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Using Fatigue Information in Design

The design to prevent fatigue failures is often speculative and must be finally checked by testing the component and, in critical situations, by monitoring the actual service performance

by Horace Grover

ABSTRACT—It is impossible to find, for a specific design concern, fatigue information that is entirely adequate for an exact quantitative evaluation. Some of the approaches available for approximate design estimates are described to illustrate the problems that may occur and the considerations important in using available fatigue information in design.

Introduction

The use of fatigue information in design has increased manyfold in the last several years. One factor contributing to this increase is a growing recognition of the importance of obviating fatigue failures, not only to prevent violent catastrophes (as in aircraft, nuclear pressure vessels, etc.), but also to forestall breakdowns whose consequences are mainly economic. Another contributor is the development of significant improvements in stress analysis—both by analytical methods including computer programs and by increasingly powerful tools for experimental stress analysis. A third factor is the growing understanding of important factors in the fatigue process and the accumulation of new fatigue-test data.

All of these developments bring increased recognition that very many parameters must be considered in design to prevent fatigue failure. Most practical problems involve some factors for which there exists incomplete quantitative information, so that estimates and approximations are necessary for any solution. There is not yet in sight a simple, unified approach to design to prevent fatigue failure.

There are, of course, different situations in which a designer may need to use fatigue information to evaluate a structure or component. He may be considering the use of a new material in a part for which there is considerable background information about service loadings and resulting failures. On the other hand, he may be considering a new configuration or new loading requirements about a material for which he has considerable background experience. A third situation is one which involves a change in fabrication which could alter material properties. In all cases, a common approach is to consider the stress and strain excursions at critical locations and to try to estimate the effect of these by available information on the fatigue response of the material. Available fatigue information is mainly from laboratory tests and does not generally include the particular combinations of local stresses and strains of concern; interpolations and extrapolations must be used. These interpolations and extrapolations are based upon empirical relations that are slowly developing from an immense amount of research. At present, there are many uncertainties, so that design to prevent fatigue is often speculative and must be finally checked by testing the component and, in critical situations, by subsequent careful monitoring of actual service performance.

Some Current Approaches

Nevertheless, consideration of developments of the past few years shows much progress and much potential for future progress in the challenges of using fatigue information in design. This progress and the potential can be illustrated by reviewing some particular areas in which there have been significant advances in the past decade.

Low-cycle and Long-lifetime Fatigue

Figure 1 shows some strain–lifetime relations for a steel under fully reversed axial loading. The curves are plotted according to procedures suggested in Ref. 1:

$$\frac{\Delta\epsilon_e}{2} \equiv \text{elastic-strain amplitude}$$

$$= \frac{\sigma'_f}{E}\,(2N_f)^b, \qquad (1)$$

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Paper was presented at 1971 SESA Fall Meeting held in Milwaukee, Wisc. on October 19-22.

$$\frac{\Delta\epsilon_p}{2} \equiv \text{plastic-strain amplitude}$$

$$= \epsilon'_f\,(2N_f)^c, \qquad (2)$$

$$\frac{\Delta\epsilon}{2} \equiv \text{total-strain amplitude}$$

$$= \frac{\Delta\epsilon_e}{2} + \frac{\Delta\epsilon_p}{2}. \qquad (3)$$

In these relations,

$\sigma'_f \equiv$ fatigue-strength coefficient for material
$= 50{,}000$ psi $+ S_u$ (ultimate tensile strength)
$E \equiv$ Young's modulus
$b \equiv$ fatigue-strength exponent for material
$= -0.085$
$\epsilon'_f \equiv$ fatigue-ductility coefficient for material
$= \ln \dfrac{100}{100 - \%RA}$

and
$c \equiv$ fatigue ductility exponent for material
$= -0.60.$

It should be emphasized that these are empirical relations based upon curve-fitting a number of data from laboratory tests of small specimens[*].

The three "points" in Fig. 1 are from some experiments on the material. A first speculation that might be ventured from glancing at this figure is that the curves predict the experimental points rather well. This is misleading: the small slope of the $\Delta\epsilon/2 - N_f$ line means an extreme sensitivity of the lifetime prediction to values assumed for the parameters in the long-lifetime region. While there have been distinct advances in ability to predict constant-amplitude fatigue behavior from more readily determined "static" properties (see, for example, Refs. 2 and 3), these have, by no means, reached a stage of dependability for more than very speculative preliminary design.

Another observation from Fig. 1 is of greater importance. The long-lifetime behavior (beyond the "transition point" where the ϵ_p and ϵ_e lines cross) is mainly influenced by the elastic response; even though local plasticity must exist, it is apparently constrained and directed by the generally elastic field surrounding the fatigue-damage location. In contrast, at short lifetimes (before the "transition point") the plastic-strain amplitude is over riding. This has led to taking low-cycle-fatigue data in strain-controlled tests (in contrast to the older procedure of load-controlled tests). This practice is providing information more pertinent to some design situations and, at the same time, is developing deeper insights into the nature of the fatigue process.

Focusing attention upon the strain behavior has increased interest in the stress–strain hysteresis loop. It has been found that metals generally "shake down" into some dynamic pattern which may denote, for a fixed strain range, a larger stress range (for strain-hardening materials) or a smaller stress range (for strain-softening materials) than estimated from the monotonic stress–strain curve of "static" testing. It appears that fatigue-test information may be more widely applicable when data afford characterization in terms of actual cyclic strain amplitudes rather than of the nominal strain amplitudes estimated from "static" loading.

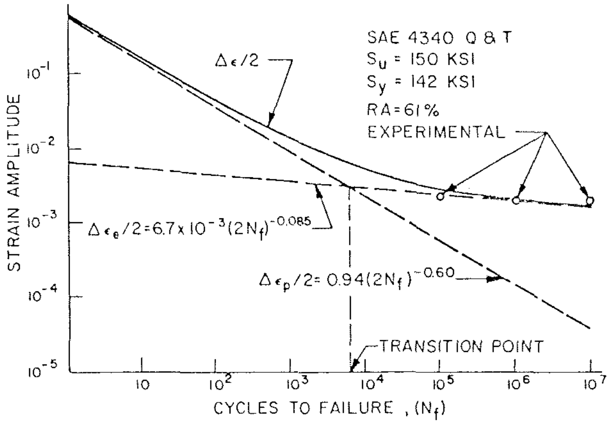

Fig. 1—*Fatigue data in terms of strain amplitudes*

It has long been recognized that fatigue-strength reduction factors (K_f) may differ significantly from "theoretical stress-concentration factors" (K_T). This difference is especially large in the low-cycle region. Recognition of the importance of strain amplitude in determining fatigue behavior leads to the use of strain-concentration factors, particularly in the low-cycle region. Modern computer programs can handle some elastic–plastic calculations and may, in the future, provide more realistic ways of allowance for plastic effects at notch roots.

A great deal of concern in the low-cycle region of fatigue is associated with "thermal fatigue". One expedient here is to associate a term $\alpha\Delta T/2$ (where α is the linear coefficient of thermal expansion and ΔT is the temperature excursion) with strain amplitude. Use of this expedient with data from strain-controlled fatigue tests raises many questions such as the appropriate temperature and cyclic rate for the mechanical fatigue tests, and the importance of constraints in making thermal expansion strains fatigue-inducing. Answers to such questions are likely to require further research and, ultimately, still further sophistication in design procedures.

Thus, considering strain and strain amplitude in contrast to (or in addition to) stress and stress amplitude has led to some improved procedures for design to avoid low-cycle fatigue and some possibilities in regard to thermal fatigue. It has indicated some directions to pursue toward a better understanding of fatigue. It has also raised as many questions as it has answered. Problems not fully answered include: the effect of mean strain, the proper design procedure for strains in a combined stress field, the optimum

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[*] *There is available information for better values of some of the parameters for specific materials and directly determined values can and should be used when available.*

approach to design for thermal cycling, and many others.

Fatigue-crack Initiation and Propagation

Figure 2 indicates another viewpoint of the fatigue process that has recently contributed to design approaches in some situations. The total number of cycles to failure may be considered as

$$N_f = N_i + N_p$$

where N_i is the number of cycles required to initiate a fatigue crack, and N_p is the number of cycles required to grow this to a critical length (l_R) at which it will rupture on the next loading. The initiation of the crack in regard to nominal stresses is much influenced by the stress concentration at which it starts; the propagation stage may be essentially independent of the starting stress raiser. The application of the principles of fracture mechanics[4] has contributed not only to some estimates of the critical crack lengths for rupture, but also to ideas for formulation of crack-propagation rules. The schematic breakdown in the figure is oversimplified: the conclusion of the initiation stage is not readily definable; propagation may involve more than one mode; the critical length for final rupture is not always easy to evaluate. However, for many situations there seems to be a stage of N_i cycles during which a crack forms or a pre-existing flaw grows into a determinable crack and a distinguishable stage of N_p cycles during which the crack grows according to a definable rate to a length which is critical for rupture in one or a very few further cycles. In relating the anticipated behavior of large structures to fatigue information based upon small test pieces, distinguishing these two stages is sometimes important.

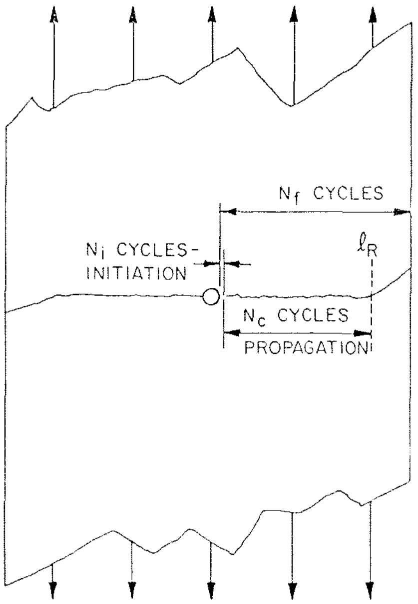

Fig. 2—Two stages in fatigue: crack initiation and crack propagation

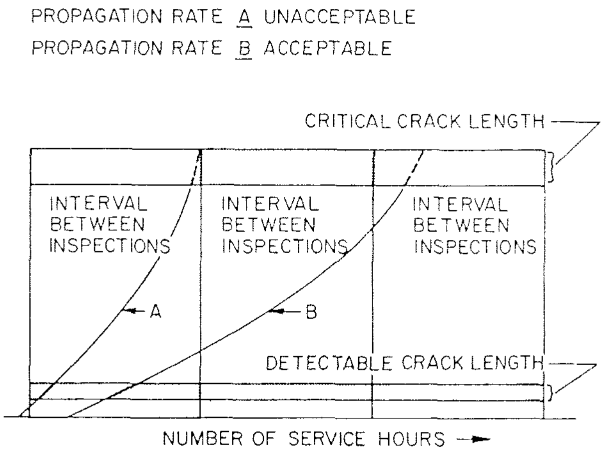

Fig. 3—Crack-propagation rates and inspection intervals

One aspect of this breakdown of the fatigue process into two stages has important implications in regard to "fail-safe" design. A practical concern is that of determining suitable inspection intervals for a component which may be designed closely but is accessible to inspection. This is indicated schematically in Fig. 3. Current practices in regard to fail-safe design are generally empirical with emphasis on demonstrating that a structure can withstand a large defect until subsequent inspection and repair. Conceptually, however, it is most important to design for slow crack growth under expected service conditions.

Other consequences of viewing the fatigue process in separate stages of crack initiation and crack propagation include insights into the effects of mean stress, effects of notches and cumulative damage behavior. These are discussed subsequently. In general, the concept provides some help in design for long lifetimes, but its advantages are less clear for short lifetimes where the plastic-strain amplitude overrides the elastic-strain amplitude.

Design for Uniaxial Loading

Discussion to this point has been, at least implicitly, in terms of completely reversed stress- or strain-controlled loading of unnotched specimens. Frequently, the designer is concerned with a part having a stress concentration and expected to be subject to a combination of mean stress and alternating stress, and for which test results, under exactly pertinent conditions, are unavailable.

Some of the factors involved may be illustrated by considering a design procedure suggested in Ref. 1. This scheme is mainly suitable for long lifetimes (beyond the "transition point" in Fig. 1). Consider three criteria: general yielding, fatigue-crack propagation, and fatigue-crack initiation. As a criterion for yielding, suppose

$$S_a + S_m \geq S_y. \tag{4}$$

As a criterion for crack propagation, assume

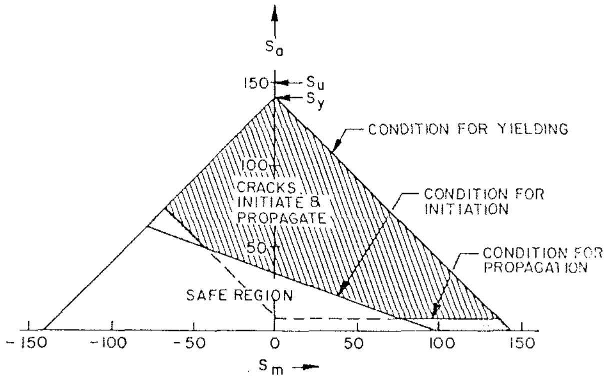

Fig. 4—A schematic fatigue-design diagram

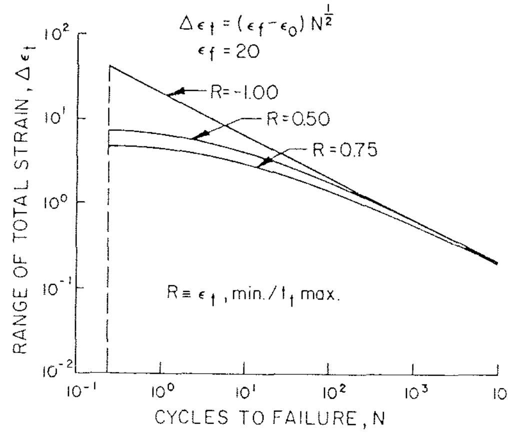

Fig. 5—Mean strain, strain range and lifetime

$$S_{ta} = S_{\mathrm{max\ tensile}} - S_m \geq S_{pc}. \qquad (5)$$

As a criterion for crack initiation, assume

$$S_a + \frac{m}{\sqrt{2}} S_m \geq \frac{S_N}{K_f}. \qquad (6)$$

In these relations:

S_{pc} = a material parameter which may be obtained experimentally or taken as an approximate value from 3 to 10 ksi
m = a material parameter, from experiment or taken as an approximate value of about 0.5
S_N = fully reversed axial fatigue stress for an unnotched specimen for the desired lifetime
K_f = fatigue-notch factor for whatever stress raiser is involved—obtained from experiment or by estimation from K_t (the theoretical stress-concentration factor).

A plot of S_a vs. S_m from these assumed relations and with S_{pc} = 10.0 ksi, m = 0.5, S_N = 70 ksi, and K_f = 2.0 is shown in Fig. 4. This plot provides the designer with estimated values for regions of safe design. It should be noted that relations other than the linear ones above can be used as considered desirable—others have been suggested and actual test data, when available, are most desirable.

For conditions such as low-cycle fatigue, in which the plastic strains are significant in comparison to elastic strains, there are several possibilities. In some situations, stresses and strains do not settle down into a repetitive pattern and cannot be treated simply. One important subclass of such problems is that of thermal ratcheting. We will omit further account of such situations. One suggestion for conditions in which stresses and strains do settle down into a repetitive pattern is that the effect of mean strain, ϵ_o, on the total-strain range, $\Delta\epsilon_t$, for N cycles may be estimated by

$$\Delta\epsilon_t = (\epsilon'_f - \epsilon_o) N^{-1/2} \qquad (7)$$

where ϵ'_f is approximately the static fracture ductility (but may be better represented by curve fitting for fully reversed strain tests). Figure 5 illustrates results from this relation for controlled-strain loading. For load-controlled tests that extend into regions of macroplasticity, the mean stress may "shake down" to have a negligible effect. The distinction between criteria for crack initiation and for crack propagation in the low-cycle region is not as extensively explored as for long-lifetime fatigue: in many situations, this distinction may be relatively less important for short lifetimes.

Thus, consideration of (1) the importance of strains as well as stresses, particularly in low-cycle fatigue, and (2) distinction between crack initiation and crack propagation, particularly in long-lifetime fatigue, has led to more sophisticated approaches in design for uniaxial loading. These approaches involve more detail in fatigue information, such as tests with stress control and measurement of strain, tests with strain-control and measurement of stress, cyclic stress–strain data, distinct failure criteria (cracking or rupture), more detailed consideration of fatigue-strength reduction by notches, etc. The modern approaches also involve more extensive evaluation of stresses and strains in structures such as the use of elastic–plastic computations in local regions. Identification of values computed for the structure with values (computed, often by extrapolation or interpolation) from laboratory fatigue-test data may involve pitfalls in the application of such empirical relations as eqs (1) through (7).

Fatigue Under Multiaxial Conditions

Many, if not most, structural components operate under conditions of "combined-stress" loading. Criteria for fatigue behavior under combined stresses have been the subject of much research, especially for long-lifetime fatigue.[5] A widely used formulation is in terms of an equivalent or effective stress

$$\sigma_{\mathrm{eff}} = [(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\tau_{xy}^2 + 6\tau_{yz}^2 + 6\tau_{zx}^2]^{1/2} \qquad (8)$$

where σ_x, σ_y and σ_z represent stresses perpendicular to three orthogonal planes and the τ's represent shearing stresses on these planes. If cyclic loadings in the three directions are in phase, one may compute an effective stress amplitude and a mean effective stress and use these values in a relation such as eq (6) for crack initiation. There have been suggestions of a modified shear-stress rule and of a modified octahedral-stress rule; the modified rules utilize an additional parameter to be determined experimentally.* One advantage of separating the fatigue process into at least two stages is that different allowances for combined stresses may be used for the different stages; thus, an "effective" (octahedral shear) stress may be used for initiation, but a maximum tensile-stress criterion retained for propagation.

For low-cycle fatigue, plastic strain becomes an important consideration. Even under uniaxial loading, there are biaxial or triaxial strains—this complication may be implicitly included, for uniaxial loading, by using strain-controlled uniaxial test data. For multiaxial loading in a region where there may be significant plastic strain, there are many conceivable variables. Manson[6] has discussed some of the considerations and has speculated on the possibility of using an effective strain range, analogous to an effective octahedral-shear-stress range for long-lifetime fatigue. However, there exist few test data on low-cycle fatigue under multiaxial loading and present suggestions for design under these conditions must be considered speculative.

Other Concerns in Fatigue

As outlined in the preceding discussion, there are appropriate procedures for design to withstand uniaxial, constant-amplitude (of either stress or strain) loading; there are also (at least speculative) procedures for design estimation under multiaxial loading. However, there are, in practical situations, many problems for which these design approaches are approximate and uncertain.

STRESS CONCENTRATIONS—A notched member has, in the region of elastic behavior, a theoretical stress-concentration factor

$$K_t \equiv \frac{\sigma}{S_{\text{nom}}}$$

where σ is the peak stress at the root of the notch and S_{nom} is the nominal stress (P/A for axial loading) at a distance from the notch. At high loads, there is local yielding at the region of stress concentration; an approximation for the stress-concentration factor may be estimated as

$$K_\sigma = 1 + (K_t - 1)\, E_s/E \tag{9}$$

where E_s is the secant modulus and E the elastic modulus. A strain-concentration factor may be estimated by

$$K_\epsilon K_\sigma = K_t^2. \tag{10}$$

Figure 6 shows values of K_σ and K_ϵ so computed for an aluminum alloy. It is found that dividing the nominal stress by K_t or by K_σ and using fatigue data from tests on unnotched specimens usually gives conservative estimates for the behavior of notched specimens. Closer predictions for the notched specimens are often obtained from using an "effective stress-concentration factor"

$$K_{\text{eff}} = 1 + \frac{K_\sigma - 1}{1 + a/r} \tag{11}$$

where r is the notch root radius and a is an empirical material-property value (ranging from about 0.002 in. for a very hard alloy to about 0.01 in. for a soft metal).

Thus, there exist relations for estimating the fatigue behavior of parts with geometrical notches. These relations account for behavior such as local yielding and for the effect upon the fatigue response of the stress or strain concentration, but in an empirical and only partly understood manner.

Modern computation methods afford the possibility of calculation of actual stresses and strains at the roots of notches (of simple geometries) and may suggest other characterizations than factors such as K_t, K_σ, and K_ϵ. Improved techniques of testing provide better possibilities for separating crack initiation (presumably much influenced by stress-concentrating notches) and crack propagation (presumably little influenced by the starting notches). These developments may clarify the "notch-size-effect" and provide more satisfactory means of allowance for this in design. At present, the most desirable procedure is to obtain an experimental value for K_f and utilize relations such as eqs (9) through (11) only as rough guides.

In addition to geometrical stress raisers, there are discontinuities of metallurgical structure, such as inclusions, fiber orientations, weld beads, etc. These are known to affect fatigue, but allowance for them is almost wholly on the basis of experience.

CUMULATIVE FATIGUE DAMAGE—Many structural parts do not operate under conditions of constant-load amplitude or of constant-strain amplitude. For nearly 50 years, efforts have been exerted to develop means of estimating lifetime under conditions of variable-amplitude loading. Most of these have focused upon

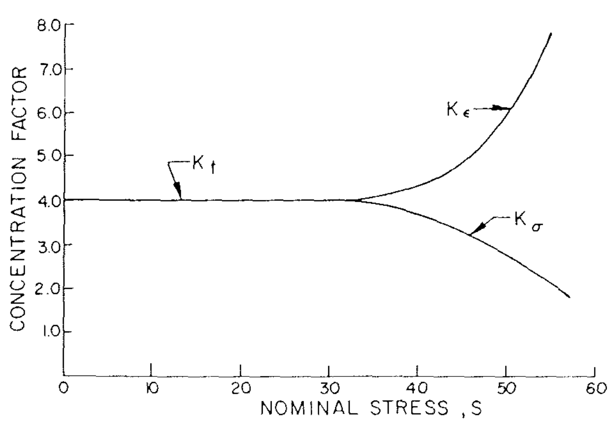

Fig. 6—Stress and stress-concentration factors

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* *Modifications seem particularly necessary for anisotropic materials.*

defining a damage factor to be associated with each amplitude of a load spectrum. To date, such efforts have had limited success from the point of view of the designer.

The most widely used approach (on account of its simplicity) is the Palmgren-Miner formula that anticipates failure when

$$\sum_i n_i/N_i = 1 \qquad (12)$$

where n_i is the number of cycles incurred at stress condition i and N_i the number that would produce failure if run at this condition alone. Experiments have shown values of the summation $\Sigma n_i/N_i$ as high as 8 (which means the estimate highly overconservative) and as low as 0.5 (which means the estimate unconservative).

A method suggested by Corten and Dolan[6] estimates the total number of cycles that can be withstood as

$$N_g = \frac{N_1}{a_1 + a_2(S_2/S_1)^d + \ldots + (S_n/S_1)^d} \qquad (13)$$

where

N_1 = number of cycles to failure at highest stress level, S,
a_i = n_i/N_g,
d = empirical parameter from experiment (the inverse slope of the S-N curve as modified by the cycles at S_1).

Relation (13) is slightly more cumbersome to use than eq (12), requires more "input" (a value for "d"), and gives somewhat better estimates of lifetime.

While such relations permit an estimate of service lifetime, it is well known that the estimates may be seriously inaccurate. Consequently, for engineering purposes, computations of lifetime under variable-amplitude loading are used only in preliminary design. For final evaluation, a better estimate is made on the basis of simulated-service testing which is described in another paper.[7] Meanwhile, studies continue toward formulation of improved calculation procedures based upon more extensive data and more detailed understanding of the fatigue process.

TIME-DEPENDENT FACTORS—Long-lifetime fatigue at room temperatures and under noncorrosive conditions seems essentially time independent—failure depends on the number of cycles and not on cyclic frequency. At elevated temperature, creep and creep rupture occur even under steady loading. A scheme sometimes used for design, when both creep and fatigue may exist, is to suppose that failure will occur when

$$\left(\frac{S_a}{S_f}\right)^2 + \left(\frac{S_m}{S_R}\right)^2 = 1 \qquad (14)$$

where S_a is the alternating stress amplitude, S_f is the fully reversed stress amplitude that would produce failure in a selected time (t = number of cycles/cyclic rate), S_m is the mean stress, and S_R is the steady stress to creep rupture in time t. This relation seems to fit a number of situations in which the loading is sinusoidal and there is no strong creep-fatigue interaction. However, there are numerous practical situations for which such conditions do not apply; nonsinusoidal loadings which involve significant hold times, circumstances in which creep under cyclic loading is significantly different from that under steady loading at the same mean stress, etc. However, information about fatigue at high temperatures and under multiaxial loading is not yet adequate for quantitative design.

Corrosion may also interact with fatigue to result in time-dependent as well as cycle-dependent considerations. Here, also, available information is not yet adequate for dependable design.

Discussion

The preceding review of some current approaches to using fatigue data in design suggests considerable progress in the past several years. We have advanced to viewing fatigue differently for low-cycle and for long-lifetime needs, to considering (at least in long-lifetime situations) differentiation between crack initiation and crack propagation, and to allowing different design criteria for yielding and for crack initiation and for crack propagation. Allowances for geometric stress concentration have been extended beyond the simple use of a theoretical stress-concentration factor. Some considerations in regard to design for thermal cycling have been advanced.

At the same time, it appears that design practices have not been greatly simplified. More fatigue information and more complex stress analyses are needed for utilizing modern design knowledge than was the case a decade or two ago. In fact, increasing knowledge seems to increase the importance of consideration of numerous details and to make design to avoid fatigue failures increasingly sophisticated.

The relevance of this to design is a little more def-

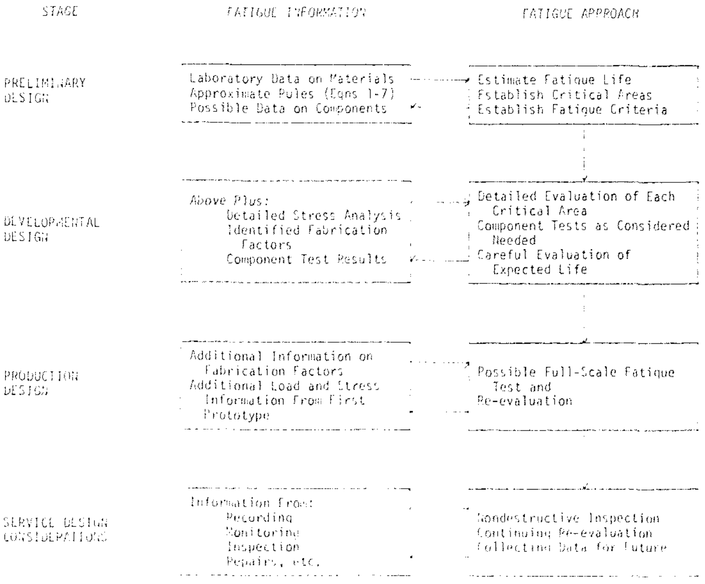

Fig. 7—Various stages of design

inite upon consideration of various stages of design engineering. The schematic diagram in Fig. 7 shows one breakdown to avoid fatigue failure. Each of the four stages indicated is supposed to be carried out (going back and forth between fatigue analysis, changes in configuration, and/or material, and/or fabrication practices) until the results are deemed acceptable. Then design proceeds to the next stage, with the eternal possibility of being forced "back to the drawing board" of a preceding stage.

Preliminary design is mainly dependent upon available background information (as to expected loads and functions as well as fatigue properties). The fatigue information will often be just laboratory data on small specimens (unnotched or notched by simple geometrical discontinuities). Needed values may have to be obtained by interpolation or extrapolation by such relations as eqs (1)-(3) and lifetime estimates made by such relations as eqs (4)-(6) and (12)-(14). Resulting estimated lifetimes must be considered very approximate; however, if these are not significantly greater (say, by a factor of 20) than considered necessary, a redesign should be made. The preliminary design stage should also define critical areas to be watched in succeeding stages. Of course, fatigue-design criteria (infinite life, safe-life, fail-safe) should be selected at this early stage.

The stage listed as *developmental design* is particularly difficult to characterize in any general way. Here, a detailed stress analysis and identification of "fabrication" factors (methods of forming, of joining, of assemblage, etc.) provide a good deal of additional information and very many more items for concern in fatigue analysis. Often, the most careful evaluation of critical areas discloses uncertainties. Some of these may be resolved by fatigue tests of fabricated components. The general background of material fatigue behavior, part of which has been outlined in the preceding sections, is helpful in guiding such tests although it may be inadequate to predict lifetimes. The result of the "developmental design" evaluation of expected lifetime should be considered very critical in the decision to go into production.

During *production*, several items of added information may warrant a re-evaluation of fatigue. Careful checks of quality control may show differences (in tolerance, in finish, etc.) between the "custom-made" components previously tested and those expected from production runs. When a first structurally complete prototype is available, testing (even under static loads) may indicate variances from the previous stress analysis. The first prototype subjected to service may indicate somewhat different loads than previously anticipated. All such factors should be considered in a re-evaluation of fatigue-life expectancy. At least in situations where fatigue failure may be catastrophic, a full-scale fatigue test of an entire structure may be necessary. Further discussion of this will be given in a subsequent paper in this session.

Design to prevent fatigue should continue through the *service* lifetime of a machine or structure. During this period, additional information becomes available from records (which may include intentional monitoring of loads), from inspections (which may be periodic and, at least, partly set by fatigue considerations), from repairs of failures (hopefully minor) and even from reassignment of use (as in new missions for older aircraft). Such information may require reassignment of inspection plans, as well as re-evaluation of fatigue-life expectancy. Moreover, information from service is a major help in design of a new component or structure.

Conclusions

Design to avoid fatigue failure rests presently (and for the foreseeable future) upon identifying values of excursions of stress and strain at critical points in a structure with values estimated to be tolerable on the basis of available information about the material involved. Usually, this involves interpolation among or extrapolation from available information. Rules for interpolation of material properties are based largely upon data from laboratory tests of small specimens under simple loadings. Extrapolation on the basis of such rules is dangerous (although sometimes necessary in the absence of any alternative procedure). Hence, quantitative estimates of fatigue lifetime must be considered speculative and suitable mainly for preliminary design considerations to be eventually checked by experiments on a prototype structure. The estimates can be helpful in making some early choices, and in guiding structural tests.

There are many areas in which fatigue information and dependable rules for using fatigue information in design are incomplete. At least four areas, important in real structures and difficult to evaluate on the basis of present fatigue information, are (1) behavior under variable-amplitude loading, (2) behavior under multiaxial stress and strain conditions, (3) proper allowances for metallurgical "stress raisers", and (4) elevated-temperature effects with the involvement of thermal stress and/or creep. Better design approaches will undoubtedly develop from additional research in these areas. Priorities for research could well be established by mutual agreement of design engineers and fatigue-test engineers. Since the major hope for utilizing material-property information in design lies in stress analysis, closing the gaps between design needs and available material-strength data is a worthy challenge to members of SESA.

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