SECTION E

SECTION E1

FATIGUE

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

E1 FATIGUE.

1.1 INTRODUCTION.

1.1.1 General Considerations for a Fatigue Analysis.

Before detailing the many factors involved in a fatigue analysis and design, it is desirable to give an overview of the general considerations that comprise a fatigue analysis. Often when a new vehicle, structure, etc., is being considered, there are many concepts, designs, and configurations to be evaluated, and the engineer must provide ready assistance in the selection of materials, writing of preliminary test requirements and the life evaluation.

Figure E1-1 shows a general flow diagram of information for a fatigue analysis. As can be seen from this figure, there are two primary groups of information that are necessary as input to a fatigue analysis and/or determination of preliminary test requirements for a given structural component.

One group of information is the necessary data on the given material. These data include curves, graphs, etc., of laboratory tests to determine stress versus cycles to failure (S-N) diagrams, Modified Goodman diagrams and other factors which would affect the life of the component in question. The other information, which is usually the first information that is required, is the life cycle or service history of the structural component. This is usually presented in terms of stress-environment versus time curves which show pressures, temperatures, and other environmental considerations. In general, with these two groups of information a fatigue analysis and/or the preliminary test requirements can be determined for the component. Actually, the preliminary test requirements can usually be determined from the life cycle information alone.

1.1.1.1 Life Cycle Determination.

The important elements in the formation of life cycle data are the design life, mission profile (or condition lists), and significant fatigue loadings (see Fig. E1-1). The design or anticipated operational life and service loading spectra are primary considerations in evaluating effects of fatigue on the structural component of a flight vehicle.

Design life is generally specified by contractual or managerial agreements, or FAA and Military specifications, usually in terms of number of flights, landings, pressurizations, flight hours, etc.

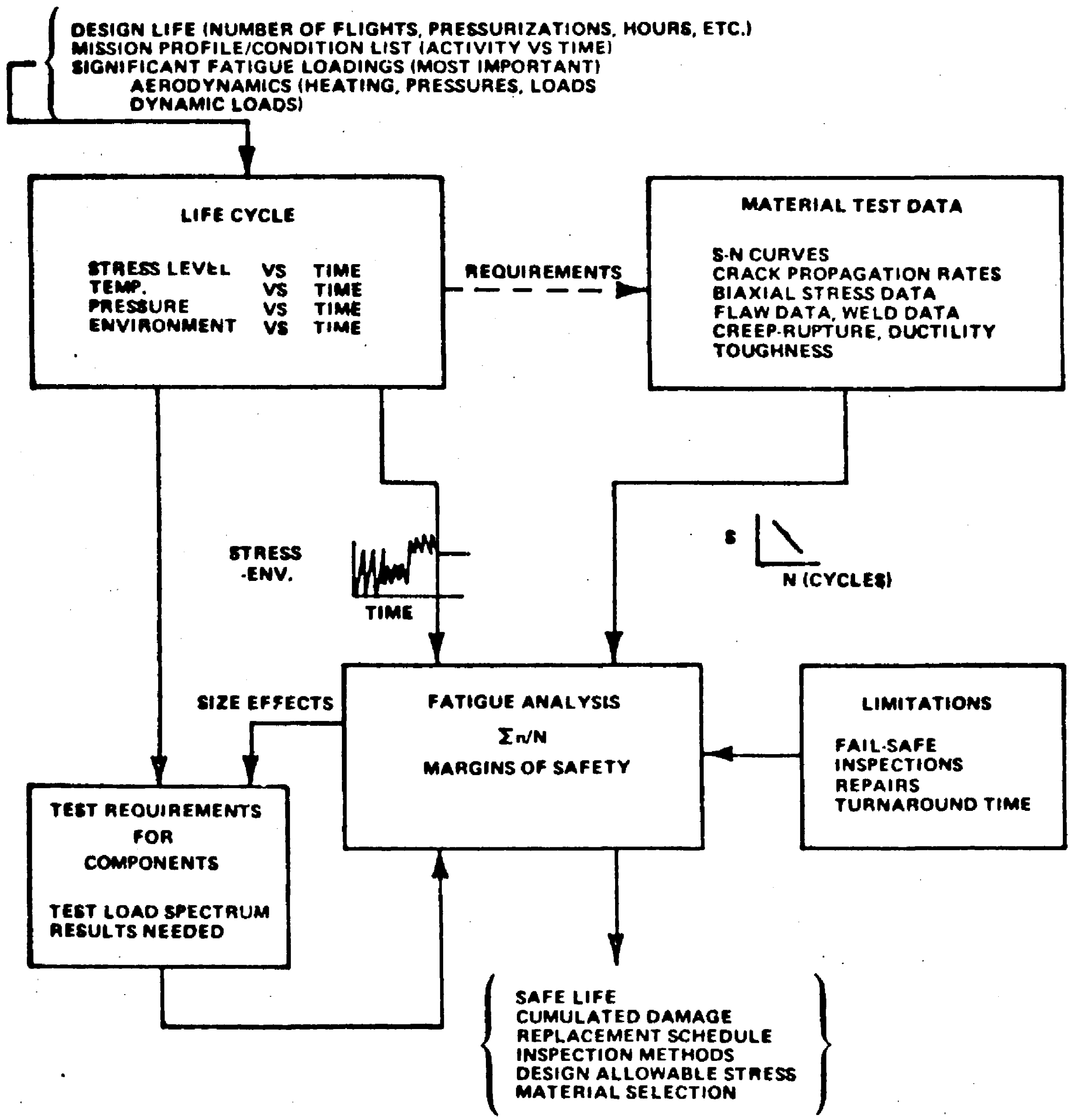


FIGURE E1-1. PROCEDURE FOR TYPICAL FATIGUE ANALYSIS

Mission profiles, or condition lists, are generally used to provide a basis for the selection of design stress levels, the choice of structural components to be tested, the definition of the fatigue test spectra, and evaluation of the service life. Figure E1-2 contains a typical mission profile for an aircraft. These mission profile and/or condition lists must contain a detailed description of the activity versus time (or distance) applicable to each portion of the flight. Also, the flight configurations and anticipated changes in weight due to fuel usage, altitudes, speeds, and any other parameters that could affect the fatigue loading spectra are required. The spectra used for analytical and experimental evaluation of fatigue should realistically represent the total operational loading history described by the mission profile and/or condition lists.

For preliminary considerations, all of the detailed data on mission profiles may not be available. It is then necessary to consider what are the most significant considerations for the component in question. For example, in

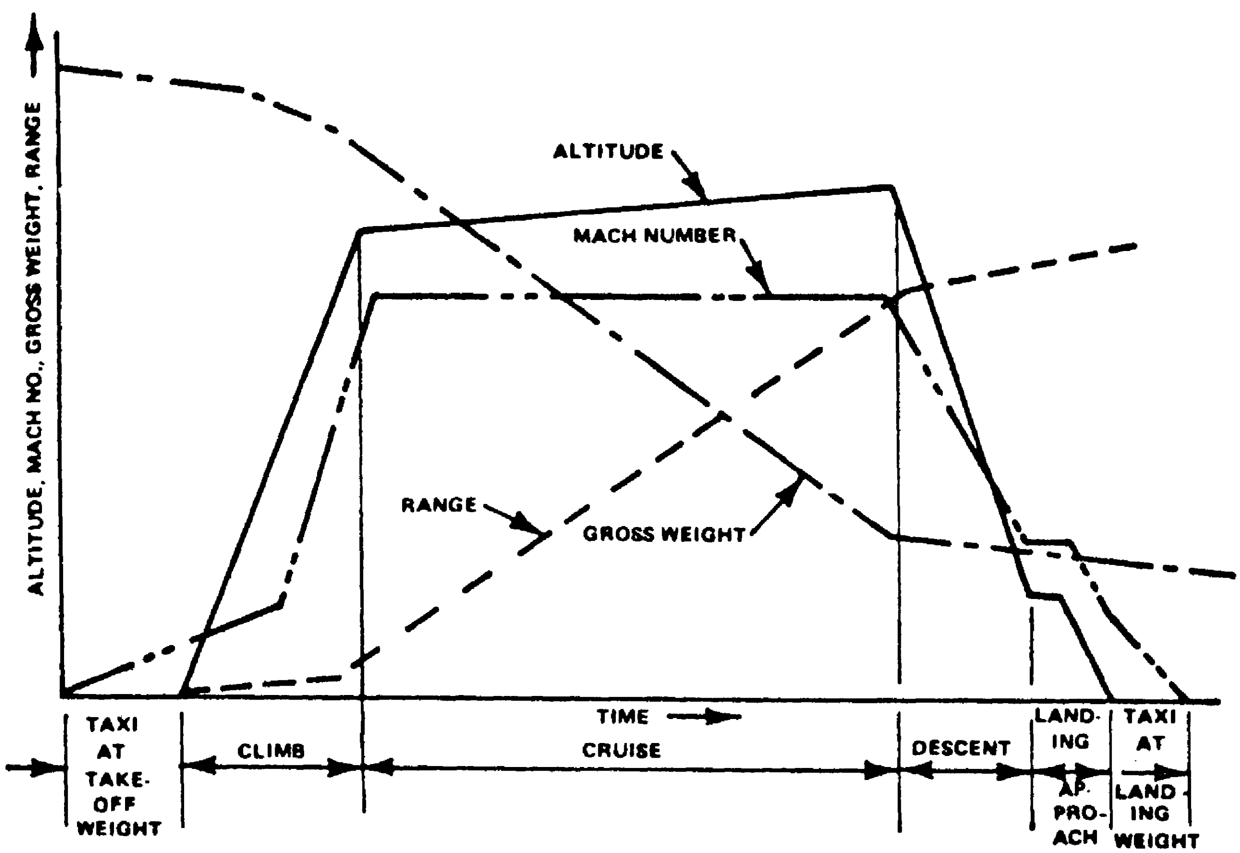


FIGURE E1-2. TYPICAL MISSION OR FLIGHT PROFILE FOR AIRCRAFT tankage, the most important factors may be pressure and temperature; for wings, the most important factor may be only temperature.

Now, given all the information above, it is required to evaluate the stress versus time curves for a given component. Ordinarily, the aerodynamic data and dynamic loads must be considered as input to aid in the evaluation of load and stress levels. In conceptual designs, however, these may be "best-guess" data. The stress-versus-time curves must, of course, reflect temperature versus time, and other environmental factors present over part of a mission profile. An example of a life cycle for a component is given in Fig. E1-3.

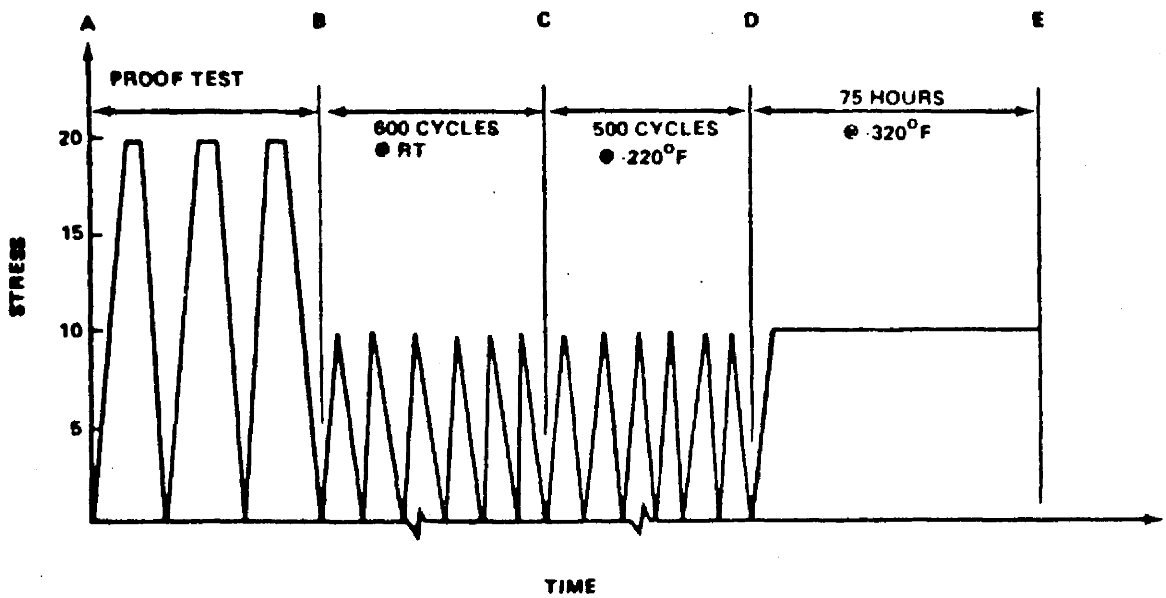
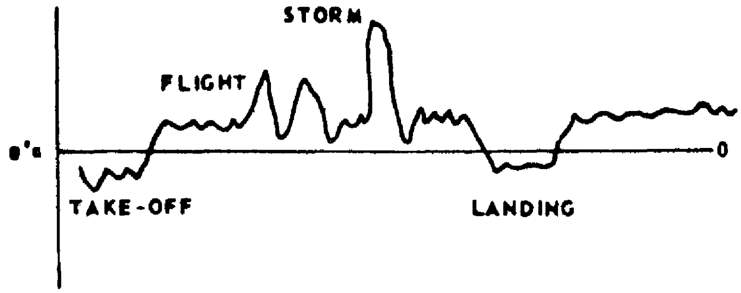


FIGURE E1-3. LIFE-HISTORY CURVE

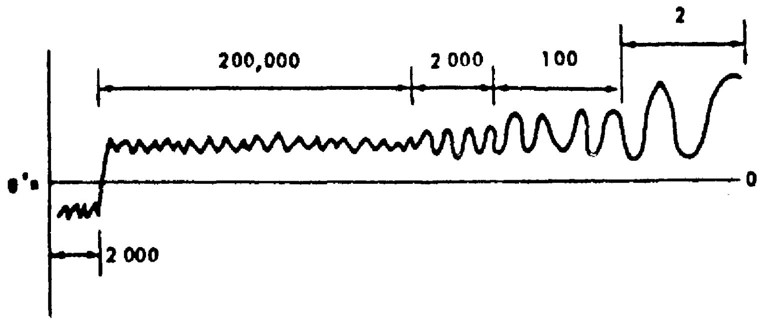
Of course, the actual life cycle history for a given component may contain many random type loads which must be condensed into a form which can be used in fatigue life evaluation. Many techniques are available to accomplish this, and they will be discussed in a later section. For example, the spectrum shown in Fig. E1-4 for an aircraft flight is simplified to a more usable form.

1.1.1.2 Material Fatigue Data.

The fatigue strength of a material may be defined as the maximum stress that can be applied repeatedly to the material without causing failure in less



a. Actual Aircraft Spectrum



b. Simplified Spectrum

FIGURE E1-4. SIMPLIFICATION OF A FLIGHT SPECTRUM

than a certain definite number of cycles. The endurance strength is that maximum stress which can be applied repeatedly to a material for an indefinite number of cycles without causing failure. The relationship of the magnitude of repeatedly applied stress to the number of cycles to failure is conventionally presented in the graphical form known as the S-N curve. The S-N curves are discussed in detail in Paragraph 1.2.3. The shape of the S-N curve, which is a representation of the fatigue life, will vary according to the conditions represented. Some factors influencing the shape of the S-N curve are as follows:

1. Type of load
    a. Tension
    b. Compression
    c. Torsion
    d. Combined Loads
2. Relationship of maximum to minimum loads
3. Manner of load application
    a. Axial
    b. Flexural
    c. Torsional
4. Rate of load application
5. Frequency of repetition of loads
6. Temperature of the material under load
7. Environment
    a. Corrosive
    b. Abrasive
    c. Inert
8. Material condition
    a. Prior heat treatment
    b. Prior cold work
9. Design of part or structure
10. Fabrication techniques

Thus, it can be seen that the mission profile or load spectra can dictate what type of S-N data are required for a fatigue analysis.

Other material information which may be necessary for input into a fatigue analysis are low-cycle fatigue data, fracture toughness, crack propagation rates, biaxial stress field data, welding, flaw size effects, and creep rupture data.

1.1.1.3 Fatigue Analysis.

Referring again to Fig. E1-1, with the input as discussed above, a fatigue analysis can be performed on the structural component or element in question. Other information which may be required includes limitations on inspection techniques, determination of a design (fail-safe or safe-life), and reliability and safety.

Fatigue analysis is usually performed in two phases. The first is the design phase, which is the structural sizing, material determination, and factor-of-safety study phase. Usually, in this phase only preliminary data are available concerning the life cycle and material properties; thus, best estimates must be made. From this design phase, design stress levels and requirements for developmental fatigue tests are determined.

The second phase of the fatigue analysis is the interpretation, in terms of actual flight-measured data, of the results obtained from fatigue tests conducted on structural elements. Also, the vehicle is assessed for damage and qualified for reuse on subsequent missions.

The details of the fatigue analysis will be discussed in the following paragraphs; but, generally, the fatigue analysis will determine the safe life for a structural component, will evaluate accumulated damage during service life, will specify inspection requirements, and will determine allowable stresses and/or test requirements.

Therefore, the analysis of fatigue life is a continuing process of study and reevaluation in light of newly acquired data. The acquisition of new loading and other environmental data can provide additional insight into the levels of assurance that exist in the evaluation of the service life of structural components on flight vehicles. Any significant variation between service-recorded loading histories (and related environmental conditions) and the spectra used to determine fatigue life would require a reevaluation of anticipated structural life.

1.1.2 General Background on Fatigue.

A rapid growth of metallurgy, with iron and steel coming into widespread use in many types of machines and structures occurred during the middle of the 19th century. During this time, engineers were confronted with failures that occurred at calculated nominal stresses considerably below the tensile strength of the materials involved, and, although the materials were considered ductile, the failures generally exhibited little or no ductility. It was soon discovered that most of the brittle fractures developed only after the structures had been subjected to many cycles of loading. Therefore, it came to be supposed that the metal degenerated and became fatigued under the action of cyclical stresses and that its ductile behavior turned brittle. However, later experiments showed that no degeneration or fatigue of the metal occurred as a result of cyclical stressing and, therefore, the idea of metal fatigue is false. Hence the term "fatigue" is still widely used although it has quite a different meaning.

Generally speaking, fatigue can be defined as a progressive failure of a part under repeated, cyclic, or fluctuating loads.

Fatigue failures may be simple or compound. Simple failures result when a fatigue failure starts from a single crack and propagates until ultimate failure occurs. A compound fatigue failure results when the origin of the fatigue crack originates from two or more locations and propagates; the joint effects cause total failure. The sequence in which failure occurs consists of three parts: The initial damage occurs in a submicroscopic scale, the crack initiates and propagates, and the final rupture takes place. The rate at which the crack propagates varies considerably, depending upon the intensity of stress and other related factors. Nevertheless, the rate is always much lower than that observed for low-temperature brittle fractures in steel.

It has proved difficult, however, to detect progressive failures in the part during its life; hence, fatigue failures can occur with little warning and can cause catastrophic failures. Also, periods of rest (the fatigue stress removed) do not lead to a recovery from the effects of stress; in other words, the fatigue damage is cumulative.

The criterion for fatigue failure is the simultaneous action of cyclic stress, tensile stress, and plastic strain. If any one of these is eliminated, fatigue is also eliminated.

Rarely is a mechanical component or structural element subjected to constant loads throughout its entire service history. Cyclic loading can result from vibration, variations in atmospheric gust pattern, variable wind loadings, repeated temperature changes, and repetition of design load, to mention only a few.

Many fatigue failures that occur in service are only minor, but others, such as those which result in the loss of a wing, propeller, or wheel, constitute a serious threat to life or property. Such failures have become more prevalent in recent years because of the following factors:

1. The continuing trend toward higher strength/weight ratios.

2. More refined static design techniques and the use of higher working stress.

3. The use of materials of ultra-high static strength.

Good static design does not necessarily result in satisfactory performance under repeated loading, and the choice of a design stress close to, or even higher than, the yield point of the material would almost inevitably result in failure after a relatively short period of service. There is every possibility that the fatigue problem will become more acute and that, consequently, the limiting strength criterion in many future designs will be adequate fatigue resistance. Therefore, the likelihood of a fatigue failure should be an early design consideration.

A major problem in designing to prevent fatigue failure lies in the identification of all the factors that affect the life of a part. Even with the knowledge of which problems to consider, one is still short of the goal: the exact determination of fatigue life. Techniques are furnished in the following sections to enable the engineer to develop fatigue data for a particular part.

All the basic definitions used in fatigue testing and failure are discussed in Paragraph 1.2. The many types of effects which influence fatigue strength are presented in Paragraph 1.3. A separate section (Paragraph 1.4) is devoted to low-cycle fatigue because of its unique application and terminology. Various cumulative fatigue damage theories are discussed in Paragraph 1.5. Paragraph 1.6 is a special section which will be useful in selecting certain materials to resist fatigue failures. Design guides are given in Paragraph 1.7.

1.2 BASIC DEFINITIONS.

This paragraph describes the basic mechanism of a fatigue failure and the general methods used in fatigue testing and documenting of the results.

The following definitions are some of the terms frequently used in this discussion of fatigue analysis:

<u>Stress Cycle</u> — The smallest division of the stress-time function that is repeated. (See Fig. E1-5.)

<u>Nominal Stress</u> — Obtained from the simple theory in tension, bending, and torsion, neglecting geometric discontinuities.

<u>Maximum Stress</u> — The largest or highest algebraic value of a stress in a stress cycle. Positive for tension. S_{max}

<u>Minimum Stress</u> — The smallest or lowest algebraic value of a stress in a stress cycle. Positive for tension. S_{min}

<u>Mean Stress</u> — The algebraic mean of the maximum and minimum stress in one cycle. S_m

<u>Stress Range</u> — The algebraic difference between the maximum and minimum stresses in one cycle. S_r

<u>Stress Amplitude</u> — Half the value of the algebraic difference between the maximum and minimum stresses in one cycle, or half the value of the stress range. S_a

<u>Stress Ratio</u> — The ratio of minimum stress to maximum stress.

<u>Fatigue Life</u> — The number of stress cycles which can be sustained for a given test condition.

<u>Fatigue Strength</u> — The greatest number of stress cycles which can be sustained by a member for a given number of stress cycles without fracture.

Fatigue Limit — The highest stress level that a member can withstand for an infinite number of load cycles without failure.

Fatigue Life for P Percent Survival, N_P — The fatigue life for which P percent of the sample has a longer life; for example, N_{90} is the fatigue life for which 90 percent will be expected to survive and 10 percent to fail.

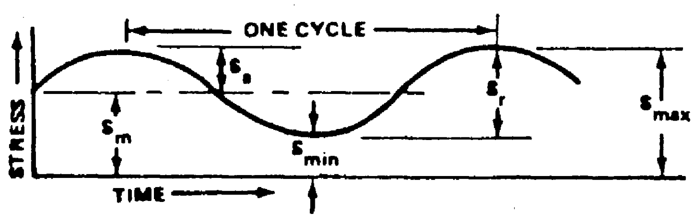


FIGURE E1-5. STRESS VERSUS TIME CURVE

1.2.1 Mechanism of Failure.

In investigating a fracture surface which resulted from fatigue, two zones are evident, namely, a fatigue zone and a rupture zone. The fatigue zone is the area of the crack propagation; the area of final failure is called the rupture, or instantaneous, zone. The instantaneous zone provides the following information for investigating a failed specimen: ductility of the material, type of loading, and direction of loading. The distortion and damage pattern will be sufficiently apparent to designate the type and direction of loading. In addition, the relative sizes of the instantaneous zone and the fatigue zone relate the degree of overstress applied to the structure. The degree of overstress can be categorized as follows: Highly overstressed if the area of the fatigue zone is very small compared with the area of the rupture zone, medium overstress if the size or area of both zones are nearly equal, and low overstress if the area of the instantaneous zone is very small.

The following features are characteristic of the fatigue zone: a smooth, rubbed, velvety appearance; a presence of waves known as clam shells or oyster shells, stop marks, and beach marks; and a herringbone pattern or granular trace which shows the origin of the crack. Most clam shell marks are concave with respect to the origin of the crack but can also be convex, depending on the brittleness of the material, degree of overstressing, and the influence of stress concentrations. In general, the stop marks indicate the variations in the rate of crack propagation due to variations in stress amplitude in a cyclic application varying with time. There are some aluminum alloys that may not exhibit these waves but instead have a smooth appearance. (See Fig. E1-6.)

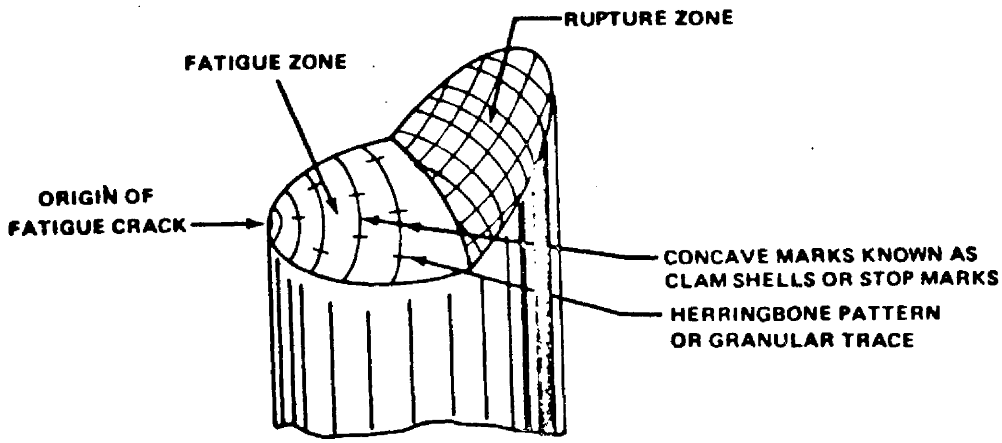
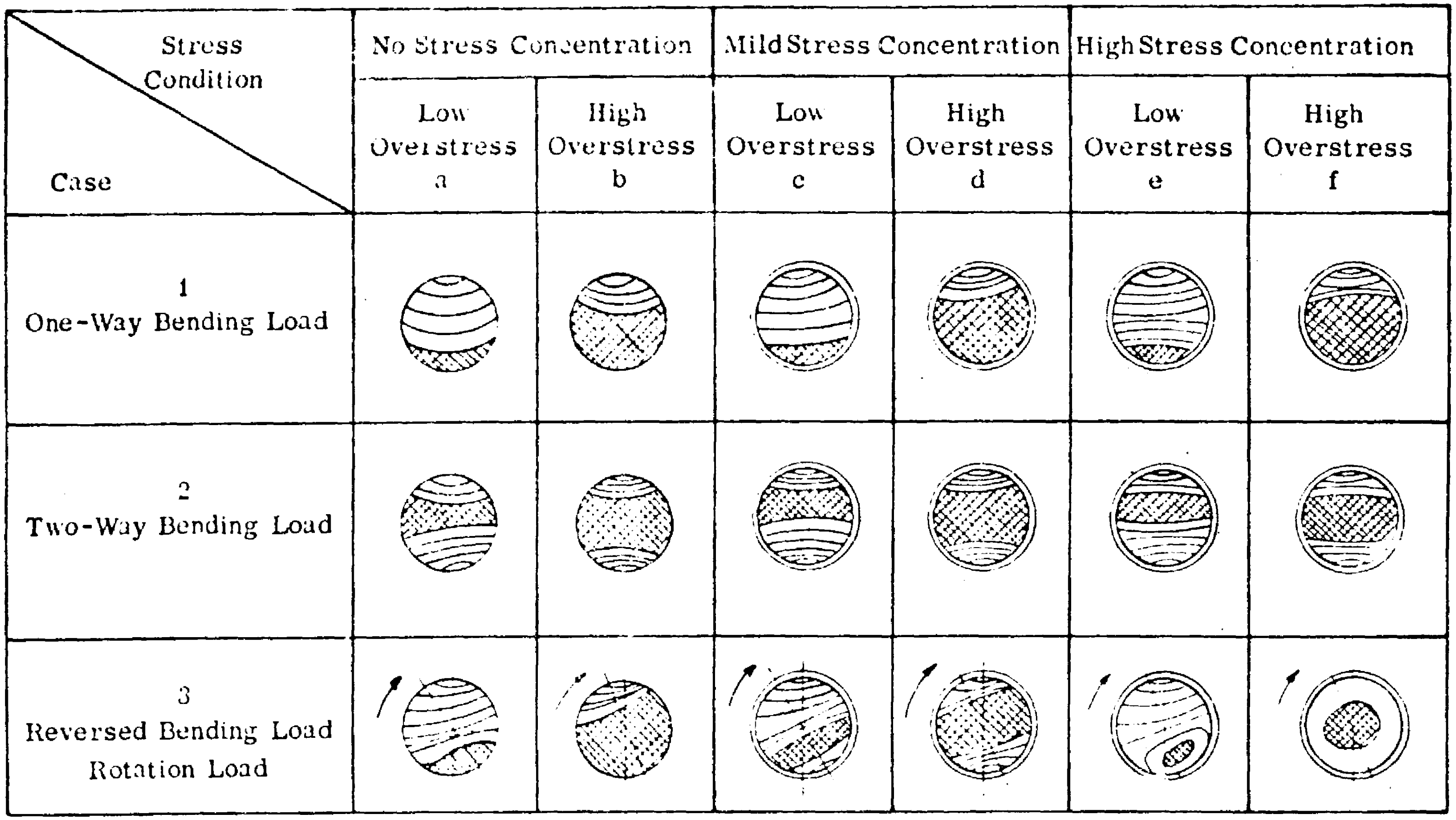


FIGURE E1-6. A TYPICAL FATIGUE FAILURE SECTION SHOWING IDENTIFYING MARKS

A fatigue fracture, whether the material is ductile or brittle, follows that of a brittle fracture. Not all brittle failures are fatigue failures, however. The most recognizable features of a fatigue failure are lack of deformation pattern and the existence of a singular plane of fracture, usually a 90-degree cross section.

Most of the fatigue cracks discussed above were caused by tension loads, tension strains, and tension stress. Typical fracture appearances of fatigue failures in bending and torsion are shown in Fig. E1-7. Bending fatigue failure can be divided into three classifications according to the type of bending load, namely, one-way, two-way, and rotary. The fatigue crack formations associated with the type of bending load are shown in Fig. E1-6. Torsional fatigue failures occur in two modes: (1) Longitudinal or transverse along planes of maximum shear and (2) helical at 45 degrees to the axis of the shaft and along planes of maximum tension. Transverse fractures are commonly associated with a smooth surface because of the rubbing of both sides, a characteristic that can be used to identify this type of fracture.

FIGURE E1-7. FRACTURE APPEARANCES OF FATIGUE FAILURES IN BENDING



However, a statement of the signs and features of fatigue fractures does not explain the true nature of the physical changes which take place inside metals under cyclical stress to cause their breakdown.

To understand these changes, it is necessary to study the internal mechanism of fatigue behavior in the whole volume of the metal; but this subject has yet to be thoroughly investigated. A considerable amount of theory has been written about fatigue fracture, and there are many interpretations as to the process of metal fatigue. (See Ref. 1.)

Fatigue is basically a property of crystalline solids, and the initiation of fatigue cracking is a problem in dislocation physics. It is the result of the motion and interaction of dislocations activated by cyclic stress. A simple description of the mechanism of fatigue cracking is given in three stages:

Stage 1. During the early cycles of stressing, the dislocations originally present in the crystal grains multiply and their density increases sharply. An irregular and disoriented cell wall, or subgrain boundary, starts to form. The fine slip lines that appear at first in some favorably oriented grains are thin and faint, according to the maximum resolved shear stress law. As the number of stress cycles increases, slip lines become more numerous. Some are localized, some continuously broaden, and the very pronounced ones become the so-called persistent slip bands. Meanwhile, the crystals are distorted and strain-hardened to saturation. Then, dislocation motion in one direction may be fully reversed with the stress. New dislocations and their movements are generated only in some local slip zones in which microstructural features are not the same in both directions of motion. Sometimes annihilation of dislocations, or other dislocation mechanisms, may lead to relief of lattice strains or strain softening. Strain softening, local recrystallization, overaging, clustering of point defects, and other thermal activation processes are considered to be secondary, or side effects.

Stage 2. After the persistent slip bands are fully matured, thin ribbon-like protrusions, called extrusions, of metal are emitted from the free surface, and fissures, called intrusions, appear. Both develop along the persistent slip planes. Several dislocation models or mechanisms have been proposed to explain how the extrusions and intrusions are formed. (See Ref. 1.) In some of the proposed models, dislocation cross slip is considered to be a critical process.

Because the intrusion is the embryo of a crack, the crack initiates along slip planes according to the maximum resolved shear. Sometimes cracks may initiate at cell walls or grain boundaries, although the majority start at the surface of a member.

Stage 3. The crack propagates in a zigzag transgranular path along slip planes and cleavage planes, from grain to grain, and maintains a general direction perpendicular to the maximum tensile stress. As much as 99 percent of the fatigue life of a member is spent in the development of fissures into microscopic cracks, and finally complete fracture ensues. Many factors affecting fatigue properties are those that mainly influence the rate of crack propagation.

1.2.2 Fatigue Testing Techniques.

The only way to obtain a quantitative measure of fatigue strength is to carry out fatigue tests under controlled conditions. There are many different methods of carrying out such tests, and numerous types of testing equipment have been developed.

Probably the most widely used method is the rotating bending test, in which small cylindrical specimens, with or without notches, are loaded either as cantilevers or as beams under four-point loading. As the specimen is rotated, the stress at any point in it varies between upper and lower limits which are equal in magnitude, but opposite in sign, the plane and direction of the loads remaining constant throughout. A possible arrangement of such a test is shown diagrammatically in Fig. E1-8. This type of test is simple to carry out, generates results comparatively rapidly and makes use of equipment and specimens that are reasonably inexpensive. It is particularly suitable for use in determining what might be called the inherent fatigue strength of materials,

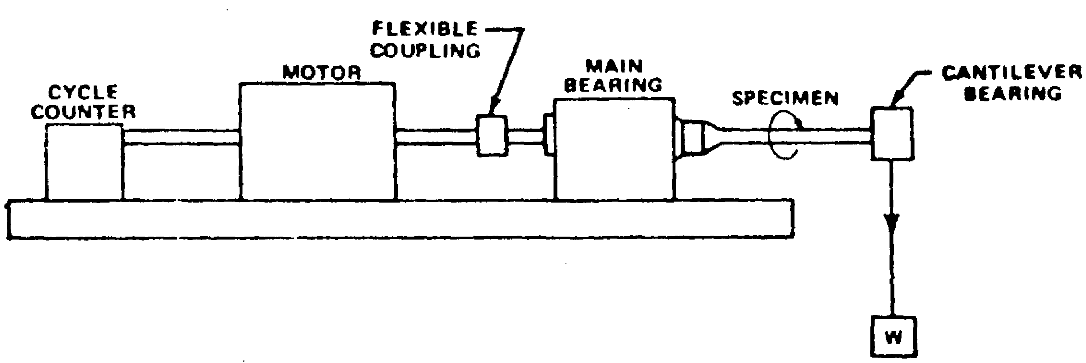


FIGURE E1-8. GENERAL ARRANGEMENT OF ROTATING BENDING (CANTILEVER TYPE) FATIGUE-TESTING MACHINE since in such work one is interested in the material itself, i.e., its composition, microstructure, etc., rather than its form in the engineering sense.

However, to provide data for design purposes, such tests are not of great value since designs can rarely, if ever, be reduced to such a degree of simplicity that it is necessary to know only the basic fatigue strength of the material. To provide specific information for the designer, tests must be carried out on the actual joint forms. This is true of structures fabricated by any means, but is particularly relevant in the case of welding. The welding process cannot satisfactorily be scaled down without simultaneously altering some of its effects.

Therefore, fatigue testing of welded components normally involves the use of equipment of much larger capacity than that used for fundamental investigation. The method of loading is also different, the objective being at all times to reproduce as faithfully as possible the type of loading that is likely to occur in service. With this end in view, the loading conditions used in the fatigue testing of welded joints and structures can be reduced essentially to three types:

1. Axial load testing

2. Tests in bending, mainly on specimens in the form of beams

3. Pulsating pressure testing of pressure vessels and pipework.

All the numerous testing machines that are available and suitable for carrying out such tests will not be described here in detail, but it may be useful to describe some of the essential features since, to some extent, the characteristics of fatigue-testing machines have influenced the research work that has been carried out.

Axial load fatigue-testing machines may be divided essentially into three types according to the method by which they are driven, i.e., hydraulically, mechanically, or electromagnetically. Hydraulic machines which give higher loads than those operated either mechanically or electromagnetically are available, but testing speeds are limited.

A mechanically operated machine which has been used extensively in fatigue testing of welded components is the walking beam machine, first developed in the United States at the University of Illinois. The arrangement of this machine is shown diagrammatically in Fig. E1-9. It consists of a simple lever

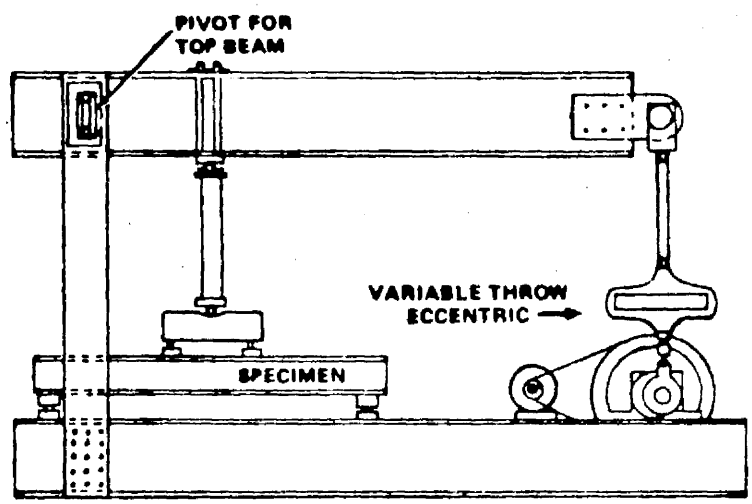


FIGURE E1-9. GENERAL ARRANGEMENT OF WALKING BEAM MACHINE

with the upper beam actuated by a driven eccentric which is continuously variable up to a maximum throw of 4 inches. The load is transmitted to the beam through a dynamometer, which can be used for load measurement, but since the dynamometer also measures any frictional loads in the bearings, it is more satisfactory to adjust the load by using strain gages attached to the specimen. The beam may be used either as a first-order lever, with the specimen mounted in the end grips, or as a second-order lever, which is particularly satisfactory for testing flexible specimens (such as beams in bending) that require a fairly large strain amplitude at lower loads. Figure E1-8 shows the arrangement for the latter case. It should be noted that it is a constant strain amplitude machine, in contrast to the hydraulic machines referred to above which supply constant loads.

Fatigue is a problem of such magnitude in the aircraft industry that often full-scale components, or even entire aircraft, are tested. In one method, the load is applied to the specimen by means of hydraulic jacks in specially constructed test rigs. Another method is to excite a structural component near its resonant frequency by attaching it to a mechanical oscillator and supporting the component at its node points. Because each fatigue test of a large-scale aircraft costs several million dollars, usually only one aircraft is tested.

Special techniques relating to thermal stress testing and low cycle fatigue testing will be discussed in the following sections.

1.2.3 Presentation of Test Results.

1.2.3.1 S-N Diagrams.

Since the beginning of fatigue testing, S-N curves have been the backbone of fatigue data. S denotes stress amplitude or the maximum cyclic stress, and N denotes the number of stress cycles to complete fracture. The linear S versus log N scale is the most common and is used almost exclusively in engineering. (See Fig. E1-10.)

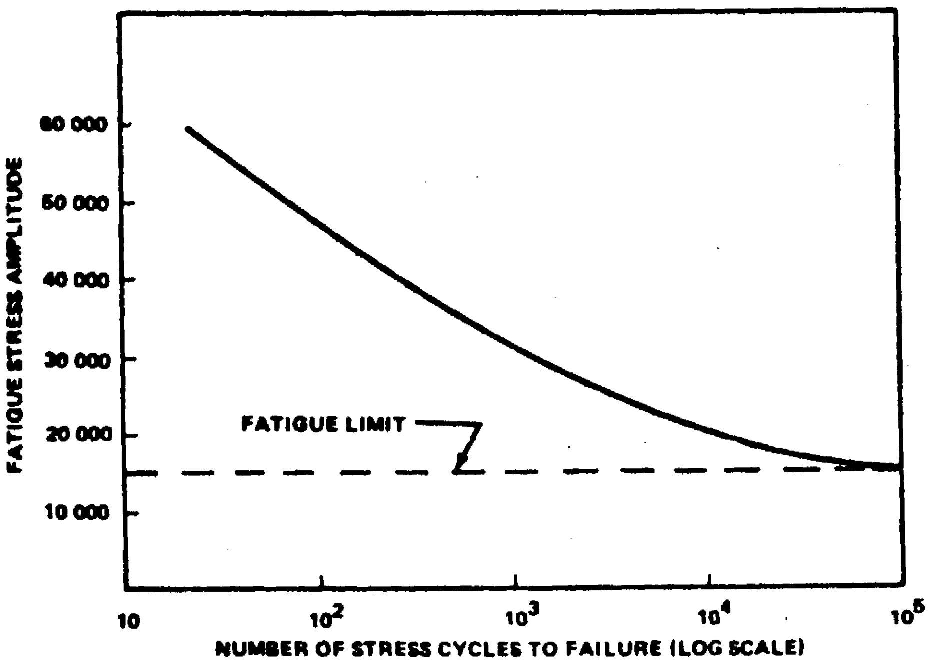


FIGURE E1-10. GENERAL FORM OF S-N CURVE

Several attempts have been made to find general mathematical laws for the relation between load and life, and several equations have been proposed to express the S-N relations more or less empirically. Use of these equations will embody the data in a mathematical form for data reduction, analysis, and standardization of curve-fitting methods. It may also provide some understanding of the S-N relations.

For certain metals and alloys, including the ferrous group, the S-N curve becomes asymptotic to a horizontal line. The stress value corresponding to this asymptote, or the stress corresponding to failure at an infinite number of cycles, is called the fatigue (or endurance) limit.

The fatigue limit of a material tested in axial loading is usually lower than that of the same material tested in reverse (rotating) bending. In axial loading the stress is uniform throughout the cross section; whereas, a large stress gradient exists when a bending load is applied. Thus, in axial loading, it is probable that the maximum stress will occur at a discontinuity in the material. Fatigue tests in torsion or shear loading indicate that the torsional fatigue limit of polished steel specimens is approximately 58 percent of the flexural or tensile fatigue limit. This figure is consistent with the distortion-energy theory which predicts that the shear properties of steels are 57.7 percent of tensile properties.

1.2.3.2 Goodman Diagrams.

The preceding discussion on S-N curves and fatigue limits has dealt with stress cycles that alternated about a zero mean stress. But the stress cycle usually varies about a mean static value that may be positive, zero, or negative. When a cyclic stress varies about a nonzero static value, prediction of failure must consider the combination of static and varying stresses.

Several types of failure diagrams relate the range of operating stress to the material properties in a general manner. All the diagrams indicate that the allowable stress range decreases as the mean stress approaches some maximum value.

The Goodman diagram was the first type proposed, and the modified Goodman diagram is the form most commonly used. Because it consists of straight lines, it is easy to construct. The Goodman equation is

$$S_a = S_e - S_e\left(\frac{S_m}{T}\right)$$

where S_a is the fatigue strength in terms of the stress amplitude, S_m is the superimposed mean stress, S_e is the endurance limit when $S_m = 0$, and T is the ultimate tensile strength. This equation is plotted in Fig. E1-11.

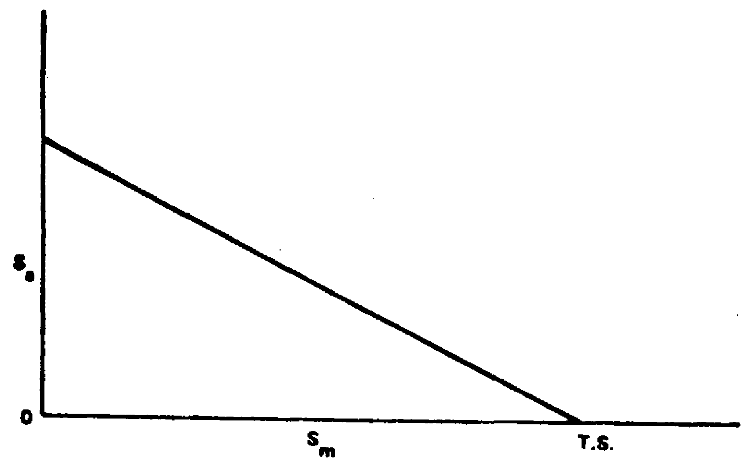


FIGURE E1-11. GOODMAN DIAGRAM

In the modified Goodman failure diagrams (Fig. E1-12), the range of operating stresses is described by three values: mean stress, maximum stress, and minimum stress.

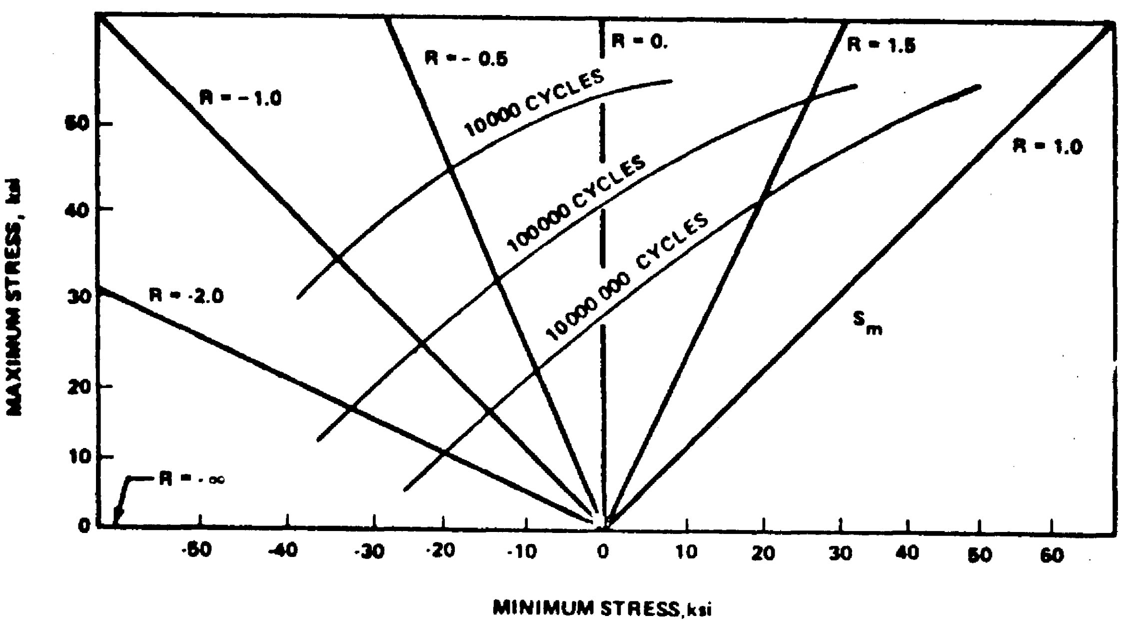


FIGURE E1-12. MODIFIED GOODMAN DIAGRAM

In the maximum-minimum form of modified Goodman diagram, a stress cycle is plotted as a point on the diagram instead of as a line. This form of diagram is advantageous for it requires only the determination of the maximum values of a half cycle; finding the mean cycle is not required.

In the maximum-minimum form of diagram, a stress cycle in which stress is zero is plotted as a point on the line of zero mean stress. Similarly, a stress cycle from zero stress to a tensile value is plotted as a point on the maximum stress axis. Although these points have different mean stress values, they represent equivalent reversed stress cycles. In this form of diagram, the fatigue limit for reversed stress is plotted as a line of constant equivalent reversed stress instead of being a point as in the other forms of failure diagrams.