the Paris law with statistical distributions. Other modifications of the Paris law have also attempted to achieve improved predictions of crack growth rates. The Walker equation[37] accounts for the effect of the mean stress ratio, $R = K_{min}/K_{max}$, which was found to contribute to crack growth as shown in Eq. (2) of Table 1. Another crack growth rate equation, proposed by Forman et al.,[38] is given by Eq. (3) in Table 1. The Forman equation includes the mean stress ratio R, as well as the critical stress intensity factor K_{IC} at which fracture occurs. This factor is a measure of a material's ability to withstand fracture, and it is also known as the fracture toughness of a material. By incorporating this factor into his equation, Forman obtained improved crack propagation data.

The stress intensity factor approach is based on a linear elastic analysis of the stress field in the vicinity of the crack tip. Since plastic deformation occurs at the crack tip, this analysis is valid only if the plastic zone is small compared with the other geometric dimensions of the crack. A review of elastic-plastic, nonlinear analyses of crack growth is given by Miyamoto et al.[39]

After successfully treating crack extension under constant amplitude loading, Paris[30] proposed a similar method for treating crack extension under a stationary, Gaussian random loading. This method involves the stress intensity factor power spectral density function given by

$$K(f) = S(f)F(2a)$$

where $S(f)$ is the stress power spectral density function and $F(2a)$ is a function of the crack length. The power spectral density function can then be substituted for the stress intensity factor K in the Paris equation for crack growth.

Rizzi[40] recently developed an approach based on the crack closure technique to calculate stress intensity factors directly in the frequency domain. His hybrid finite element/modal analysis/spectral analysis method makes the contribution of one or more vibration modes to the total stress intensity factor possible. He demonstrates the method for a center cracked panel subject to static inplane and acoustic loading.

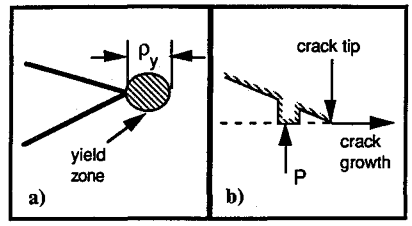

Fig. 5 Crack growth retardation/acceleration models: a) the Willenborg model and b) a closure model.[52]

Many other techniques exist for determining fatigue crack growth rates under random loading based on statistical quantities such as the root mean square (rms) intensity,[41] the mean stress, the greatest rise or fall in stress intensity levels, and the distribution of maxima and level crossings.[42] It has been shown that the primary cause of fatigue damage under random loading depends on the rise and fall in the loadings rather than other statistical quantities.[43,44] Recently, two modified Forman equations have been proposed to account for random loading.[38,45] Equation (4a) in Table 1 incorporates the threshold stress intensity factor ΔK_{th} below which a crack will not grow into the crack growth equation.[38] Another modified Forman's equation,[45] shown in Eq. (4b) of Table 1, accounts for the rms value of the stress intensity range K_{rms} and the mean stress intensity factor, $K_{mean} = K_{max} - K_{rms}$.

Another recent analysis of fatigue crack growth under random loading has been conducted by Huang and Hancock.[46] These investigators statistically analyzed the stress intensity range between cycles to predict the distribution of crack lengths after a given number of cycles and the distribution of cycles to grow a crack to a given length.

Load Interactions

The stress intensity factor approaches outlined earlier are useful methods of studying crack growth, but inadequacies in the methods exist since load sequence effects are ignored. Block loading at different amplitudes has been widely used to study these effects. Hudson and Hardrath[47] showed that cycling at a high stress level followed by a low stress level results in slower than predicted crack growth. Other investigators also observed crack growth retardation following tensile overloads, and many studies have been conducted to analyze this behavior.[45,48–58]

An illustration of crack growth retardation caused by a tensile overload in an aluminum plate is shown in Fig. 4. The crack growth for a constant amplitude load is represented by curve A. Curve B illustrates the effects of tensile overloads applied at the positions designated by open circles. Following each tensile overload, the slope of the curve approaches 0, and crack growth is slowed considerably. Curve C illustrates the effects of a tensile overload immediately followed by a compressive overload. The retardation effects are significantly reduced due to the additional compressive overloads, as shown in the graph. In contrast, several investigations found that a low followed by a high stress level resulted in accelerated crack growth. Two distinct models currently exist to explain these crack growth retardation/acceleration effects: the Willenborg model and a crack closure model.[52]

The Willenborg model,[53] illustrated in Fig. 5a, postulates that tensile overloads introduce plastic yield zones at the crack tip. The shape of the plastic zone can be determined from an elastic-plastic stress analysis of the structure. A simplified plastic boundary, approximated by an ellipse extending a distance ρ_y from the crack tip, is shown in Fig. 5a. There are many numerical and approximate elastic-plastic analysis procedures available to determine the shape of the plastic zone.[59–61] This zone produces residual compressive stresses at the crack tip that cause a reduction in the induced stresses and in the effective stress ratio, $R = K_{min}/K_{max}$. This results in a deceleration of crack growth after the overload. The retardation effect is terminated once the crack has advanced beyond the yield zone until another overload is encountered. Alternately, compressive overloads result in crack growth acceleration, and modifications have been made to the Willenborg model to account for this effect.[52]

The second model is based on the formation of a plastic wake along the crack surface that prevents crack closure, as shown in Fig. 5b. A tensile overload induces this plastic wake, which is represented by the shaded region in the figure. The crack begins to close as it is unloaded from the maximum load. Once the upper and lower faces come together, forces are introduced at each of the many points of contact along the crack. Only one contact point is shown in the figure (with the force P resisting crack closure) for simplification. These forces cause the minimum stress intensity factor to be increased, thereby reducing the stress intensity range, $\Delta K = K_{max} - K_{min}$. Consequently, crack growth is slowed down or retarded. In contrast, compressive overloads compress the plastic wake and accelerate crack growth. Other descriptions of crack closure are also available.[54]

Recent predictions for nonlinear crack growth due to load sequence effects in random loading have been proposed by Fuhring.[56] His model is based on the crack closure mechanism, from which he formulates a generalized memory criterion to include the loading history of the specimen in the crack growth evaluation. Fuhring proposed a retardation factor (proportionate to a ratio of plastic zone sizes) and an acceleration factor (a function of the affected crack length) to account for loading sequence effects. This model is a major contribution to the study of crack growth under random loading since it accounts for retardation as well as acceleration effects. Several other mathematical equations to quantitatively account for load sequence effects on crack growth are also available.[49,53,57]

Semi-elliptical Cracks

Although most of the theories on crack growth consider through-the-thickness cracks, part-through cracks are important in real structural applications. Semi-elliptical cracks grow in length and depth, requiring a two-dimensional analysis. In 1960, Irwin proposed a new stress intensity factor for part-through cracks. Other researchers have since modified Irwin's stress intensity factor and conducted detailed reviews of semi-elliptical crack growth.[47,62]

Palmgren-Miner Cumulative Linear Damage Theory

The cumulative linear damage theory widely used in the estimation of fatigue damage is the Palmgren-Miner theory. Palmgren[63] proposed this rule in 1924, and it was later restated by Miner.[64] This rule provides an assessment of the fatigue life of structures under varying loads by accounting for the stress amplitude variations. A brief review of the derivation of the Palmgren-Miner rule is now presented.

A loading history of $n_1, n_2, \ldots, n_m$ cycles at respective stresses $s_1, s_2, \ldots, s_m$ will result in fracture when the sum of the individual damages n_i/N_i (where N_i is the total fatigue life under the stress s_i) equals unity. This linear damage theory is known as the Palmgren-Miner rule:

$$\sum_{i=1}^{m} \frac{n_i}{N_i} = 1$$

Several modifications, aimed at achieving better estimates of damage, have been proposed. Experiments conducted by Freudenthal[65] showed that experimental values of cumulative damage scatter about unity. He found that these deviations could be effectively represented by factoring n_i/N_i by some quantity α. Similarly, Miles[66] replaced $1/N_i$ by $(1/N_i)^\alpha$ where α represents an experimentally determined constant. Shanley[67] replaced α with 2α.

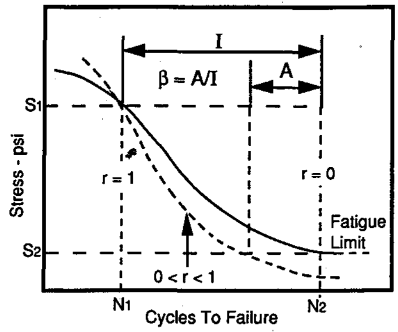

Fig. 6 β model for a two-level block test.[75]

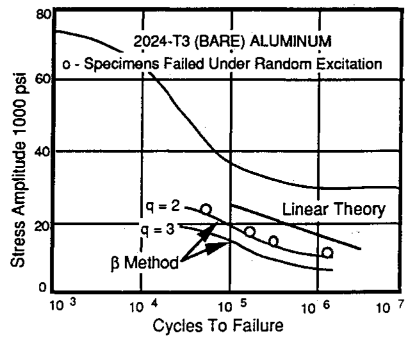

Fig. 7 Comparison of β method and linear theory fatigue curves with actual random test fatigue data.[75]

To analyze random stress fields, the Palmgren-Miner rule can be expressed with probability distributions and parameters such as the rms stress level, taken from the power spectrum of the loading. This has been accomplished by using statistical methods to modify the original theory.[1,6,68]

Although the linear damage rule provides a good estimate for the fatigue life of structures subjected to random loading, some limitations of the theory do exist. The chronological loading sequence is ignored, static applied loads cannot be assessed, and in many applications, stresses below the fatigue limit are ignored. Theories capable of evaluating cycle by cycle stress behavior to achieve more accurate predictions of fatigue damage are therefore needed. Various alternative quasilinear and nonlinear damage theories have also been proposed.[69-74]

β Method

The β method has been found to predict random fatigue curves with a greater degree of accuracy than the linear method.[69,75] The method is based on a bracketing procedure in which the cycles to failure are related to the probability distribution of the stresses between the maximum and minimum cyclic stresses. An estimate of the stress time history is therefore needed to apply the method.

This method can be best understood by considering a two-level cyclic block loading. The distribution factor β determines the expected fatigue life as a fraction of the interval I between the maximum and minimum cycles to failure. As shown in Fig. 6, $\beta = A/I$, where A is the distance between the vertical line through the variable *S-N* curve (designated by the broken curve) failure point at S_2 and the vertical line through the regular *S-N* curve (the solid curve) failure point at S_2. In this case, β is equal to the following function:

$$\beta = f\left(\frac{N_1}{N_1 + N_2}\right)$$

where

N_1 = number of cycles in the loading pattern at the highest cyclic stress S_1

N_2 = number of cycles in the loading pattern at the lowest cyclic stress S_2

If the β ratio r equals 1, the stress cycles would all be at the highest stress level and failure would occur at the designated lower limit of cycles on the regular *S-N* curve. Conversely, if r equals 0, the stress cycles would be at the lowest stress level and failure would occur at the upper limit of the interval. For $0<r<1$, the variable *S-N* curve is represented by the broken curve in Fig. 6.

For random loading conditions, β can be determined from the following equation:

$$\beta = \frac{1}{qS_1}\int_0^{S_1}\left[\log\left(e\frac{-s^2}{2\sigma^2}\right) + q\right] ds$$

where

q = the material fatigue stress sensitivity factor (a constant, generally ranging from 2.0 to 3.0)

S_1 = the effective maximum cyclic stress

σ = the rms stress

Random fatigue curves were calculated by Coté[75] using the β equation just defined for a 2024-T3 aluminum specimen, and the results are shown in Fig. 7. The curve extending completely across the graph is the regular *S-N* curve. The three lower curves are predicted by linear theory and the β method (for $q = 2$ and 3) as shown in the figure. The circles on the graph represent actual specimen failures under random excitation. According to the graph, the β method predicts the aluminum random fatigue curve with more accuracy and more conservatism than the linear method. Several detailed descriptions of the β method and its limitations are available.[69,75]

Testing Procedures

Many methods are currently used to detect and monitor fatigue cracking in structures subjected to unsteady loading. There is an increasing need for noncontacting, nondestructive techniques capable of rapid, real-time detection of flaws. A review of nondestructive testing methods was presented by Achenbach and Thompson at the 1990 Symposium on Structural Integrity of Aging Airplanes.[16] A brief review of some crack detection and monitoring techniques currently available is now presented.

Methods of Crack Detection and Measurement

Photography

Photographic techniques have been widely used to study crack propagation. Several automated photomicroscopic systems have been developed[76,77] to monitor the growth of cracks microscopically. These systems typically consist of a camera mounted on a microscope as shown in Fig. 8a. A computer is used to control the rate at which the photomicrographs are taken and record data. Dyes are frequently used to detect initial crack formation.

Electrical Potential

Direct current electrical potential techniques have also been used to study crack growth. This method is commonly used to determine crack depth by measuring the voltage drop across crack openings. Several cases of experimentation with this method are available.[47,62,78]

Ultrasonics

Ultrasonic monitoring techniques are based on either the attenuation of wave amplitudes or the reflection of energy from the crack. Deep material penetration is possible with this method, allowing internal cracks to be detected. High-intensity ultrasonic waves are also used to induce fatigue cracks in materials and hence accelerate testing procedures. A typical ultrasonic test setup is shown in Fig. 8b. A more detailed description of ultrasonic testing methods is given by Ensminger[79] and Zirinsky.[80]

X-Rays

Fatigue cracks have also been examined with high-resolution x-ray equipment.[81] Although internal cracks can be detected with this procedure, the test must be stopped periodically for specimen inspection.

Infrared Radiation

A crack detection device based on infrared techniques has been developed specifically for acoustic testing.[82] This nondestructive, real-time detection system involves injecting heat energy into the specimen with a sharply focused radiative heat source. Local temperature rises can then be measured with an infrared detector. Surface and near-surface fatigue cracks represent discontinuities of thermal conductivity and cause increased local temperatures. An infrared radiation system is shown in Fig. 8c. Several other investigations of failure detection systems based on infrared techniques have also been conducted.[81,83]

Optical Correlation

Another improved technique for failure detection that relies on lasers is known as optical correlation. Marom and Mueller[84] used this method with lasers and holographs to detect failure in materials. Optical correlation is based on the recognition of patterns of scattered light from a target.

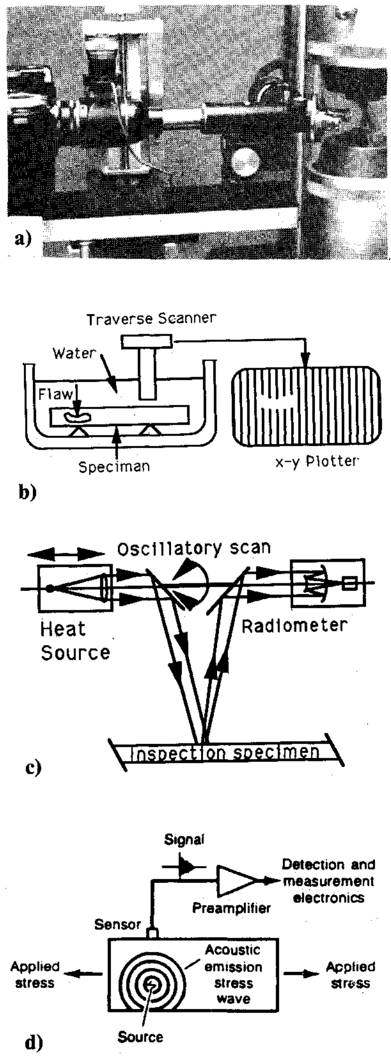

Fig. 8 Crack detection methods: a) a photomicroscopic system,[76] b) an ultrasonic system, c) an infrared radiation system,[82] and d) an acoustic emission test (Figs. 8b and 8d are courtesy of the Georgia Institute of Technology).

Acoustic Emission

When a material is plastically deformed or cracked, transient elastic energy is spontaneously released from the defect. This phenomenon, known as acoustic emission (AE), has been used to detect fatigue cracks in various structures. AE signals are thought to be broadband at the source and generally fall within the frequency range 30 kHz to 30 MHz.[85] The signals can be detected with sensors (piezoelectric transducers are common) and amplified for analysis (see Fig. 8d). Since AE signals travel rapidly in metals, sensors may be placed some distance from the source of the defect. It is difficult to identify the exact location of the defect, but AE may be used to isolate areas requiring more detailed examinations with other nondestructive tests. Another problem with AE is the contamination of signals by background noise. AE can often be discriminated from background noise by differentiating between the frequency spectra of the sources.[86] Numerous studies of acoustic emission have been conducted on materials (including composites) under various loading conditions.[87-90]

Failure Detection in Composites

Since most composites do not exhibit crack growth in a manner similar to metals, some of the detection techniques indicated may not be suitable for these material systems. Composite laminates have complex failure modes including delaminations, fiber pullout, and matrix cracking. Alternate methods such as loss of stiffness or residual strength tests are commonly used to detect composite failures.

Poursartip and Chinatambi[91] studied delamination growth and matrix cracking in carbon fiber-reinforced laminates. They found a stiffness reduction associated with delamination growth and a further reduction due to matrix cracking. They also noted a greater stiffness reduction under fatigue loading than under static loading. Other investigations of failure detection in composites were presented at the Second Symposium on Composite Materials: Fatigue and Fracture, 1987.[92]

Previous Experimental Research

Over the last 40 years, a great deal of experimental research has been conducted on the behavior of structures subjected to unsteady loading. The emphasis here will be on crack propagation and structural failures induced by acoustic loading.

Metal and Metal Alloy Structures

Since early aircraft structures were constructed primarily of metals and metal alloys, initial acoustic fatigue tests were conducted on these materials. In 1961, Dyer et al.[93] determined the acoustic fatigue resistance of various metal structural designs. A program to obtain acoustic fatigue design charts was carried out by McGowan[94] in 1963. Ballentine et al.[95] later refined McGowan's work to include new design criteria. Continuing refinement programs have resulted in new and improved acoustic fatigue designs for metal/metal alloy structures.[96–98]

Testing metal panels or "coupons" under acoustic loading provides engineers with valuable information about crack initiation and growth in aircraft structures. The random fatigue lives of several common aerospace materials are shown in Fig. 9.[99] The ratio of the rms acoustic stress (S) to material ultimate tensile strength (UTS) provides a gross measure of the acoustic fatigue susceptibility. As this stress ratio increases, the fatigue life is shown to decrease logarithmically. The graph indicates that aluminum is the least resistant (of the metals tested) to acoustic fatigue. Typical crack propagation curves for two aluminum alloy panels at various sound pressure levels are shown in Fig. 10.[6] As expected, the rate of crack growth in the thicker panel was slower at all sound pressure levels.

Aircraft panels are typically subject to steady pressurization tensile loads as well as acoustic loads. This motivated Clarkson[6] to study the propagation of a fatigue crack in a tensioned flat panel subject to acoustic loading. He found that, as the crack grew under these conditions, the rate of propagation increased with increasing crack length until an unstable length was reached and the free edge of the crack buckled. The postbuckled crack was found to propagate much faster than the prebuckled crack. Similar investigations conducted by Richards and Mead[1] substantiated Clarkson's results. Many other studies of acoustic fatigue in flat plates, including studies of plate thickness variation, are also available.[2,93,97–102]

Studies of other panel configurations have also been conducted. Skin-stiffened panels,[2,95–97,103,104] for example, were found to have greater fatigue resistance than unstiffened panels. An increase in weight is required, however, for these panel designs. Panels stiffened with internal structures, such as ribs and stringers, typically contain many small cutouts to allow skin stiffeners to pass through. The cutouts represent stress concentration sites that increase the sensitivity of these structures to acoustic fatigue. Clarkson and Abrahamson[103] proposed a method to measure the response of skin-rib structures to jet noise by assuming skin-rib

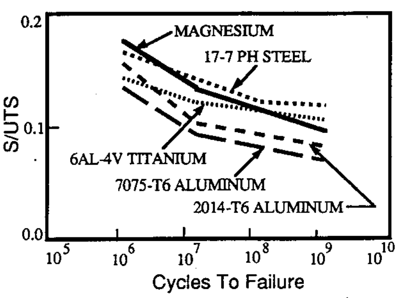

Fig. 9 Random fatigue life of common aerospace metals.[99]

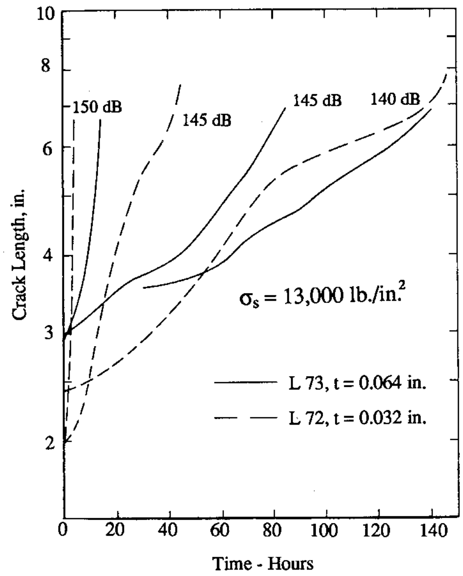

Fig. 10 Typical crack propagation curves for various sound pressure levels.[6]

coupling across the structure. Design equations for estimating acoustic fatigue of skin, stringer, and rib structures were developed by Rudder.[96] In his study of box structures, he confirmed the importance of designing the structure so that the rib and skin were highly coupled.

Edge and Rucker[105] and Bayerdorfer[97] studied the effects of curvature on aluminum alloy panels. They found that an increase in curvature was associated with an increase in the time to failure of the panel. Several other investigations of panel curvature and acoustic fatigue have also been conducted.[2,95,96]

Acoustic studies of four typical panel configurations (corrugated, bonded-beaded, chem-milled, and skin-stringer) were conducted by Van der Heyde[104] and Van der Heyde and Wolf.[106] The time to failure of each of the four configurations at various sound pressure levels is shown in Fig. 11. The corrugated panels were found to have superior acoustic fatigue resistance compared with the other configurations. Internal failures and delaminations of corrugated panels, however, are difficult to detect without expensive inspection equipment. Failures are more easily detected in skin-stringer panels that were found to provide the least resistance to acoustic fatigue.

Sandwich panels are frequently designed for use in aerospace structures and have been shown to have high acoustic fatigue resistance. Honeycomb core sandwich panels, for example, are beneficial not only because of their high resistance to acoustic fatigue but also because they are lightweight structures. Investigations of the response of these panels under acoustic loading and the associated failure modes have been conducted by Sweers[107] on aluminum honeycomb panels and by Wallace[108] on brazed steel honeycomb panels. Kurtze and Westphal[109] studied these and other promising sandwich panel designs.

Fiber-Reinforced Composites and Nonmetallic Structures

The advent of composites has led to the widespread application of these materials in aerospace structures. Fiber-reinforced composites are an attractive alternative to metal structures because of their high strength-weight ratio and because they may be tailored to satisfy specific design needs. The fiber orientations found in the individual plies that compose these composites determine the direction-dependent strength of the material. Composites are consequently sensitive to strain in particular directions. The need for both analytical and experimental studies of crack propagation and subsequent failure is therefore apparent. Some of the studies that are available on fiber-reinforced composites (materials, configurations, and associated failures) are now reviewed.

Fiber-reinforced composites consist of a variety of fiber (graphite, boron, carbon, glass, etc.) and matrix (epoxy and other resins)

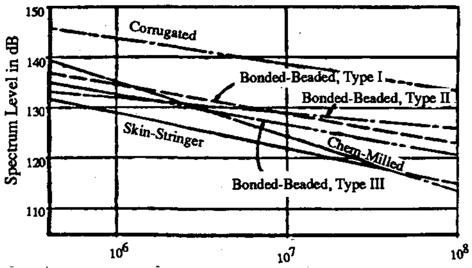

Fig. 11 Fatigue life of various panel configurations subject to acoustic loading.[106]

materials. Since composites are relatively new and inherently complex materials, due to variations in fiber orientations and lamina lay-ups, little research concerning the fatigue failures of these materials under acoustic loading is available. A few of the studies that are currently available, however, are discussed next.

Skin-stiffened panels are commonly made of composites, and several studies of the acoustic failure of these structures have been conducted. A semi-empirical acoustic fatigue design method for curved and flat graphite-epoxy skin-stringer panels was developed by Holehouse.[110] Other graphite-epoxy acoustic fatigue tests have been conducted by Soovere on integrally stiffened panels[111,112] and on the NASA L-1011 composite aileron.[113] He observed large amplitude, nonlinear responses in the panels (this behavior will be discussed in a following section). Both linear and nonlinear modes of failure, involving delaminations and resin cracking, were observed in the aileron.

Panels with fiber-reinforced facings to increase panel strengths are also common. Acoustic fatigue design information for S-glass and boron fiber-reinforced structures was obtained by Jacobson[114] and Jacobson and Van der Heyde.[115] In their experimental programs, acoustic tests were performed on honeycomb panels with S-glass, boron, and aluminum alloy reinforced facings. The effects of various ply orientations on panel life and the modes of failure in the facings and the core were reported. The fiber-reinforced honeycomb panels were shown to offer greater resistance to acoustic fatigue than aluminum honeycomb panels of comparable weight and thickness. Another study by Wolf and Jacobson[116] of boron-epoxy and graphite-epoxy cross-stiffened panels attached to internal structures of metal and composite materials showed these structures to be suitable for high-intensity noise environments.

Other fatigue tests were conducted on viscoelastic (high polymer) and aluminum control panels, subjected to various sound pressure levels by Edge and Rucker[105] at room temperature and 200°F. The viscoelastic panels were found to endure longer than the aluminum control panels before any signs of skin cracking became visible. The margin of improvement was less, however, for the 200°F conditions. Leatherwood et al.[117] recently conducted acoustic tests on high-temperature carbon-carbon composites. He examined flat and blade-stiffened panels, and a discussion of his results can be found in the following section on thermal/acoustic environments.

Large Deflection, Nonlinear Analysis

Mei and Wolfe[118] found that small deflection linear theory provided poor analytical fatigue data for aluminum panels subjected to high sound pressure levels. One reason for the discrepancy between analytical and experimental data was that the test panels responded with large deflections under the acoustic loading. Similar acoustic tests on composite panels have also resulted in the observation of large deflection. Soovere[111–113] performed acoustic fatigue tests on stiffened panels and on the NASA L-1011 composite aileron and observed large amplitude, nonlinear panel response. He determined that these structures must be designed with high random strain allowables to withstand the nonlinear response. The composites were found to be capable of longer acoustic fatigue lives than the aluminum alloy structures where nonlinear panel response was associated with a short acoustic fatigue life. In both cases, analytical studies of large deflection panel response are needed for accurate predictions of acoustic fatigue data where small deflection theory is inadequate. Other investigations of the effects of large deflection and nonlinear response to high-intensity acoustic pressures have led to similar conclusions.[119,120]

Short Crack Growth

Several researchers have investigated anomalies in short crack behavior under variable amplitude loading. Ritchie and Suresh[121] reviewed the mechanics and physics of short fatigue crack propagation in metals. They considered cracks to be short when their length was small compared with relevant microstructural dimensions, their length was small compared with the local plasticity scale, or they were physically small (e.g., < 0.5–1 mm). For all three cases, the short cracks were likely to propagate faster than long cracks under the same loading conditions. Cook and Edwards[122] found similar differences in crack propagation rates for short and long cracks. They suggested that short cracks remain open below zero stress due to the large local plastic zone and hence propagate more quickly than predicted by linear elastic fracture mechanics. For this reason, elastic-plastic analyses of crack behavior are necessary for more accurate predictions of short crack growth.

Stress Concentration Sites

Structures inevitably contain stress concentration sites, where fatigue failures are commonly initiated. For example, the attachment of one structural configuration to another—whether by weld bonding, adhesive bonding, riveting, or other means—introduces imperfections, or stress concentrations, at the attachment points. Structures are more likely to experience fatigue failures at these attachment points where stresses are concentrated. Several studies have therefore been conducted to determine the effects of fatigue induced by random loading on various structural joint configurations.[1,93,105,123–125] Bonding methods have been found to be advantageous because of the associated improved fatigue lives and reduced manufacturing costs. These advantages are primarily due to the elimination of holes and fasteners where cracks often originate and the reduction in man-hours required to assemble and maintain the many fasteners.

Holes or notches in materials inevitably lower the fatigue strength and are also stress concentration sites. Inglis calculated the local increase in stress for elliptical and round holes, known as the stress concentration factor,[17] given by

$$\left(1 + 2\sqrt{\frac{a}{r}}\right)$$

where
a = crack length
r = radius of curvature of the crack tip

Since $a = r$ for a round hole, the stress at a rivet hole of any size is intensified by a factor of approximately 3 in its vicinity. A small hole can therefore weaken a material as much as a large one, and it is clearly the shape, rather than the size, of holes that affects the local stress. The sharpness of the re-entrant, and not the amount of material removed, causes the increase in the stress. Stress concentrations found at notches have been studied extensively by Neuber.[126] He derived equations for obtaining notch stress concentration factors and investigations of others have verified his findings.[127]

Stress concentration sites also exist in structures at other locations of concavity. The dynamic buckling of panels, for example, produces high stresses along the flexure lines of the buckle.[1,4] Studies of various structural configurations and associated failures at stress concentration sites under acoustic loading have been conducted by Rudder.[96]

Environmental Effects on Structures: High Temperature, Moisture, and Corrosion

Most structures are subjected to environmental effects such as temperature, moisture, and corrosion as well as high-intensity noise. If not accounted for, these effects may cause the time to failure of structures to differ from predicted values. A review of these environmental effects follows.

Thermal/Acoustic Environments

There are many instances of simultaneous thermal/acoustic loading on high-performance aircraft where aerodynamic heating is an important consideration. Increasing temperatures have been found to cause a reduction in the acoustic fatigue life of many materials. Several investigations have been conducted on thermal/acoustic loading and the associated fatigue of advanced aerospace structures such as fighter bomber aircraft,[128] the Space Shuttle,[129] and other hypersonic flight vehicles.[8,99]

Little fatigue data are available for many of the new materials that are often desired because of their superior resistance to high-temperature fatigue. René 41, a nickel-base superalloy, is an example of a material being considered for high-temperature applications. Fatigue tests were conducted under random loading at temperatures up to 1400°F by Phillips[130] on this material. Cumulative damage predictions based on Miner's rule underestimated the fatigue life in practically all cases. Other metals, including aluminum and titanium, have also been fatigue tested in thermal/acoustic environments.[131] Studies on advanced composite fuselage panels were conducted by Soovere[132] and Jacobson[133] in the early 1980s.

Leatherwood et al.[117] recently conducted acoustic tests on high-temperature carbon-carbon composites. The strain response and sonic fatigue behavior of flat and blade-stiffened panels were examined at ambient and elevated temperatures. The time to failure of both types of panels was longer at elevated temperatures, implying fatigue tests conducted at room temperature may be a sufficient measure of carbon-carbon panel integrity.

Dynamic buckling, known as "snap-through" or "oil canning," is typical of panels in thermal/acoustic environments and is found to promote early fatigue failure. Criteria for predicting oil canning in such environments have been proposed by Jacobson and Finwall[131] and Jacobson and Maurer.[134] Other design criteria, including equations for the dynamic response of buckled panels in thermal/acoustic environments, have been developed by Schneider.[135,136] Recently, Ng[137] derived a single mode transverse displacement formula to interpret the nonlinear motion of snap-through.

Moisture

Exposure to moisture for an extended period of time reduces the fatigue life of metal and metal alloy materials. Moisture may also cause a reduction in the fatigue life of composite materials, particularly by creating conditions favorable for delaminations. To make more accurate predictions of fatigue lives and crack growth rates, the effects of moisture (if applicable) should be included in the analysis of materials subject to any type of loading.

Corrosion

Corrosive environments are known to contribute to early fatigue failures. Corrosion tends to break down the external protective coatings frequently found on structures exposed to harsh environments. The effects of corrosion are particularly evident in and around holes and crevices. Holes containing fasteners, for example, permit moisture and/or chemical intrusion. The relative motion between the fastener and the surrounding structure, caused by fatigue loading, will therefore promote corrosion.[138]

Methods of Acoustic Fatigue Prevention

Many approaches for preventing fatigue caused by unsteady loading have been explored. The following is a brief review of some prevention methods currently available.

Damping Materials

Vibration amplitudes and associated stresses may be reduced by damping the significant modes of vibration. Damping causes a free motion to be just aperiodic and results from 1) the absorption of energy by the structural configuration itself, 2) dissipation of energy away from the structure, and 3) various sources such as frictional effects from stowed equipment, etc.[1]

The acoustic fatigue and crack growth in structures may be reduced by increasing material damping. One method that is widely used involves the application of thin layers of antivibration materials to the structure. These are usually viscoelastic materials with very high natural damping properties. Several investigations of damping materials and the optimal thicknesses of these materials on various structures have been conducted.[1,75,139–144] In other cases, mechanical damping systems have been used to reduce acoustic fatigue.[145] Nonlinear damping has also been found to play an important role in panel response at high sound pressure levels.[146,147]

Other Methods

Several other methods for reducing acoustic fatigue also exist. Structural modifications to reduce or prevent further crack growth in materials that have already undergone fatigue cracking are commonly implemented. Placing stiffeners parallel to a crack, for example, has been found to reduce subsequent crack growth, and this procedure is commonly used to increase structural fatigue life. Drilling small holes at crack tips is another method of inhibiting crack growth. Although holes are stress concentration sites, the stress concentration factor is reduced by increasing the radius of the crack tip, and crack growth can be halted at least temporarily.

Numerous methods for improving material fatigue strengths before fatigue loading are available. Various material hardening techniques, such as strain hardening, are commonly employed to strengthen materials. Shot peening (adding residual compressive surface stresses to materials) is another means of raising yield strengths. The effectiveness of material strengthening methods under unsteady loading conditions needs to be further explored.

With the advent of high-speed computers, it is now practical to control sound in a given region by injecting sound of a given phase and amplitude from a secondary source such that the resulting sound can almost be canceled. This process of canceling sound by the so-called "antiphase" sound is referred to as active noise control.[148–150] In a recent study, Salikuddin and Ahuja[148] showed that high-intensity sound responsible for sonic fatigue in a localized region can be controlled by mounting acoustic drivers near the surface affected by high-intensity sound. Investigations of active noise and vibration control in cylinders have also been recently conducted.[151,152]

Computer Programs for Crack Propagation Analysis

Digital computers provide an inexpensive and effective means of improving the designs of structures subjected to random loading. Since actual space-time histories of random loads are often unavailable, simulation techniques may be utilized to obtain the space-time histories of input loads. Vaicaitis[153] reviews the basic concepts involved in the simulation of random processes. Numerous methods for simulating structural response, fatigue, and crack propagation under random loading are available as a result of computer technology.[46,52,154–162] Monte Carlo simulations have been widely used to study these random processes.[46] The discrete Markov process has also been used to simulate random behavior. Yuasa et al.[155] modeled fatigue crack propagation with this process, considering random loading as well as the randomness of material resistance to crack propagation. The application of other matrix methods to predict acoustic fatigue strengths has been investigated by Eshleman and van Dyke.[156]

Several computer codes are currently available to determine crack propagation properties based on cycle by cycle load spectra analyses. Two commonly used computer programs, CRACKS[157] and EFFGRO,[158] are based on the Runge-Kutta and linear approximation methods, respectively.[159] More recently, two codes named FLAGRO and MODGRO have been proposed.[52] The FLAGRO code uses modified Forman's equations to predict crack growth, but no retardation effects (which are characteristic of variable amplitude loading) are included. The MODGRO code, however, is based on the Willenborg model that does account for retardation effects.

As a result of improved crack tip models and programming capabilities, the finite element method has been used to estimate stress intensity factors in fatigue crack growth studies. Several investigations of the finite element method and its applications to crack growth under various loading conditions are available.[160–162]

Suggestions for Future Research

Although a growing interest as well as an increased amount of research in fatigue crack propagation is evident, further studies are needed to obtain a more complete understanding of crack propagation under random loading. The following suggestions for future research in this field are recommended.

1) Conduct a detailed study on the effects of various environments (physical, chemical, etc.) and combinations of these environments (especially at elevated temperatures) on crack growth under random loading conditions.

2) Develop an accurate analytical model to predict acceleration and retardation effects in fatigue crack growth under random loading conditions.

3) Conduct further studies on the effect of snap-through response and associated crack growth patterns.

4) Conduct further studies in microcrack and "small crack" propagation under unsteady loading conditions.

5) Conduct detailed studies on crack growth in various composite and nonmetallic materials subject to random loading.

6) Study crack propagation in thick plates, curved panels, and other configurations that have received little attention.

7) Exploit the usefulness of active control to minimize and even eliminate the risk of acoustic fatigue.

8) Develop nonintrusive methods of crack detection. Exploit the more recent advances in the area of image processing and optical sciences.

Conclusions

Although great strides have been made in the study of crack propagation under random loading, a vast amount of research is needed to fill the many voids in this relatively young field. Improved theoretical models and testing methods should be designed to account for various environmental conditions as well as material compositions and configurations. More accurate predictions of the fatigue lives of structures subject to unsteady loading will affect a broad range of applications. Many industries will therefore benefit from the research currently available and the refinements that will undoubtedly follow.

Acknowledgments

The authors gratefully acknowledge the support of the NASA Space Grant Consortium and the Georgia Tech Research Institute Senior Research Leadership Program. The authors also thank Ann Campbell of the Georgia Tech Library Information Services for assistance with references.

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