A REVIEW OF FRACTURE MECHANICS LIFE TECHNOLOGY

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Abstract

A review of current lifetime prediction technology for structural components subjected to cyclic loads was performed for NASA. The central objectives of the project were to report the current state of and recommend future development of fracture mechanics-based analytical tools for modeling and forecasting subcritical fatigue crack growth in structures. Of special interest to NASA was the ability to apply these tools to practical engineering problems and the developmental steps necessary to bring vital technologies to this stage. The authors conducted a survey of published literature and numerous discussions with experts in the field of fracture mechanics life technology. One of the key points made is that fracture mechanics analyses of crack growth often involve consideration of fatigue and fracture under extreme conditions. Therefore, inaccuracies in predicting component lifetime will be dominated by inaccuracies in environment and fatigue crack growth relations, stress intensity factor solutions, and methods used to model given loads and stresses. Suggestions made for reducing these inaccuracies include development of improved models of subcritical crack growth, research efforts aimed at better characterizing residual and assembly stresses that can be introduced during fabrication, and more widespread and uniform use of the best existing methods.

Introduction

In the early months of 1983, Failure Analysis Associates was in the process of completing and documenting an assessment of the state of the art in fracture mechanics life technology.[1] This project had been undertaken for NASA in the Spring of 1982 and was focused on lifetime prediction techniques applicable to oxygen/hydrogen propulsion components. NASA wanted to know what technologies are available, how good these technologies are, how these technologies might best be enhanced, and which new technologies seemed most promising for future development. To narrow the scope of the study, some limiting decisions were made at the outset. Since oxygen/hydrogen propulsion components most often fail due to the growth of cracks or defects caused by cyclic loading, the review concentrated on fracture mechanics techniques for analyzing fatigue crack growth. Also, since the majority of the component lifetime is occupied by cracks growing at relatively slow rates, and since critical crack size most often does not have a strong influence on calculated (or observed) lifetimes, the final failure criterion was assumed not to be very influential. Such criteria therefore received secondary consideration in the review.

Fracture Mechanics Review

Various aspects of fracture mechanics-based analyses of fatigue crack growth were extensively reviewed for the NASA study and are summarized in this paper. Such analyses compare the cyclic crack driving force with the material's response to this force. In the case of linear elastic fracture mechanics (LEFM), the driving force is measured primarily by the value of the cyclic stress intensity factor, ΔK ($\Delta K = K_{max} - K_{min}$), and the material response is measured by the corresponding crack growth rate, da/dn. Hence, a stress intensity factor solution — relating the applied loads (mechanical, thermal, or residual stress) and crack size and configuration to the value of the stress intensity factor -- is required.

Stress Intensity Factors

A very wide variety of stress intensity solutions are available for elastic stress analysis of cracked bodies which can be idealized as two-dimensional. Techniques for generating new solutions for two-dimensional bodies are fairly accessible and economical and can be readily provided for new stress systems and crack configurations. However, the majority of problem cracks in oxygen/hydrogen propulsion components spend most of their time as partial thickness cracks -- which are inherently three-dimensional. Although a wide variety of configurations have been treated, the current stress intensity factor solutions for three-dimensional elastic bodies are not nearly as complete as those for two-dimensional bodies. Economical numerical procedures for evaluation of K for new geometries are lacking, and the most economical techniques are not readily accessible to the technical community.

Special consideration should also be given to the appreciable additional information on crack surface opening displacements that is generated in numerical calculations of stress intensity factors, because this information can be used in the development of influence functions. Such functions could be used to economically evaluate stress intensity factors for arbitrary stresses, which would be especially useful in situations involving complex spatial stress gradients, such as arise in thermal and residual stress fields.

Subcritical Crack Growth

Oxygen/hydrogen propulsion components are typically subjected to cyclic loads, and the resulting fatigue crack growth is the process leading to final failure. The material's response to the applied driving force is measured by the value of the crack growth per cycle, da/dn. Even for the simple case of constant amplitude cycling, many factors influence the crack growth rate for a given material and value of ΔK. These include the load ratio ($R = K_{min}/K_{max}$), environment, cyclic loading frequency, and temperature.

The complex interactions between these factors are only poorly understood at the present time, and extensive experiments must be conducted to provide reliable information for lifetime analyses. The need for experimentation is one of the current drawbacks of using fracture mechanics, and can add greatly to the cost of performing a reliable lifetime analysis. A more complete understanding of the effect of influencing factors and their interactions would reduce the need for experimentation.

Many propulsion components are subjected to high frequency loadings and any initial cracks must be small in order to survive for the desired lifetime. Since some of these cracks are too small to be modeled with typical fracture mechanics methods, a means of treating the growth of short cracks is necessary. A more thorough understanding of the influence of environment and microstructure on fatigue crack growth thresholds, as well as the influence of load history, would be highly desirable.

In the more realistic case of variable amplitude cyclic loading, the crack growth per cycle is influenced by the past loading history, and the behavior becomes quite complex — even in the absence of environmental and threshold effects. Various models have been suggested for periodic overloads and other more general loading cases. These models typically consider the crack growth to be altered by threshold effects and either (1) the presence of residual stresses ahead of the crack or (2) crack closure and crack surface alteration produced by the overload. All the models have been shown to provide good correlations to selected test data. However, they are all lacking in some regard. The largest gap of knowledge in lifetime prediction areas is in characterization of fatigue crack growth for the case of variable amplitude loading in the presence of an adverse environment.

Analytical tools for the analysis of subcritical growth of part-through cracks are currently not well developed, especially in the case of complex spatial stress gradients. Additionally, criteria for the transition of part-through cracks to through-wall cracks are currently of a highly empirical nature.

Although considerable additional understanding of fatigue crack growth remains to be attained, several automated computer programs provide an adequate level of predictive capability for many applications. However, consolidation of all available predictive procedures into one general-purpose program has yet to be accomplished.

Nonlinear Fracture Mechanics

The need for nonlinear fracture mechanics arises when plastic or viscoplastic deformation becomes appreciable. In oxygen/hydrogen propulsion components, plasticity occurs predominately at the crack location, such as at a surface crack emanating from a notch-like stress raiser that causes localized yielding. Plasticity effects can be very important for accurate life prediction, and few tools are available to address these problems. These methods include adaption of Neuber's notch plasticity results[2] to prediction of nonlinear stress fields and attempts to define and use such parameters as the J-integral.

Although a comprehensive review of nonlinear fracture mechanics was not attempted as part of this study, three approaches to final failure criteria for nonlinear situations were considered: the failure assessment diagram, the design curve approach, and the J-integral approach. The first two are relatively easy to employ but generally are lacking in precision and generality. The J-integral and related tearing modulus approach are the most strongly mechanics-based, and should be readily applicable to oxygen/hydrogen propulsion components. However, very little information on the J-resistance characteristics of relevant materials is available. Even though such data would have to be generated in order to employ this approach, relevant test methods are fairly well advanced based on progress made in other fields -- such as nuclear reactor pressure vessels and piping. In cases of low-cycle fatigue, nonlinear considerations of final failure can be important, and in cases where large cyclic stresses are imposed, nonlinear consideration of fatigue crack growth can be of use.

Other Topics

Numerous other topics of interest were also reviewed. One of growing interest is probabilistic fracture mechanics (PFM). Scatter in material properties, the stochastic nature of imposed loads, and uncertainties in initial crack sizes often lead to large uncertainties in lifetime calculations that are based on deterministic fracture mechanics predictions. Fracture mechanics calculations that incorporate probabilistic considerations provide a means of quantifying these uncertainties and assessing their influence on the reliability of the component. Probabilistic considerations will undoubtly be of growing importance in fracture mechanics analyses.

Another topic of current interest and concern is the use of proof testing to assess the adequacy of component integrity. There are various approaches to selecting appropriate proof test loadings and cycles and various trade-offs to be considered between damaging good components during the proof test or allowing unsafe components to go into service. It was found that a divergence of opinion exists among various practitioners, based largely on dissimilar past experience in this area. Selection and optimization of proof test procedures is still fairly rudimentary, and this appears to be a topic for fruitful future efforts -- especially as additional information on the nature of the randomness of various fracture mechanics inputs becomes available.

Because many life-limiting defects in oxygen/hydrogen propulsion components originate in welds, and because many cracked-weld problems combine several complexities of fracture mechanics life technology and material behavior, special aspects of the use of fracture mechanics to determine the influence of weld defects on structural integrity were examined.

Directions for Development

As part of this study, NASA requested suggestions for enhancing existing technology for life prediction and for directing research into new and developing technologies. The fracture mechanics review revealed that many powerful tools and voluminous materials data now exist, and that the current technology is capable of providing adequate results under many circumstances. However, conflicting theories and inconsistent data have been reported, and there is an obvious need for both a better understanding of underlying phenomena and additional material data.

As noted before, the fracture mechanics analysis of crack growth in engine components often involves consideration of fatigue under extreme conditions of temperature and/or aggressive environment. For known loads, inaccuracies in prediction of component lifetime will therefore be dominated by inaccuracies in environmental and fatigue crack growth relations, stress intensity factor solutions, and methods used to model given loads and stresses. Therefore, the recommendations made below are heavily weighed towards filling the gaps in knowledge of the growth characteristics of cyclically loaded cracks. In addition, these recommendations are not restricted to fracture mechanics topics, but include closely allied areas that are necessary for comprehensive fracture control.

Using and Improving Existing Technology

Current fracture mechanics technology is in many ways highly sophisticated and suited to the needs of the fracture mechanics practitioner. One problem is that the best available methods are not always utilized due to the inaccessibility of some tools and techniques and the degree of complexity involved in the use of others, such as automated computer codes that are difficult to use and available to only a limited number of users. Therefore, the first step in expanding the usefulness of fracture mechanics for lifetime prediction is to provide more easily used and accessed software.

Software Development. A logical starting point would be to develop a widely accessible, user-friendly software package for determining stress intensity factors for a wide range of crack configurations and loadings. This computerized "K-handbook" (see Tada[3], Sih[4], and Rooke and Cartwright[5]) should be interactive and functional on personal computers. Software should not require the user to be a programmer and should be designed to interface between personal, mini- and mainframe computers. Programs already exist (such as BIGIF[6]) which begin to meet these criteria, covering a wide range of loading and geometry combinations and easily expandable to accept new information and formats.

Provisions for easily interfacing the uncracked-structure stress analysis (especially finite element results) with the fracture mechanics code for the determination of stress intensity factors would be desirable. Suggestions for follow-on projects which could be developed separately and then incorporated into the "K-handbook" program include:

- Develop software that would use procedures such as the Neuber approach[2] to treat contained plasticity due to notches and other local stress raisers.

- Create a more widely accessible package for analyzing flaw growth. Currently available codes could be merged to form a code that would contain most of the required capabilities for practical applications.
- Develop software for predicting critical flaw sizes for various crack configurations in typical engine components and materials. Since accurate knowledge of critical crack sizes is not required for accurate lifetime prediction. A high degree of sophistication in this software is not necessary. Current codes and procedures capable of generating stress intensity factors for two-dimensional configurations not already analyzed should also be made more user-friendly and accessible.

A user-oriented code should also be developed to generate the J-integral, tearing modulus, and C* (energy release rate due to creep) solutions required in some low cycle fatigue and/or high temperature applications. Nonlinear finite elements appear to be the best candidate for general applicability to two-dimensional problems. An alternative approach would be to generate new nonlinear solutions for geometries of relevance to engine components.

The development of widely available and user-friendly software for determination of stress intensity factors in two- and three-dimensional bodies would reduce the need for the following efforts. However, these efforts, which are specifically tailored to engine components, would assist in the transfer of technology to the day-to-day engine fracture mechanics practitioner. In brief they are:

- Identify typical engine component geometries (e.g., bolted, flange fillet radii, typical weld joint configurations) for which existing stress intensity factor or J-integral solutions are inadequate and generate such solutions for future use.

- The new stress intensity factor results should be exercised for both hypothetical and practical problems which encompass most geometries, stress, material and environmental combinations to be expected in the field. The analyses created could serve as modeling examples and guidelines.

Generating Test Data. While the existing fracture mechanics life prediction technology provides powerful tools for the prediction of crack growth, these tools depend heavily upon appropriate test results as input data. Suggestions for expanding the store of test data include:

- Identify key material/environment combinations of relevance to oxygen/hydrogen engine components for which adequate fatigue crack growth data is unavailable. Perform tests to characterize the subcritical crack growth of the material over a wide range of crack growth rates.
- Test to discriminate between various proposed models of crack growth under variable amplitude loading.
- Attain a clearer understanding of transition behavior of part-through cracks through limited testing.
- Generate J-resistance curves for ductile materials at temperatures at which critical crack lengths have an important influence on predicted lifetimes. The technology of such testing is fairly advanced, and these tests would therefore not be overly expensive. Tests to generate J-resistance curves for use in analysis of part-through cracks would also be useful.
- Research crack growth under mixed mode cyclic loading for typical engine materials.

Filling the Gaps in Existing Technology

Improving Subcritical Crack Growth Models. A general model for estimation of fatigue crack growth under agressive environments would be very useful -- even for the relatively simple case of constant cyclic load amplitude. The development of such a model is one of the most difficult undertakings suggested here, but is also the one with potentially the largest payoff. This model would allow predictions to be made of the influence of a particular environment on fatigue crack growth, including the effects of temperature, loading frequency, and R-ratio. This would circumvent the need to perform numerous tests each time a new loading condition or environment was encountered. Such a model has proven very elusive in the past because of the complexity of the phenomena involved as well as the interdisciplinary nature of the problem. Lacking a general model, several viable techniques for "interpolating" or "extrapolating" from test conditions to the desired conditions are available and should be pursued.

Research into improving methods of predicting crack growth under variable amplitude cyclic loading and understanding the influences of environment and previous load history on fatigue crack growth histories would be especially valuable as input to the "K-handbook" program suggested earlier. Further research into already established areas would also be desirable in order to establish creep crack growth characteristics, explore creep and fatigue interactions, and provide (through testing) crack growth rate-C* correlations for relevant materials and temperatures.

The conditions under which net section stress (σ_n), K, J, and/or C* provide the suitable parameters for engine conditions needs to be clarified through solid mechanics-based studies of the relevant parameters for correlation of creep crack growth under typical oxygen/hydrogen engine conditions. Applicable tools for analyzing creep crack growth would also need to be developed. The J or C* solutions for relevant defects should be developed so that the laboratory correlations with crack growth characteristics can be used to predict the behavior of actual cracked components operated at high temperatures.

Integrating Crack Initiation Analysis with Fracture Mechanics. Many oxygen/hydrogen engine components are currently designed based on a fatigue analysis that assumes an initially flaw-free material. The analysis then proceeds with an S-N type of approach for predicting component lifetime. Since NASA currently has a research project underway to develop procedures for calculating lifetimes under random cyclic loading, and to verify the prediction by comparison with observed service conditions and corresponding failures, a follow-on research program is recommended for developing methodologies that combine the S-N approach with fracture mechanics. This combination provides a consistent tool for life estimation of initially unflawed components that includes both the initiation and propagation of cracks. Improved tools for the treatment of short cracks would be important in the treatment of the early behavior of initiated cracks. Procedures for treating the randomness of the initiation phase would be useful in probabilistic fracture mechanics (PFM) analyses.

Treating Residual and Assembly Stresses. Residual stresses, such as due to welding and assembly stresses, can be introduced into engine components during fabrication. These stresses can have an important influence on subcritical and catastrophic crack growth and should be better characterized. Through-thickness variations due to welding residual stresses have an important influence on the effect such stresses have on the behavior of cracks, and should be included in any research efforts in this area.

Implementing Probabilistic Fracture Mechanics. Improvements in (deterministic) fracture mechanics resulting from research efforts recommended above should be closely coupled to research efforts for expanding the usefulness of PFM for engine components. As a first step, data bases should be developed for improved definition of the statistical distribution of the materials-related random variables. This would include studies of the distribution of toughness of typical engine materials as well as the distribution of cyclic crack growth properties for a given ΔK and cycles to initiation for a given stress history. The applicability and utility of "effective-initial-crack-size" distributions presented in the literature should also be explored, and investigation into initial crack sizes is recommended — including more data on initial crack depth and length, as well as the relationship between these two random variables. The often-made assumption that the crack depth and the aspect ratio are independent should be scrutinized.

It is suggested that any PFM research efforts be coordinated with on-going NASA programs related to NDE of engine components. Coordination of these projects would improve the likelihood that the NDE procedures would concentrate on the most relevant types and features of defects from a fracture mechanics standpoint while also providing the information on flaw detection probabilities necessary for the PFM evaluation. This is not the only research effort that would profit from such coordination, but it is one of the few for which a companion effort can at present be identified.

Optimizing Proof Test Procedures. A coordinated effort is recommended for the development of procedures to apply PFM to the optimization of proof test procedures. The magnitude of proof loading and the number of proof cycles could be optimized based on the cost of various types of failure and their probability of occurrence. Improved J-resistance curve information on engine materials subject to stable flaw growth and improved data bases for random variables would provide important inputs to proof test optimization.

Expanding Existing Technology

Generalization of J-Integral. The J-integral is strictly applicable only to nonlinear elastic materials. This lack of generality makes its use suspect in applications involving either non-monotonic loading or crack growth. Atluri's T-integral[7] appears to be a promising beginning point for efforts to provide a more general parameter for the characterization of crack stress fields and/or energy release rates.

Cyclic Plasticity - Fatigue Crack Growth Interfaces. A research effort aimed at unifying the fracture mechanics approach to fatigue crack growth and the cyclic plastic deformation characteristics of materials would be worthwhile, in that it would unify these two largely independent areas to provide a better and more fundamental understanding of fatigue crack growth. Progress in this area could have an important impact on fatigue crack growth model development -- one of the directions already suggested for development.

Transient Creep Crack Growth. Current theories of creep crack growth assume that creep is occurring under steady-state conditions (i.e., secondary creep). This allows J-integral approaches to be employed, but ignores the transient portion of the creep behavior (primary creep), which could be important for the time-temperature combinations relevant to creep cracking of typical oxygen/hydrogen engine components. As additional information is gained on the creep crack behavior under relevant conditions, the suitability of ignoring transient creep should become apparent. The desirability of a research effort into this area could be assessed at that time.

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