MATERIAL SELECTION AND DESIGN TO COMBAT FATIGUE

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ABSTRACT

This paper describes developments in fatigue design and assessment practice in light of advances in the field of fracture and damage mechanics. Current design practices are described. The challenge to the design engineer presented by new generation materials is then highlighted by reference to their complex fatigue damage mechanisms and anisotropic nature. The requirement for alternative design concepts is presented with reference to the automotive industry.

1. INTRODUCTION

Fatigue and fatigue related failures in components and structures occur relatively frequently and make headline news when loss of life is involved. Most people will be aware that tragedies such as the capsizing of the Alexander Kielland North Sea accommodation rig and the loss of an El Al Boeing 747 more recently in Amsterdam, with considerable ground casualties, have been attributed to fatigue.

In addition, a great number of minor fatigue failures with considerably less disastrous consequences occur every day of the year in countless industrial and domestic equipment. All together, fatigue failures extract a high price in both human and economic terms.

Nevertheless, despite the considerable advances in our understanding of the fatigue process during the last decade and improvements in key areas such as design practice and pre-service testing we still witness a high level of fatigue failure(1).

2. FACTORS GIVING RISE TO FATIGUE FAILURE

The factors which result in unexpected fatigue failures can be grouped into three classes:

1) **Design** - Lack of attention to stress concentrating features such as abrupt changes in section, weldments and the presence of a poor surface finish can all result in premature fatigue failure.

2) **Manufacture/fabrication** - The utilisation of incorrect materials (eg unsuitable welding consumables) or the accidental introduction of stress raising flaws are deleterious to the fatigue life.

3) **Operation** - Operation outside of the conditions assumed at the design stage (eg. cyclic over-stressing) will lead to premature failure. In addition, the contribution of factors not accounted for at the design stage will accelerate the failure process. For example, operation in an aggressive environment may give rise to surface pitting corrosion which

can initiate fatigue cracks. Further poor maintenance practice can lead to component damage or modification of material properties.

In the automotive industry as is the case in the aerospace industry there is a good understanding of the importance of fatigue as a damage and failure mechanism. For the case of complex geometry components such as those used in chassis construction, considerable emphasis is placed on ensuring a fatigue resistant design given a knowledge of the likely loading regime. Consequently, failures due to poor design are rare. Similarly, rigorous quality control procedures associated with manufacture minimise the contribution of factor 2) in failures. By far the largest contribution to fatigue failure results from factor 3), where even the most rigorous and thorough attention to fatigue damage mechanisms at the design stage cannot prevent failure due to operational modes or actions not envisaged at the design stage.

The factors listed above highlight the principle variables governing the incidence of fatigue failure. These are cyclic stress and cyclic strain ($\Delta\sigma$, $\Delta\varepsilon$) and flaw size (a). Further, these fatigue governing parameters may interact with additional time dependent damage processes such as creep and corrosion to accelerate failure.

3. A QUANTITATIVE DESCRIPTION OF FATIGUE

The fatigue process involves the initiation and growth of predominantly surface defects under cyclic stress/strain. The process can be operative over a large range of stress and strain levels and be significant for an equally broad range of defect sizes. Dependent on geometry and material properties, pre-existing defects may propagate at cyclic stress levels of only a small fraction of the material yield stress after millions of cycles, whilst a similar process applied to a different geometry and material may result in failure after only tens of cycles of reversed plasticity.

The stress/strain range over which fatigue cracks can initiate can vary from strain levels only limited by the intrinsic ductility of the material to stress levels of the order of half the material yield stress. The crack growth rate attributed to an initiated crack also varies from a few atomic dimensions per cycle to millimetres per cycle.

Crack initiation to the order of 1mm is often considered to be a lengthy process constituting a substantial fraction of the life of a component. However, in many cases crack initiation can be a very rapid process with life controlled by the crack growth phase. In fact, basic fatigue laws expressed as the number of stress or strain cycles to failure, N_f, are in reality integrated crack growth laws. Figure 1 shows a generalised fatigue endurance curve for a precracked and plain specimen respectively. In the low cycle fatigue regime (< 1000 cycles/high plastic strain) an increase in the initial crack size, a_0, has much less effect on life than in the high cycle regime. Even small defects (< 1mm) have a significant effect in the high cycle regime. This effect, which is largely attributed to a reduction in the fatigue limit value highlights the significance of defects introduced during manufacture or maintenance in components which have been designed for resisting high cycle fatigue.

Figure 2 shows a generalised fatigue crack growth law, in this case, expressed using the linear elastic crack tip alternating stress intensity parameter ΔK, which is a strong function of the applied stress range and crack size. For the low cycle regime where a large plasticity component is present this characterising parameter is unsuitable and elastic-plastic descriptors have been employed based on either bulk strain accumulation or crack tip strain intensity. Such parameters have been employed to describe the non-linear extremes of Figure 2.

It should also be stressed that the interaction of other time dependent damage processes can significantly enhance both crack initiation and growth. The effect of corrosion and creep can reduce the fatigue life by up to a factor of three. The effect of the combined mechanisms is such that the simple summing of their respective contributions to total life leads to a non-conservative result indicating the mechanisms are interactive.

4. FATIGUE DESIGN & ASSESSMENT

The design of an engineering structure or component is related to its primary function and involves consideration of its intended operating environment. Fatigue may be a major or minor issue in this regard but should be a matter for design assessment rather than a basis for design.

If an assessment of a design indicates fatigue to be a potential problem, the designer has a number of options. These include reduction of component stress levels, the improvement of local stress concentration details or the use of an alternative material.

The fatigue design of a component is usually approached using one of two philosophies. These are, namely, "safe life" or "damage tolerance." The former relies on the provision of data relating cyclic stress to failure (the S-N or ε-N curve) which can be factored to yield a conservative basis for design. Such data is available for both materials and design features with factoring based on levels of certainty associated with applied stress levels and stress state together with material and test data scatter. In addition, application criticality determines the level of conservatism employed.

Although the "safe life" approach is still commonly used for fatigue life assessment, the uncertainty and, in some cases, large degree of in built conservatism has resulted in the increased use of the "damage tolerance" philosophy. This approach relies on an understanding of acceptable levels of damage in a structure or component and uses models describing damage accumulation to predict the safe service life. Consequently, the approach requires damage or defect detection. Since crack defects can be considered as damage an assessment can incorporate the initially flawed state of a structure or component.

Advances in non-destructive examination and fracture mechanics methodologies has provided the foundation for the development and increased use of this philosophy in design.

5. APPLICATION & LIMITATION OF THE "SAFE LIFE" APPROACH

The S-N endurance curve is essential to the "safe life" approach. The determination of these data involves extensive testing using a specimen of plain material or material containing a stress concentrating feature typical of a service geometry. To produce a useable relationship, tests must be carried out at a number of stress or strain ranges with substantial duplication in order to quantify the experimental uncertainty. Conventional tests for the determination of S-N data are carried out using a simple sine wave under tension/compression loading.

The resultant endurance data does not distinguish between crack initiation and growth and neither does it specifically account for the initial damage state of the material. However, the approach has a successful track record (albeit excessively conservative) in dealing with fatigue at the design stage in a number of engineering sectors. Difficulties arise however, when complex geometries or loading patterns are to be considered. At present the major complicating factors and the way in which they are dealt with are detailed below:

1) **Surface stress concentrations** - These are allowed for through elastic stress concentration factors which translate to fatigue strength reduction factors or, in elastic-plastic (low cycle fatigue), cases the use of strain superposition techniques.

2) **Stress Gradients** - Stress concentrations and thermal stresses involve stress gradients within components. A particular concentrated surface stress may not characterise failure adequately in components of variable geometry and thickness.

3) **Operational History** - The variable loading spectra experienced by components and structures provides one of the major uncertainties for fatigue assessment. The linear additive Miner rule is widely used for dealing with variable loading conditions but the advent of waveform analysis and advanced testing equipment has resulted in increased reliance on full scale simulative component testing. This is particularly the case in the aerospace and land transport sectors.

4) **Stress State** - Mean stress and multiaxial stress fields affect fatigue behaviour. A number of standard procedures exist to treat these phenomena

In addition to the specific factors above, the "safe life" approach has two further major limitations. Firstly, no regard to the initial flaw state of the component is made in the fatigue analysis, and secondly, the effect of damaging, time dependent phenomena (eg. creep) are neglected. The uncertainty introduced by these two features has provided the primary driving force for the increased application of the "defect tolerance" approach.

6. APPLICATION AND LIMITATIONS OF THE "DEFECT TOLERANCE" APPROACH

The "defect tolerance" approach allows the designer an increased level of certainty in both fatigue design and assessment. Damage in the form of cracks, and most recently, cyclic plasticity, can be quantified and related quantitatively to a development rate. Consequently, the technique has application not only to design but can also be used during service to predict life and to guarantee service beyond a nominal design life.

When only elastic stresses are to be considered the procedure consists of a few simple steps:

1) Detect and measure an initial or service induced defect of size a_o

2) Determine the stress intensity factor range, (ΔK), for the crack. This requires a knowledge of the magnitude and distribution of the cyclic stress field and the local geometry characterised by a factor, Y. ΔK is then determined according to the relationship:

$$\Delta K = Y \Delta \sigma \sqrt{a}$$

3) Determine the crack growth rate (da/dN) from a materials database or experimental data.

4) Estimate by integration of the crack growth law the number of cycles, N, for the crack to grow to an unacceptable size (This is determined on the basis of an acceptable remaining ligament stress and/or the intrinsic toughness of the material).

In practice, difficulties and limitations are encountered within each of these steps. The following are examples of those most frequently faced.

1) The detection and sizing of cracks relies on the application of non-destructive examination (NDE) techniques with varying degrees of resolution. Typically, pre and inservice inspection cannot guarantee the detection or sizing of defects of less than 1mm. (It should be noted that this size is several orders of magnitude greater than the 1-10μm initial crack sizes encountered in naturally occurring fatigue cracking from a plain surface). Since fatigue crack growth laws are approximately exponential, estimates of the fatigue life by integration are sensitive to the initial crack size. Hence, the accuracy of such calculations are often limited by the resolution and confidence in NDE techniques.

2) The determination of ΔK is dependent on a detailed knowledge of the relevant stress range and local geometry. In many instances estimates of ΔK can be made from published compendia of typical cases. However, this may not be possible in some situations and use of finite element or boundary integrals must be made. In such cases the calculation of crack growth must be carried out using numerical techniques. For regions of stress concentration where plasticity may occur, ΔK is not an appropriate parameter for the characterisation of crack growth and alternative strain based descriptors must be

employed.

In short, a sound understanding of the stress distribution, state and effect on deformation and growth characteristics is required for the analysis.

3) The central linear portion of the fatigue crack growth plot shown in figure 2 is simple to apply. However the behaviour in the threshold region is less easily interpreted. In this region the crack growth rate is extremely sensitive to small variations in cyclic stress, mean stress, environment and local microstructure. Further, the nature of the plot in this region depends greatly on the size of the crack. Most data used in assessment is obtained from cracks of several tens of mm in length. However, in highly stressed, thin section components, cracks in this region are likely to be an order of magnitude smaller, and it is known the behaviour of "long" and "short" cracks are not directly comparable around threshold values of ΔK.

Although the difficulties detailed above present significant obstacles to the accurate assessment of fatigue there exist procedures to treat most of the circumstances which arise. The majority of these involve simplified assumptions which yield a conservative value of life or identify future inspection requirements. However, the defect tolerance approach removes a large part of the conservatism associated with the "safe life" approach and provides the engineer with a powerful tool for both design and assessment.

The majority of fatigue failures seen today, not due to operation outside of those assummed at the design stage, are due to the incorrect treatment of secondary factors which accelerate or modify the fatigue life.

7. THE CHALLENGE OF NEW MATERIALS

Both of the design philosophies discussed above have been applied traditionally to metallic materials which have well understood material and mechanical properties. However, the last decade has seen the increasing structural application of advanced and composite materials. This is particularly the case in the land transport and aerospace sectors.

Designers have chosen these materials since they offer considerable performance advantages in a variety of areas. In general, key properties such as stiffness to weight ratio have been enhanced or resistance to a particular damaging condition has been optimised. Nevertheless, these tailor made materials provide a major challenge to existing design methodologies and in many cases have resulted in radical changes to the design process.

A revised approach for fatigue design for these materials has arisen as a consequence of firstly, the highly anisotropic nature of the majority of these materials and secondly the complex damage mechanisms which give rise to fatigue failure. Advanced materials which are seeing increased structural application are ceramics, polymers and polymeric composites and metal matrix composites. Composite materials constitute a particular problem for the design engineer since the fatigue behaviour of the complete component can rarely be predicted on the basis of the fatigue properties of its constituent parts. In addition, conventional concepts concerning fatigue damage require modification in many composite materials. For example the development of fatigue damage in a fibre reinforced composite material can not successfully be characterised by a single growing crack. Fibre debonding and the density of inter fibre matrix cracks are parameters which are central to describing fatigue life.

Consider the application of metal matrix composite materials (MMC's) in the automotive industry. MMC's offer the following benefits to the designer:

- Reduced mass in reciprocating parts
- Increased temperature capability for inner engine parts.
- Improved wear resistance for valves and pistons
- Improved stiffness and strength for structural components

By way of example, current applications of MMC's within the automotive industry(2) are illustrated in Figure 3.

The use of components manufactured from MMC's has given rise to the following dilemma which is equally as true for other advanced material classes. A simple replacement component to a conventional design is not satisfactory. The use of a component manufactured using MMC's often requires the complete redesign of the components with which it interacts. For example, whilst it has been found possible to manufacture and install MMC piston rings this has ultimately required the complete redesign and use of alternative materials for the surfaces against which it rubs.

In many applications the use of advanced materials has necessitated revolutionary new power unit designs in order to optimise the benefits obtained from the materials. This requirement is clearly illustrated by the development of a predominantly reinforced plastic engine as part of a joint European research programme(3) funded under the Commission of the European Communities BRITE scheme. The project undertaken by a partnership of European motor and component manufacturers together with polymer producers and engineering research organisations has led to the development of a lighter and more fuel efficient engine. In this case an extensive redesign of the engine was required in order to integrate, and benefit from, the plastic components.

8. CONCLUSION

Several decades of dealing with conventional metallic materials during which advances in fracture mechanics has enabled the designer to deal confidently with fatigue. However, the inability to deal adequately with the factors which interact with fatigue and reduce life is a major contributor to the premature failure of structures and components.

The advent of new classes of material has presented a new and important challenge to the design engineer and researcher respectively. Fatigue damage mechanisms and methodologies for assessment are, for many of these materials in their infancy. Considerable research effort is required before the designer can apply these materials confidently in his work. Nevertheless, it is clear that these materials will be increasingly utilised and, with this, comes the requirement for totally new design concepts.

9. ACKNOWLEDGEMENT

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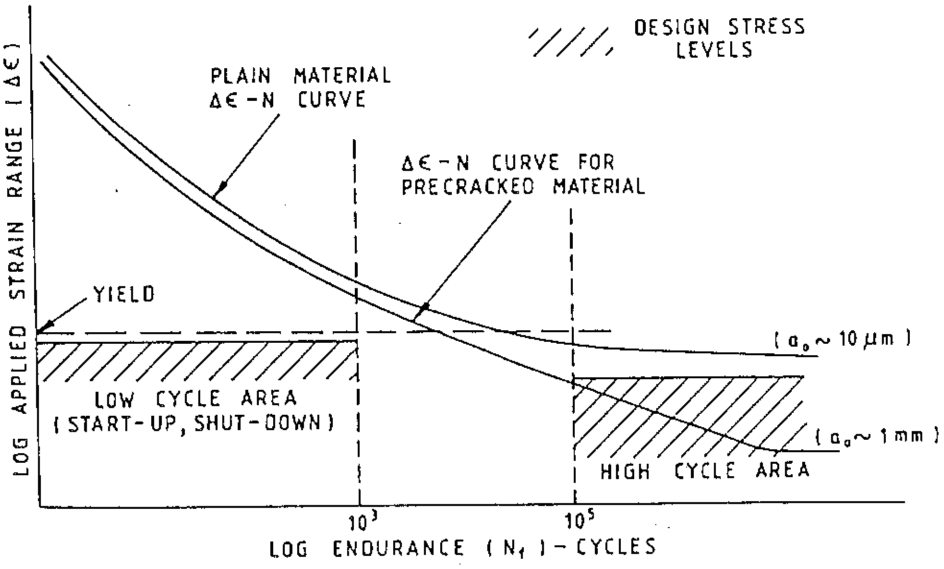

Figure 1. Schematic Δε - N*f* curve illustrating the influence of surface crack size.

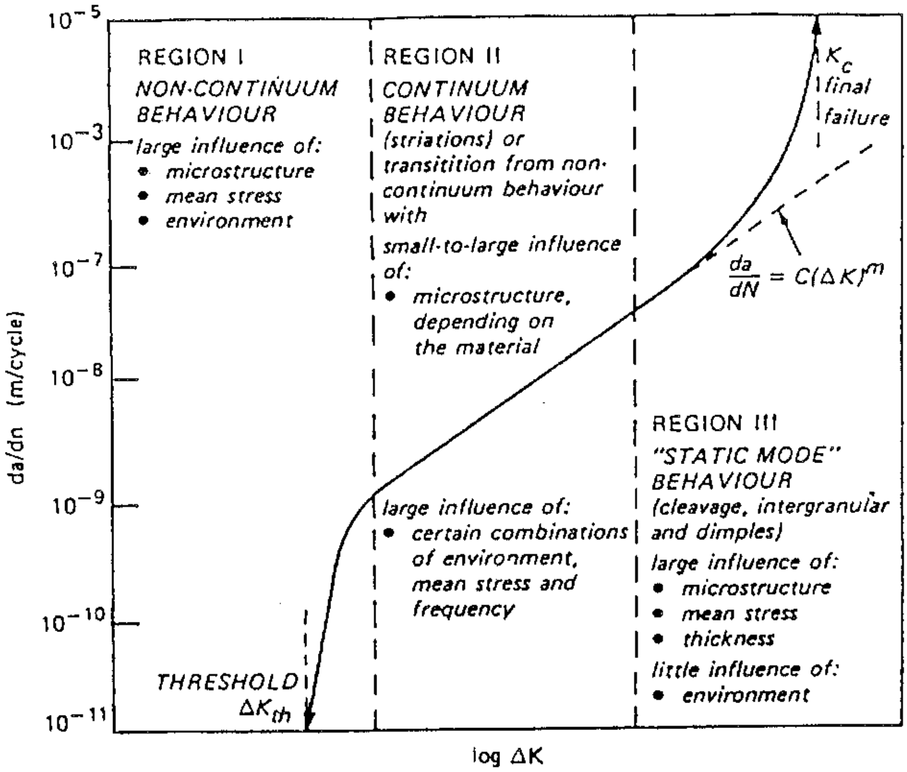

Figure 2. Characteristics of the fatigue crack growth rate curve, da/dN - ΔK.

MMC Alloy	Application	Improved Properties	Feature	Manufacturer
Aluminium short fibre reinforced Al alloy	Piston (abrasion proof rings) (piston rings)	Abrasion resistance performance lower cost	Higher engine temperature	Toyota
Aluminium short fibre reinforced Al alloy	Piston (combustion bowl)	Higher temperature performance	Greater engine durability and operating temperature	Various (T + N, KS, JPL)
SiC whisker reinforced alloy	Connecting rod	Specific strength, stiffness	Higher engine performance	Nissan
SiC particle reinforced aluminium alloy	Connecting rod	Specific strength, stiffness	Higher engine performance	DWA Duralcan
Aluminium fibre reinforced alloy	Connecting rod	Specific strength, stiffness	Higher engine performance	Du Pont Chrysler
Particulate	Propshaft	Specific stiffness	Parts reduction	GKN

Figure 3. The application of MMC components in the automotive industry.