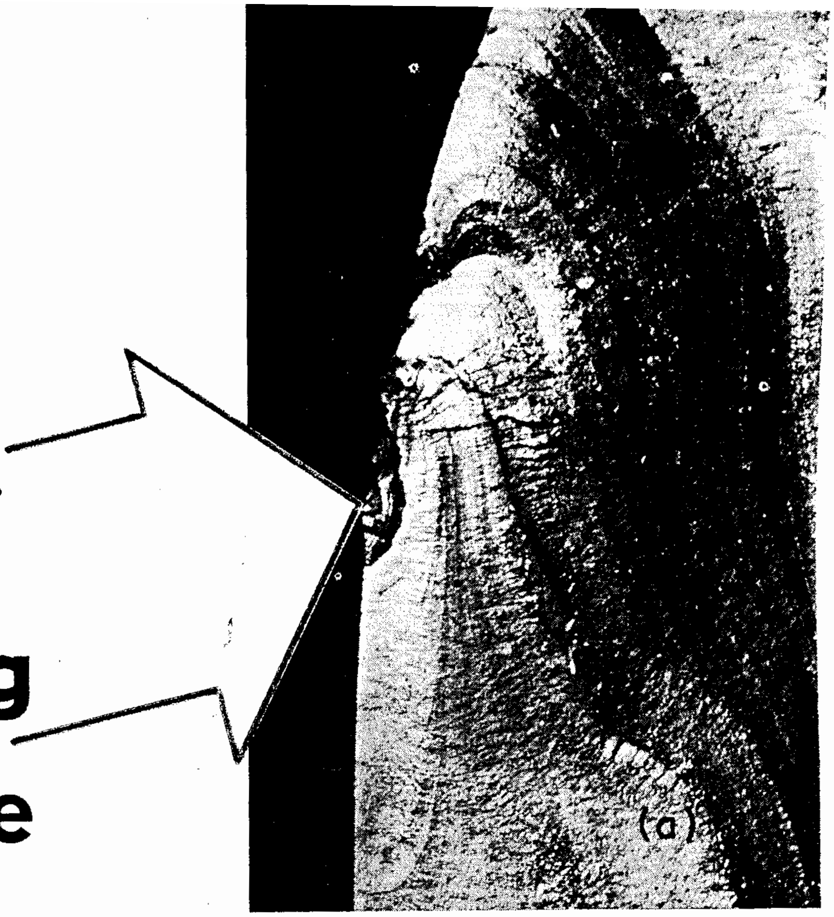

A design guide:

Preventing Fatigue Failures

Part 1 — Basic Factors

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Although fatigue failures have been investigated for more than 100 years, the basic mechanism of fatigue is still unknown. However, many methods have been formulated for the prevention of fatigue failures during expected service life of a part.

This series of articles discusses factors that affect fatigue strength. More important, it outlines methods which are helpful in the design of machine components and structural elements that must resist fatigue loading.

This first article discusses the factors which, in general, influence design for the greatest possible fatigue life. Subsequent articles will discuss geometric stress concentrations, effect of metallurgical and mechanical treatments on fatigue life, calculations for determining fatigue life, and effect of biaxial stresses on fatigue life.

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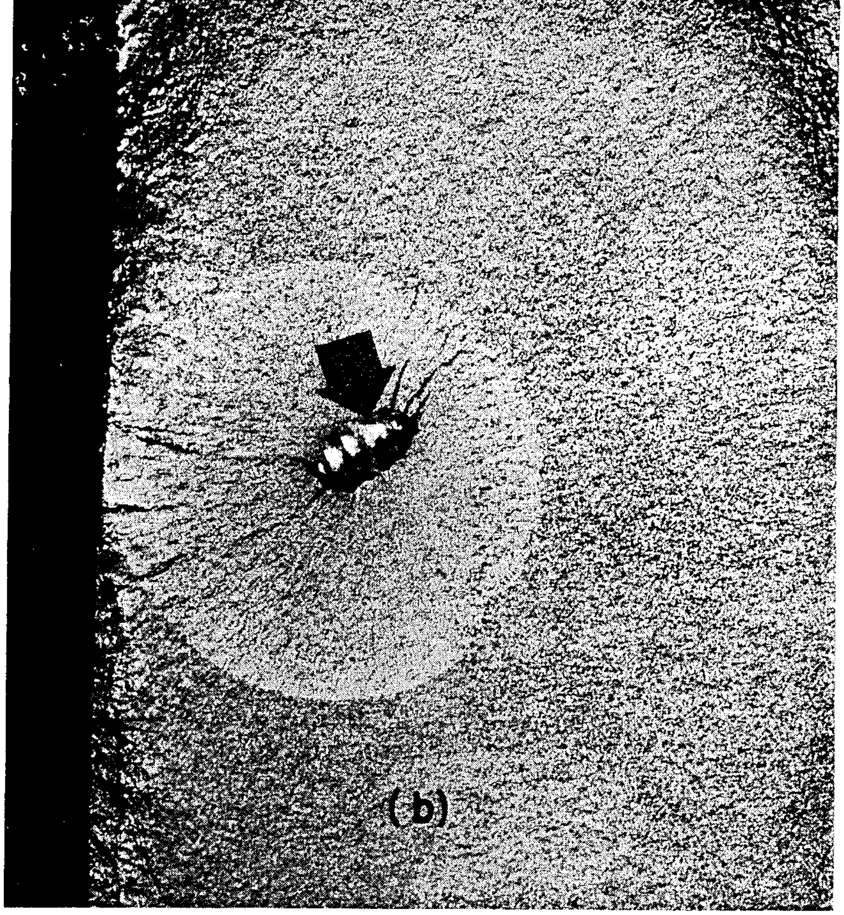

Fig. 1—Fatigue fractures in structural components caused by, *a*, galling at the point indicated by the arrow and, *b*, blowhole in the material.

MOST fatigue failures can be traced to deficiencies in design rather than inadequacies in material or improper manufacture or maintenance. These failures are usually caused by relatively high stress concentrations that might have been eliminated or minimized in the original design with relatively little effort and expense. Fatigue damage in materials is caused by imposed vibratory stresses or by variations in imposed stresses. The damage may range from a submicroscopic, microscopic, or macroscopic crack to a complete fracture.

Fatigue failure usually means the complete fracture of a structure or machine part caused by alternating loads, Fig. 1. However, a fatigue failure may also be defined as the inception of a fatigue crack—particularly if complete fracture of the part will eventually occur.

Generally, fatigue data obtained from laboratory tests of small specimens or assemblies are based on complete fractures of the specimens. These data are of considerable value to the designer, who is often interested in the period between the inception of a fatigue crack and the final fracture.

Failure (fracture) strength depends upon many factors. If the loads are static, the failure strength is closely tied to the ultimate tensile strength, or ultimate yield strength. But if loads are cyclic, the failure strength may range from the full ultimate static strength to a small percentage of the ultimate, depending on life requirements and environment. For example, it is not enough to simply assume that the fatigue strength of a given material is 100,000 psi for 10,000,000 cycles. Such values are usually based on small, highly polished laboratory specimens. Conditions might be such that the allowable fatigue stresses should be not over 15,000 psi for 10,000,000 cycles of loading. Of course, if the part is to be designed for only 10,000 cycles the stresses might be allowed to go as high as 35,000 psi. Fatigue stresses in the given material for other conditions of use might be twice as high. Obviously, any tabulation of allowable fatigue stresses would have to contain many different values for any single material, and include environmental conditions.

No such tabulations are available. However, a great deal of fatigue testing has been done and reported in books and technical papers.[1,2,3] These include both test data and the specific conditions un-

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[1] References are tabulated at end of article.

der which they were obtained.* The designer should start with such data and modify the values in accordance with the conditions for which he is designing. In any case, such test data should be used with great caution.

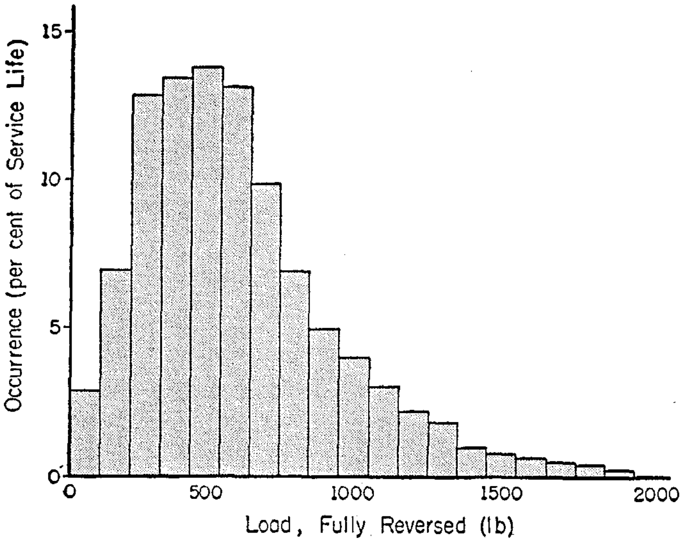
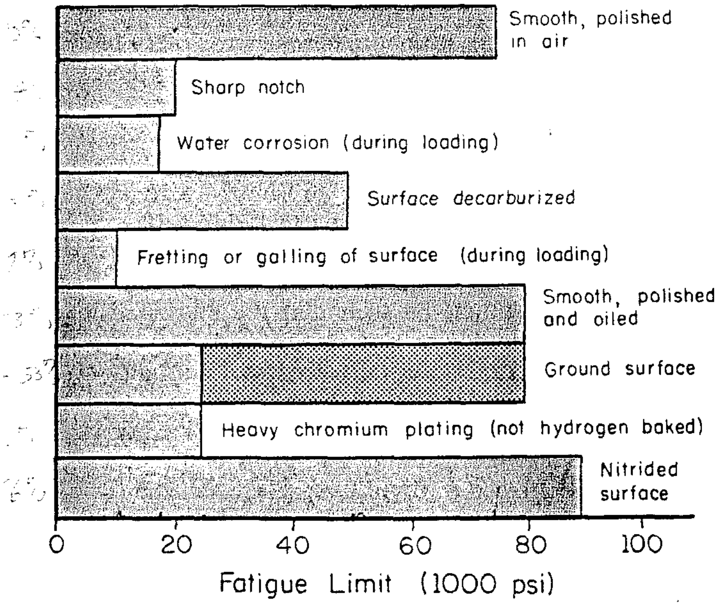


Fig. 2—Histogram of expected fatigue loads on a structural part. The ordinates represent the number of cycles expected for each load interval.



TS = 150,000 psi
↑

Fig. 3—Approximate fatigue limits of SAE 4340 steel hardened to Rc 31 for various surface conditions. The shaded portion of the graph indicates fatigue limits for the normal range of ground finishes.

Three major factors must be considered in designing a machine or component to withstand fatigue loads:

1. Service loads
2. Critical stresses
3. Material behavior

Service Loads

The many factors involved in analyzing service loads require careful evaluation by the design engineer. These factors can best be represented by a cycle-load histogram of the machine, which should represent all conditions, environments, and malfunctions expected during service life. A typical histogram is shown in Fig. 2.

Various loads and the corresponding vibration cycles for each critical component of the machine or structure during the expected life of the component should be determined as completely and realistically as possible. This should include loads induced by improper operation and by malfunction, since service life may be limited by the number and magnitude of loads occurring during infrequent overloads or improper operation. For example, the life histogram of rotating machines (reciprocating engines, steam turbines, turbojets, etc.) should include resonant loads or stresses that may occur while the machine is brought up to operating speed.

For some types of equipment, load measurements may have been made on similar pieces of equipment during typical service operation. In this case, it is possible to extrapolate (cautiously) this information for a new design. More often, however, load histograms are not available to the designer and he must estimate a histogram on the basis of past experience and available test data.

One point which should not be overlooked in constructing a histogram is that in many cases so-called static loads are actually pulsating loads. For example, the centrifugal stresses of rotating parts in machinery running at constant speed are in reality pulsating stresses, since they return to zero every time the parts become stationary.

The histogram shown in Fig. 2 indicates that the structural part must resist fatigue loads of 100 pounds during 3 per cent of its cycle life, 200 pounds for 7 per cent of its life, 300 pounds for 13 per cent of its life, etc., up to 1900 pounds for about 0.2 per cent of its life. Addition of the load frequencies of loads up to and including 1000 pounds indicates that for about 90 per cent of the cycle life of the part, the service load will not exceed 1000 pounds.

Actual stresses are likely to vary over a wide range during the cycle life of a part. This poses one of the most difficult questions in fatigue design—whether or not fatigue damage will accumulate slowly enough for the part to survive the desired number of fatigue-loading cycles.

Critical Stresses

After a histogram has been constructed, a preliminary design can be made. From this design,

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*Comprehensive bibliographies have been published annually, since 1950, by ASTM. They are titled "References on Fatigue."

critical fatigue stresses may be computed.

The following factors should be taken into account when computing critical stresses:

1. All stress concentrations that may exist at the points in question. Stress concentrations introduced by improper handling or by service environments (such as stone ingestion in turbojet engines) should be recognized, as well as those resulting from the design itself.
2. The state of stress; that is, whether stress is alternating or pulsating, or whether it is an alternating stress superimposed on a steady stress. Also, the principal stresses and their phases must be calculated.
3. The effect of stresses introduced inadvertently in the assembly. For example, transportation of parts by rail or truck involves considerable jolting, which causes fatigue stressing.
4. The effect of manufacturing tolerances on stresses.

A stress histogram based on these points should be compared with the fatigue strength of the material to be used for the part.

Material Behavior

To determine if a material will fail under calculated stresses, it is necessary to have knowledge of the behavior of the material under all environmental conditions that might affect fatigue-inducing stresses. This should include the effects of manufacturing processes. Fatigue data—including *S-N* curves

Conditions Which Reduce Fatigue Strength

Cause	Remarks
Stress concentrations due to improper design (small fillet radii in shafts, changes in sections, etc.)	Reduction in fatigue strength depends on the geometric factor and the sensitivity of the material to notches. Reduction can be as high as 75 per cent.
Stress concentrations due to improper manufacturing (file marks, rough machined surfaces, etc.)	Difficult to evaluate, since geometry of the notches is usually nonstandard.
Residual tensile surface stresses caused by grinding	Improper grinding may introduce very high tensile stresses, causing loss of fatigue strength up to 10 or 15 per cent.
Residual tensile stresses due to cold forming	Although beneficial compressive stresses can be introduced by cold forming, tensile stresses are sometimes produced, causing a loss of fatigue strength.
Fretting or galling of surfaces that are simultaneously subjected to fatigue stresses	Fretting or galling can result in a fatigue-strength loss of up to 80 per cent. All clamped or riveted joints are subject to this condition.
Corrosion	Corrosion caused by moisture or liquids can reduce fatigue strength by as much as 75 per cent. Most metals require an adequate surface protection.
Plating	Plating usually reduces the fatigue strength of a part, the amount depending on the type of plating, the thickness of the plate, the method of plating, and the embrittlement-relief treatment. Chromium plating in some instances can cause a large loss in fatigue strength.
Surface conditions introduced by heat treatment (oxide penetration, decarburization, etc.)	Only by the most careful control can the surface be protected during the heat-treating process.
Size	Most published fatigue data on materials are based on small laboratory specimens which do not adequately evaluate the fatigue strength of large parts. Large parts may be weaker than small test specimens by more than 10 per cent.
Speed	Although operating speeds ordinarily have only a minor effect on fatigue life, very high or very low speeds usually reduce fatigue strength.
Shape	It has been found that the shape of a part has some influence on its fatigue strength. Rectangular specimens may be up to 30 per cent weaker than round ones.
Inclusions in materials	Nonmetallic inclusions in high strength steels may reduce fatigue strength to a point considerably below that of relatively inclusion-free steels.
Assembly stresses	Tensile stresses induced by assembly have an adverse effect on fatigue strength.

—published on a material are not sufficient, since such information is usually based on laboratory tests of small, carefully polished specimens.

Seldom, if ever, are the fatigue strengths observed in the laboratory realized in full-scale components subjected to service environments. Numerous factors can reduce the "par" fatigue strength obtained from laboratory specimens, but there are relatively few methods of preventing or compensating for environmental effects. Also, a detailed knowledge of manufacturing processes and service environment is necessary before the structural adequacy of the component can be judged.

The magnitudes of reductions caused by some factors on a given steel are shown in Fig. 3. One factor that, although responsible for a large reduction in fatigue strength, has been overlooked by many designers in the past is fretting or galling at bolted, riveted, pinned, or press-fit joints subjected to alternating loads. Effective stress concentrations of 4:1 to 5:1 have been observed. Making the joint tighter might be expected to improve its strength. However, this only localizes fretting at the edge of the clamped joint and has little benefit on total strength. Some types of joints which are subject to this reduction are illustrated in Fig. 4.

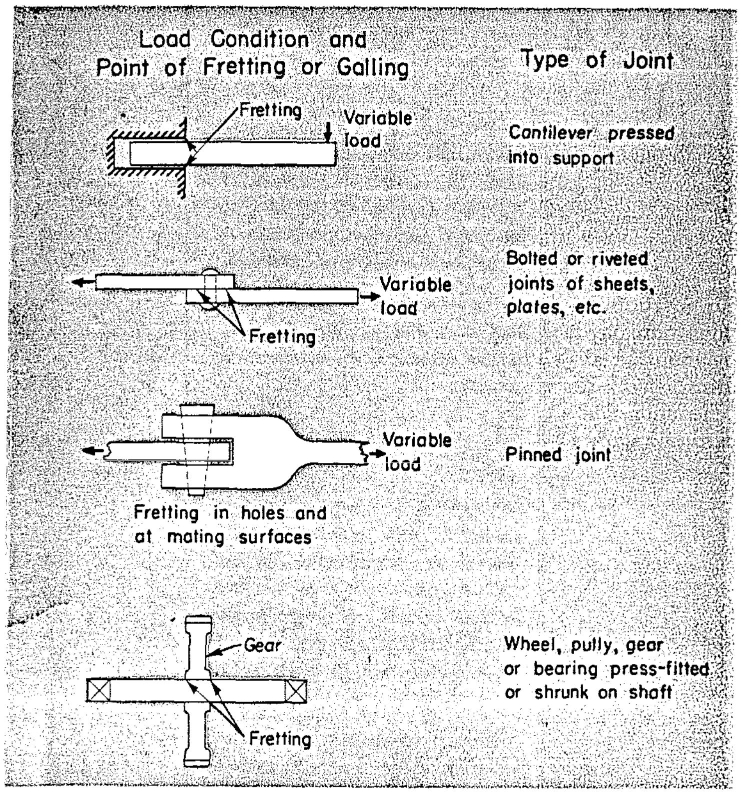

Fig. 4—Various types of joints which are subject to fretting or galling.

Fretting or galling are only two of many conditions that help to reduce the "par" value of a material. Since so many factors can reduce the fatigue strength of a material, the strength of a finished part or machine is usually only a relatively small fraction of the "par" value, unless elaborate precautions are taken in every critical region of the part. In addition, there are so many factors involved in the final strength of most parts, each of which contributes to variation in strength, that there is an inherent scatter or variation in the strength of the final part, regardless of the quality of the material.

Because the estimation of actual fatigue strength of a structure is subject to a wide variety of errors it is necessary, in most cases, to fatigue-test the entire structure—or its major components—for an accurate assessment of its fatigue strength. The testing of full-scale structures, components, or assemblies is usually very costly, since the cost of the assembly is often high, the speed of testing low, and the availability of parts limited. Nevertheless, many engineers believe (and perhaps rightfully so) that this is the only real test. Some engineers even express the extreme opinion that laboratory tests of small specimens have little value. This latter view is incorrect, since the strength of the finished structure or machine is based on the material itself.

Basic Fatigue Strength of Materials

Analyses of fatigue failures that have occurred in service have proved that most failures are caused by factors unrelated to the inherent fatigue strength of the materials. However, this does not mean that the basic fatigue strength of a material is not important. It is the starting point of all structural design.

All materials, even when fatigue tested under ideal conditions, where the variations of all outside influences have been minimized or eliminated show surprisingly large amounts of variation in fatigue life at a constant stress. The amount of variation in basic fatigue characteristics is a direct measure of the quality of the material. This characteristic is one of the basic mechanical properties of materials, although in the past it has often been overlooked. Recent investigations have been undertaken to determine the causes of variation in fatigue characteristics.

This property of materials causes difficulty when tests are conducted to compare materials and processes, or to obtain accurate values of fatigue strength or life. Variations in basic fatigue strength have obscured many important trends in materials or processes.

Part 2 of this series will cover geometric stress concentrations.

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3. H. J. Grover, S. A. Gordon, and L. R. Jackson—"Fatigue of Metals and Structures," Bureau of Aeronautics, Dept. of the Navy, 1954.