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A UNIFIED TECHNOLOGY PLAN FOR FATIGUE AND FRACTURE DESIGN

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PAPER presented at the 12th Symposium of International Committee on Aeronautical Fatigue in London, July 1973

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16. Abstract

An integrated research program is proposed that seeks to improve the technology of designing against fatigue and fracture and to develop a computerized capability for assessing the adequacy of a given design. Both fatigue life prediction and damage tolerance considerations are incorporated. The research for each of these considerations is organized to account for material behavior, the effect of structural configurations, the cumulative effects of the operating loadings, and, hopefully, for the effects of environment - temperature and corrosion. Obviously, such an ambitious program cannot be carried out by any single organization. Much valuable research is being done and will continue to be done by industrial, academic, and government laboratories throughout the world. Their accomplishments will be vital to the overall effort and should be incorporated as appropriate. The goal is to achieve a viable fatigue and fracture design procedure for any practical problem. The overall program is outlined, assessments are made of the state of the art, subgoals are proposed, and means for achieving them are suggested.

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A UNIFIED TECHNOLOGY PLAN FOR FATIGUE AND FRACTURE DESIGN

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ABSTRACT

Present procedures for designing against fatigue and fracture in aircraft depend heavily on past experience and on expensive and time-consuming ad hoc tests. Widely used analytical procedures are recognized as being deficient in their quantitative predictions. The existing technology is not always utilized to the extent possible.

Consequently, aircraft structures frequently develop significant fatigue problems requiring expensive retrofits, inspections, and repairs. Historically, many of the deficiencies developed early in the service usage of a given type. In a few cases the aircraft structures were so grossly deficient that the usefulness of the vehicle was jeopardized. Clearly, such problems are attributable to an inadequate technology or to improper analysis during design.

In many cases of military aircraft, the mission changes significantly during the service life and economic constraints force use of aircraft beyond their scheduled lifetimes. Again, improved analytical tools are needed to predict the impact of such actions on structural integrity, inspections, and costs.

An integrated research program is proposed that seeks to improve the technology of designing against fatigue and fracture and to develop a computerized capability for assessing the adequacy of a given design. Both fatigue life prediction and damage tolerance considerations are incorporated. The research for each of these considerations is organized to account for material behavior, the effect of structural configurations, the cumulative effects of the operating loadings, and, hopefully, for the effects of environment – temperature and corrosion. Obviously, such an ambitious program cannot be carried out by any single organization. Much valuable research is being done and will continue to be done by industrial, academic, and government laboratories throughout the world. Their

accomplishments will be vital to the overall effort and should be incorporated as appropriate. The goal is to achieve a viable fatigue and fracture design procedure for any practical problem. The overall program is outlined, assessments are made of the state of the art, subgoals are proposed, and means for achieving them are suggested.

INTRODUCTION

The continuing trend toward higher performance in new aircraft dictates that all possible measures be used to save weight. However, the very high cost of these aircraft also dictates that they be kept in service with high reliability for long periods of time. At the same time, the structures of these vehicles tend to be much more complex and larger than their predecessors. Clearly, the designers of new aircraft need reliable tools to satisfy these conflicting requirements.

Designers frequently use computers to assist them with the huge number of calculations required. Many companies and institutions have developed computer programs for the stress analysis of very complex structures. More recently, the computer has been adapted to design the structure to satisfy several criteria simultaneously (Ref. 1). Among the considerations that must ultimately be included in this design scheme is the assessment of structural integrity for the scheduled lifetime of the vehicle. However, today's technology in this important area is characterized by a rather heterogeneous assortment of rules of thumb, intuition, judgment, analysis, and only a semblance of theory. Certainly, no rigorous solutions are available for designing adequate parts.

Judging from the frequency of service failures, current technology is either inadequate or its application is deficient, or perhaps both. Many institutions are conducting vital research in this area, and many symposia are held to disseminate the results. The International Committee on Aeronautical Fatigue is one of the foremost groups for such information exchanges and is, therefore, a most suitable forum for discussing plans for technology improvement.

A practical discussion of a technology as broad and complex as this one requires that the problems be organized into comprehendible and manageable units, then, that the state of the art be assessed, that goals for improvement be proposed and, finally, that methods be suggested for achieving the desired improvements. This paper seeks to satisfy at least parts of these needs. The remarks contained are intended to be applicable to metallic structures. Composite constructions will undoubtedly require a parallel effort because of their multiphased constituents and highly anisotropic behavior. The technology for composite materials is not considered here. Although the design of aerospace structures is discussed, the principles are expected to be applicable to many other transportation systems, stationary machinery, and civil engineering structures.

COMPETING DESIGN PHILOSOPHIES

Certification requirements for aircraft structural integrity fall into two broad categories – safe-life and damage tolerant. The safe-life philosophy is, of course, the older of the two and is widely used to predict the overall fatigue life of a fleet of vehicles. Analyses are based on simple concepts; data are in the form of S-N curves established through tests of simple specimens; and ad hoc fatigue tests of critical joints, major components, and complete airframes demonstrate adequate life and define probable locations for service failures. Little or no account is taken of the behavior of cracks. "Failure" is subject to many interpretations, but usually refers to some significant crack which, if detected, would require corrective action before additional service is accrued. This philosophy is the basis for most European requirements and, until recently, for all U.S. military requirements.

For many years, the American civil requirements (Ref. 2) have employed fail-safe design which requires that adequate residual strength be maintained in the event of complete failure or obvious partial failure of a structural part. Recently revised American military requirements (Ref. 3) now require that military aircraft be designed to be "damage tolerant." These new military requirements are much more far-reaching than the earlier civil requirements. They differ from the civil requirements in that they require the structure to have specified "operating intervals" during which cracks that have just escaped detection at a previous inspection will not grow to critical size before the next scheduled inspection. These requirements imply analytical techniques that are much more sophisticated and will undoubtedly spur much new activity to provide the upgraded technology. However, the new requirements also require that parts that cannot be inspected or that may not be capable of being rendered damage tolerant, be designed to have a specified safe life.

The damage tolerant design depends on the stress intensity analysis of cracked configurations; materials properties are in the form of rates of crack propagation and fracture toughness; and ad hoc tests are conducted on representative structural components to demonstrate adequate resistance to crack propagation and adequate residual strength. In contrast to the safe-life philosophy, this philosophy concerns itself only with crack behavior, but usually ignores how or when the crack was initiated.

These observations suggest that both philosophies, safe-life and damage tolerant, will be applied seriously for the foreseeable future; neither is completely satisfactory by itself; and both require improvement in predictive capability to achieve improved future designs.

Regardless of which design philosophy is considered, four major parameters are proposed as being useful and necessary. These are: properties of materials, effects of configuration details, effects of variable amplitude loading, and the effects of the thermal and chemical environment. To a fair first approximation these parameters can be considered to be mutually exclusive, but strong synergistic effects are obviously present. The solution of a given design problem requires consideration of each of the four parameters.

The remarks in this paper are grouped according to the four parameters just mentioned. Because of the complexity of the problem areas, generalities are employed which may not be literally true for individual situations, but are expected to be representative of the state of affairs. In each instance, the current state of the art is evaluated, a proposal is made to upgrade the technology, and a quantitative goal is offered to focus the effort. These remarks reflect some of the special requirements associated with computerizing the technology. Finally, sample applications are described to show how a designer may approach the trades he may have to make among competing design considerations.

Selected accomplishments by the author's colleagues toward these ends have been summarized in an earlier paper (Ref. 4).

MATERIAL PROPERTIES

Designers require at least three classes of material properties in order to make intelligent choices in the design of highly reliable structures. These are fatigue properties, crack propagation resistance, and fracture toughness. Many tests are conducted in many organizations to provide these data and to certify that given lots of materials satisfy minimum requirements. Generally, these data remain in the files of the generating organization, but several continuing efforts are applied to consolidating and disseminating such data (Refs. 5-9).

As valuable as such data compilations may be, they are not well suited for use in computers. For this purpose, a much more convenient form would be a set of standardized empirical equations fitted to the data.

Fatigue Properties

To characterize fatigue behavior, the well-known S-N curve is the most frequently used data format. Because the S-N curves must be known for each combination of material, mean stress (or R), maximum stress, and stress concentration, a very large number of tests is required. Early investigators such as Goodman (Ref. 10) and Gerber (Ref. 11) foresaw the need to standardize the cross plot of S-N curves to show the relation between alternating and mean stresses for given lives. However, the technology still lacks generally accepted equations for organizing the data.

Computerized data-handling systems appear ideally suited for developing standard equations at this time. Large quantities of data have been encoded (Ref. 12) and should be used to develop adequate formulas. Once standardized expressions are developed and demonstrated to be capable of representing the data, they should become very effective in anticipating fatigue behavior for the full range of parameters after only a few selected tests are conducted. If such efforts were successful, the economies affected in conducting future tests should more than repay the cost of the research required for their development. Even if the total fatigue and damage tolerant design process were not reduced to a computer operation, working with analytical expressions should be much more convenient and reliable than working with masses of plotted data.

Fatigue Crack Propagation

Crack propagation data are usually plotted as da/dN, the rate of growth per cycle, against some measure of stress, usually the stress intensity factor, K, calculated by a modification of the Griffith-Irwin analysis.

Many "laws" have been proposed to characterize such data. Among them, the Paris (Ref. 13) equation proposes

$$\frac{da}{dN} = C\ (\Delta K)^{n} \tag{1}$$

where n was originally thought to be 4. Although this law has been widely quoted, the exponent has been shown to vary significantly, and the expression is not capable of predicting the threshold value below which many investigators have found no crack growth, nor the more rapid rates that must accompany high stresses near the critical fracture stress. Forman (Ref. 14) has proposed an expression

$$\frac{da}{dn} = \frac{C\ (\Delta K)^n}{(1 - R)K_c - \Delta K} \qquad (2)$$

which satisfies the latter objection, but does not predict a threshold. The Elber (Ref. 15) crack-closure concept may provide a rational basis for improved predictions but requires further development to become a quantitative prediction tool.

Large quantities of data are being generated to characterize crack propagation behavior and, again, standardized expressions fitted to the data would be of immediate benefit to users of the information and should help to reduce the amount of testing required to characterize materials in the future. If computerized analysis is ultimately to become a reality, such equations are clearly a requirement.

__Fracture__

The Griffith-Irwin brittle fracture concepts (Ref. 16) have been actively developed by a large number of investigators during the past two decades. A most attractive rationale for fracture has been developed. Because "brittle" failure is easy to analyze and usually represents the "worst case" for a given material, the bulk of research to date has been devoted to forcing a material to fail under plane strain conditions to simulate brittle behavior. Standard test methods (Ref. 17) are available, but have severe limitations on how they are applied and even then do not always generate "valid" data.

However, the Griffith condition of completely brittle (K_{Ic}) failure occurs in practical structures only infrequently and many investigators have come to realize that if K_{Ic} data were used in design, very severe weight penalties would be suffered. Consequently, plasticity and "plane stress" behavior at crack tips have been the subject of much research in the past few years. The underlying rationale is usually to modify the stress intensity analysis to, in principle, account for the nonlinear behavior, and thus to extend fracture considerations to the nonbrittle failure case. Much remains to be done before this technology is ready for general use by designers. Fracture theories and test procedures should be developed that are capable of characterizing all practical materials in all commonly used thicknesses.

Material Selection

The three-dimensional diagram in Figure 1 has been proposed (Ref. 18) to illustrate the choices a designer must make to select the best material for his structure. The "operating surface" for a given material intersects the vertical axis ($N = 0$, $a_o = 0$) at the ultimate tensile strength-density ratio. It intersects the right-hand vertical plane ($a_o = 0$) along the S-N curve and along the left-hand vertical plane ($N = 0$) along a curve of residual strength against crack length. Away from the coordinate planes the surface represents the combination of stress and life that accompanies any given initial crack length. For practical situations, the initial crack length will normally be the threshold sensitivity of the inspection procedures employed in manufacture or in service and the life will be the desired inspection interval.

For the simple case shown (simple configuration and $R = 0$), the equation for the surface was based upon a modified Paris relation and is given as

$$N \left(\frac{\rho}{C}\right)^4 \left(\frac{\Delta S}{\rho}\right)^4 a_o = 1 - \frac{a_o}{a_c} \qquad (3)$$

where N is the number of cycles of loading that will grow a crack to its critical size

ΔS is the range of stress

ρ is the density of the material

C is the material constant that characterizes crack growth resistance

a_o is the initial crack length

a_c is the critical crack length

(Note: The surface represented by Equation (3) does not intersect the $a_o = 0$ plane at the limits suggested, so it has been faired into the S-N curve to give a complete representation of material behavior.)

The diagram in Figure 2 provides a comparison for three such surfaces representing three arbitrarily chosen candidate materials for a given set of design conditions. The materials chosen and their pertinent characteristics were:

	Aluminum	Titanium	Steel
Alloy	2024-T3	Ti-6Al-4V	D6Ac
Tensile strength, MN/m^2	489	900	1700
Density, ρ, gk/m^3	2770	4440	7890
Fracture toughness, K_c, $MN/m^{-3/2}$	110	110	60
Crack growth resistance, C	1025	3043	23000
Crack growth exponent, n	3.64	3.12	2.62

The figure shows only that portion of each of the three operating surfaces that is higher than the other two at a given combination of initial crack length and life. Thus, the lightest part for the same loading may be made from the material whose surface is shown. From this comparison, the high-strength steel is superior only for extremely short initial crack lengths. Thus, for most practical situations requiring low weight, the titanium and aluminum alloys will provide lighter designs. The titanium alloy is better over only a small region where crack lengths and required lives are short. For the large majority of design situations the modest strength aluminum alloy leads to the most efficient design.

To become a quantitative design tool, the material-selection model described here requires extension to account for other R values, variable amplitude loading, and more complex configurations. In each case analytical expressions will be required to permit the necessary calculations to be made.

CONFIGURATION EFFECTS

Fatigue

The effects of configuration, whether on fatigue behavior or on damage tolerance, are measured primarily by the stress analysis of structural parts. By far the most common reason for deficient service life is the inadequate accounting for stress concentrations near design details. Although the designer is well aware that sharp discontinuities lead to early failures, he is hard-pressed to know quantitatively how much he must alleviate stress concentrations. Because his structure is too complex for a complete analysis of local stresses, he relies heavily on rules of thumb and past experience with similar designs. Photoelastic or other strain-surveying techniques are sometimes used for particularly sensitive areas. Tabulated data on theoretical and experimental factors for simple configurations are frequently used to supply additional judgments. The current state of art is such that an experienced designer can err in his estimate of stress concentration factors by a factor of 2. The consequent error in predicted life is frequently a disappointing factor of 10. Large numbers of ad hoc tests are needed to evaluate candidate designs.

The improvement of this state of affairs presents a formidable challenge to researchers. One obvious approach is to require a detailed stress analysis by say, finite-element procedures, to describe the local stress state for each fastener and other discontinuities in the structure. Even our largest, most sophisticated computers could not cope with so tremendous a computational chore. An alternate, and far more economically suitable proposal, would be to provide general catalogs of effective concentration factors for previously encountered details. Such catalogs should include factors for various types of fasteners probably as a function of fastener-sheet material combinations, head shapes, fastener-sheet sizes, interference fits, various doubler configurations, reinforcements around cutouts, joints, and many others. Other effects such as damage from fretting and improved behavior due to shot-peening or other cold work should also be accounted for ultimately.

Partially computerized techniques for analyzing major joints have been developed by Jarfall (Ref. 19) and probably by others. Such methods are required for many other practical situations in order to quantify the design process and to reduce the number of ad hoc tests required to prove adequacy of trial designs. Very significant improvements in safety and service life are likely to be achieved with little or no weight penalty.

Damage Tolerance

Both the rate of fatigue crack propagation and the residual static strength in structural components are characterized by the stress intensity at crack tips. The local stress concentration that may lead to early fatigue cracking is of much less concern here than for fatigue design because only the very early stages of crack growth are affected by these local stresses. However, the presence of stringers, their attachment to sheets, redundancy of construction and other such features are likely to be of great importance.

Stress intensity analyses for practical complexities in structures are being developed at an increasing rate. Particular attention is being given to cracks growing from holes, surface flaws and other three-dimensional configurations, allowances for plastic action and some cases of stiffened configurations. Many more solutions are required. Analyses such as one by Poe

(Ref. 20) indicate that rates of crack propagation can be changed readily by factors of 10 or more by judicious use of crack inhibiting stringers.

Design Trade Offs

The designer should ultimately be in a position to make a judicious choice among candidate configurations to provide the reliability and life he requires. On the one extreme, he may wish to consider a completely monolithic design with a minimum of stress concentrations. Such designs are likely to be lightweight because all material is used efficiently, but are likely to be very expensive to construct. However, if such a structure is stressed to take advantage of its superior fatigue behavior, it is likely not to possess much tolerance for inadvertent damage encountered in service. On the other extreme, the designer may wish to introduce many redundancies to retard crack growth. Such designs are also likely to be expensive, because many parts must be assembled. Further, the many fasteners that are likely to be required will introduce large numbers of stress concentrations that could invite early failures.

The optimum design is likely to be a combination of good fatigue and damage tolerant design features. The optimum will be reached best when both features can be evaluated quantitatively. Customers and certification agencies must also be assured that a well-balanced, safe and economical design has been achieved.

LOAD HISTORY EFFECTS

One of the most challenging facets of designing for adequate service life is to account for the complex load history to which most airframe components are subjected. The description of the statistical frequency of occurrence of service loadings is beyond the scope of this paper, but how such loadings contribute damage and affect fatigue crack propagation are treated here.

Fatigue

Despite many research results that illustrate the deficiencies of the well-known Miner rule (Ref. 21), no substitute cumulative damage rule has gained widespread approval. Several alternate schemes are being applied or studied.

The Royal Aeronautical Data Sheet (Ref. 9) recommends the use of the Miner rule, but based on S-N curves whose mean stress is selected to account for local residual stresses that can be left by occasional excursions to high stresses.

Kirkby (Ref. 22) and others have proposed that the anomalies in the cumulative damage analyses might be avoided if the basic S-N curve were to be generated from tests with random loadings and various root-mean-square stress levels. Life under the service load environment would then be calculated from an assembly of random load segments. Adoption of this principle is likely to be hampered by the very costly prospect of generating a new set of basic data. Special procedures will be required to account for large, nonrandom, load excursions such as the ground-air-ground cycle.

A third method suggests that the expected load time history be transformed to a local stress history accounting for local plastic stresses. The S-N curves for unnotched specimens made of the material of interest would be used as a basis for a Miner analysis. Procedures for making sequential stress calculations are being developed by Morrow and his collaborators (Ref. 23) and by Crews (Ref. 24). This method is attractive because of the attention paid to local behavior. However, the designer is unlikely to be in a position to anticipate the complete sequence of events in the service life of an aircraft. Presumably, large numbers of potential sequences having identical overall statistical characteristics might be proposed, a life predicted for each and the worst case or some intermediate case accepted as the representative prediction. The application seems cumbersome for design purposes. The method depends heavily on the detailed elastic and plastic stress analyses previously discussed under Configuration Effects and also should include effects of interference fasteners (Ref. 25) and other built-in stresses.

Whichever of these or other hypotheses is ultimately chosen for cumulative damage analysis, the accuracy must be significantly better than that of the current Miner rule, the calculations must be tractable, and should be applicable to any time history of stress that is likely to be encountered in service.

Crack Propagation

Many recent investigations have shown that a very important delay in crack propagation occurs after intermittent applications of high stresses. Prediction procedures for this so-called "interaction effect" have been developed (Refs. 26-27) from considerations of the size of the plastic zone ahead of the crack tip.

In Wheeler's model (Ref. 26) the crack growth increment Δa for a given stress cycle is

$$\Delta a = \left(\frac{r_p}{a_p}\right)^m \frac{da}{dN} \tag{4}$$

where r_p is the plastic zone size for the cycle in question

a_p is the plastic zone size for a previous cycle at higher stress

m is an adjustable constant

and $\frac{da}{dN}$ is the growth expected if no interaction were present.

The constant m is adjusted empirically to fit observed data and appears to depend on the material and on the stress history.

Willenborg (Ref. 27), on the other hand, calculates a residual stress ahead of the crack tip and postulates that the next stress cycle is ineffective until it counteracts the residual stress. Thus, the effective range of stress is reduced for all cycles following a high stress cycle. The residual stress is assumed to decay linearly with crack growth through the plastic zone.

Elber (Ref. 15) found that cracks close near their tips before all external stress is removed, because material behind the crack tip has been plastically deformed. Consequently, a "crack-opening load" must be applied before additional crack growth can take place. This model requires further development to predict behavior under variable amplitude loading.

Whichever of these or other model is found to be most suitable for design purposes, it must be applicable for any time history of stress that is likely to be encountered in service.

Fracture

Fracture behavior is expected not to be sensitive to time history effects for purposes of this discussion.

ENVIRONMENTAL EFFECTS

For purposes of this discussion, two broad categories of environmental effects are likely to be present in many practical design situations: thermal and chemical effects.

Thermal Effects

The primary effect of temperature is to modify material properties. Thus, many ad hoc tests are conducted at temperatures to determine fatigue properties, crack propagation resistance, and fracture toughness. For cryogenic applications the first two properties are likely to be reasonably unaffected, but toughness frequently is much lower at low temperatures than at room temperature. At elevated temperatures, all three properties are likely to be degraded, the failure phenomena become much more time-dependent (implying an interaction with creep) and are complicated by possible interactions with oxidation.

Because of the major effect of the elevated temperatures, designers of engine and other heated components are likely to select materials and adjust stress levels consistent with expected service conditions. However, quantitative predictions are not yet ready for computerization. The effect of temperatures on the materials properties discussed earlier should be quantified and reduced to analytical form for computer-aided design.

Chemical Effects

Much of what is known about the effect of the chemical environment on fatigue behavior has been learned from "basic" studies in which the mechanism of failure is under deliberate study. Generally, a vacuum environment leads to longer lives than are observed in air and aggressive environments are likely to lead to shorter lives. The actual life is likely to be strongly time-dependent in the aggressive environment. Quantification of the effects is progressing at a very slow rate. Even the simple case of corrosion in an outdoor seaside environment without stress has resisted attempts to produce dependable correlations.

When tensile stress and a susceptible material containing a flaw are exposed to an aggressive environment, stress corrosion cracking may occur. At room temperature the most deleterious environment is likely to be aqueous, but dry salt and liquid metals produce similar degrading results at elevated temperatures. Data are usually plotted as the stress intensity factor K against the time required for failure.

Because corrosion, even without stress, can have drastic results, it is usually dealt with by selection of resistant materials or by protective treatments. In service, lavatories, galleys, and other areas where the environment is recognized to be especially severe are inspected for damage and repaired before serious structural damage occurs. Generally, the progressive degradation of properties and the acceleration of the fatigue and crack propagation processes are not dealt with in a deliberate sense for aircraft design. Whether a quantitative life prediction scheme should or should not be pursued in the foreseeable future is a matter for debate.

For pressure vessels in spacecraft, resistance to stress corrosion cracking has been a controlling material property. Usually, the threshold stress intensity is of interest and inspections and proof tests are employed to identify the initial condition of a vehicle. Life to failure is generally not the design condition, thus, a simple listing of threshold stress intensity for given combinations of material, corrosive environment, and temperature is likely to suffice for design purposes.

Fracture toughness is currently thought not to be affected by an aggressive environment. Rather, if failure is to occur, flaws will grow by stress corrosion cracking until the critical conditions are reached that are critical for nonaggressive environments.

SUMMARY

Throughout the foregoing sections, the current design capability has been found deficient compared to what is desireable for future designs, particularly if computer-aided procedures are to be employed. Table I summarizes quantitatively the author's judgments on the errors that are possible with today's technology and on goals that might be achieved through concerted research efforts over the next decade or so. In all cases, the objective should be to provide a design tool sophisticated enough to handle the most important parameters rationally, if possible, but empirically, if necessary. In any case, the limits of application should be clearly established. Proposed methods must be capable of handling the practical complexities of at least the configurations and load histories commonly encountered in aerospace designs. Materials must be characterized for fatigue behavior, crack propagation resistance, and fracture toughness, with appropriate account for temperature effects. Extension to predict life under a corrosive environment may not be realistic in the foreseeable future and should receive lower priority.

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TABLE I

QUANTITATIVE JUDGMENTS OF THE CURRENT AND RECOMMENDED STATE OF ART FOR FATIGUE AND DAMAGE TOLERANT DESIGN

	1973	Future
Material Properties		
Fatigue	Unwieldy analysis	Standard equations
Crack propagation	Inadequate analysis	Improved laws
Fracture	Limited to plane strain cases	Extend to plane stress
Configuration Effects		
Fatigue	$0.5 \leq \frac{\text{Predicted } K_T}{\text{Effective } K_T} \leq 2.0$	$0.8 \leq \frac{\text{Predicted } K_T}{\text{Effective } K_T} \leq 1.2$
Crack propagation and fracture	$0.8 \leq \frac{\text{Predicted } K}{\text{Effective } K} \leq 1.2$ Simple cases	$0.9 \leq \frac{\text{Predicted } K}{\text{Effective } K} \leq 1.1$ More complex cases
Load History Effects		
Fatigue	$0.1 \leq \sum \frac{n}{N} \leq 10.0$	$0.5 \leq \frac{\text{Predicted life}}{\text{Observed life}} \leq 2$
Crack propagation	$0.05 \leq \frac{\text{Predicted } N_f}{\text{Observed } N_f} \leq 2$	$0.5 \leq \frac{\text{Predicted } N_f}{\text{Observed } N_f} \leq 2$
Fracture	Not applicable	Not applicable
Environmental Effects		
Temperature	Ad hoc tests	Standard equations
Chemical	Ad hoc tests, inspect repair	Quantitative predictions?

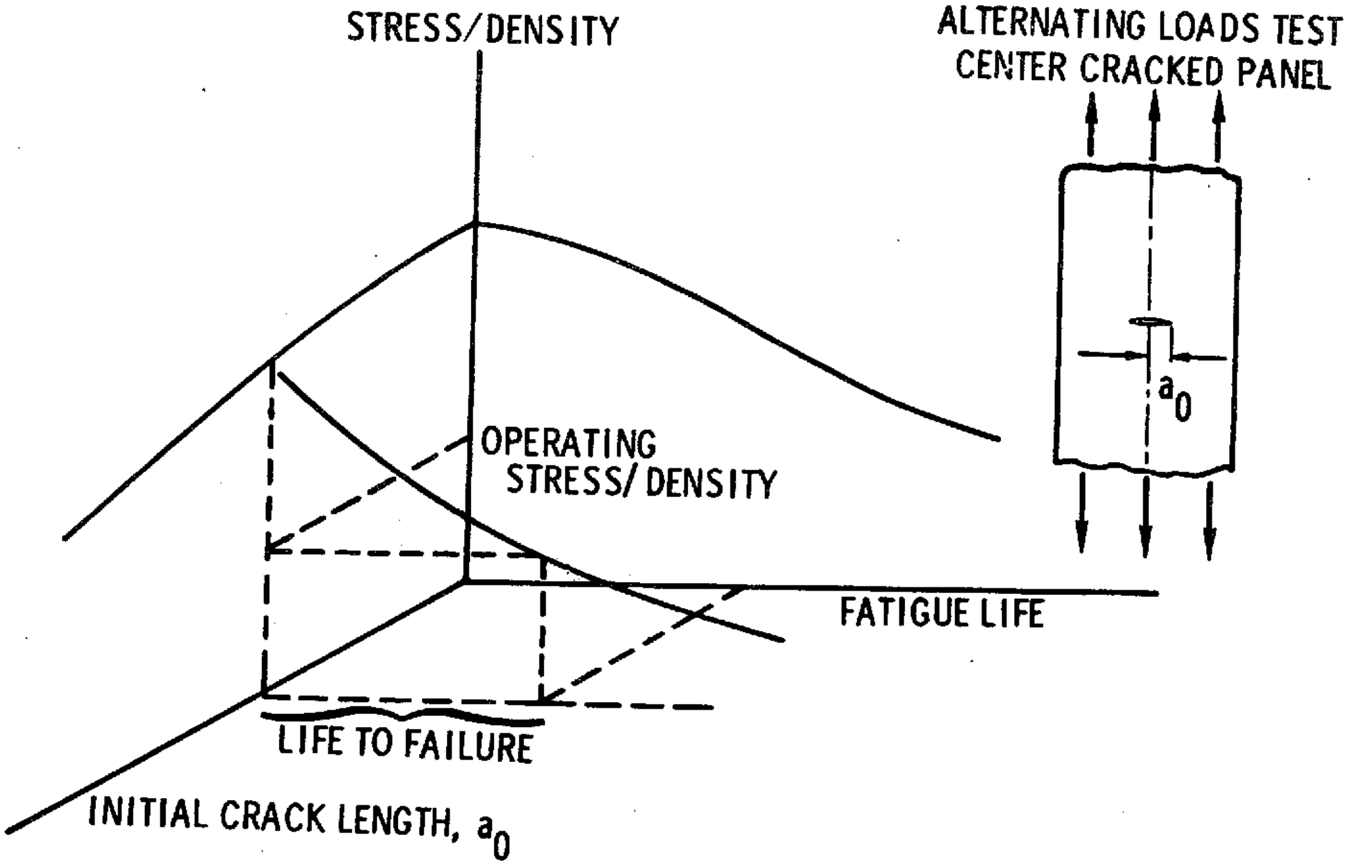

Figure 1. Operating stress for specified life and initial crack.

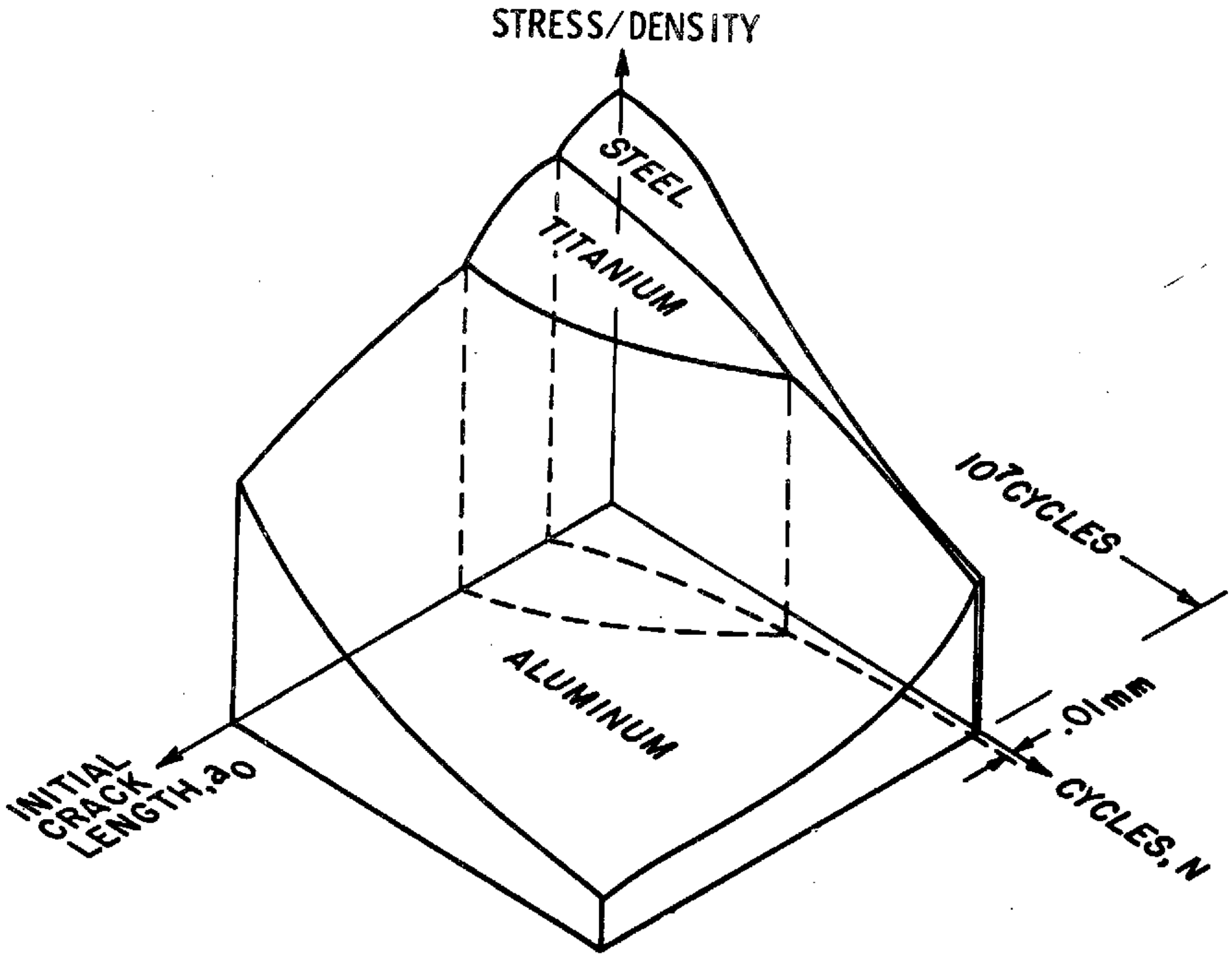

Figure 2. Best choice among three materials for specified life and initial crack.