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DEVELOPMENT OF FATIGUE CRITERIA FOR REMAINING LIFE ASSESSMENT OF SHELL STRUCTURES

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ABSTRACT

A technical approach is presented for developing improved fatigue life evaluation criteria for extended life of shell structures. The object is to develop S-N curves which include aging and environmental effects on ductility, strength, crack initiation and crack propagation properties. The use of J-integral approach is proposed for crack growth and high strain cycling along with special consideration for short cracks. The procedure also includes an approach for developing fatigue life evaluation curves for aged weldments based on crack initiation, crack growth and fracture.

INTRODUCTION

Environmental and aging effects are addressed in the design fatigue curves of the ASME Code by assigning arbitrary factors to cycles and strain ranges in the fatigue data for materials tested in an air environment. The proposed approach is to separate the crack initiation and propagation phases of fatigue failure. Fracture mechanics concepts have been extensively used in recent years for the quantification of crack growth rates including environmental effects. Problems in quantifying crack initiation, crack propagation threshold conditions and their dependence on environmental interactions, critical crack sizes for various materials after thermal and strain aging, and other complex issues remain to be resolved. The proposed procedure is to combine the S-N and fracture mechanics approaches in order to make a major improvement in the methods of quantifying the remaining safe life of aged nuclear plants.

There are very significant economic benefits to be gained by extending the life of existing nuclear plants. This can help maintain energy supplies until new plants, based on improved technology are simultaneously designed and constructed. The proposed technique combines the existing S-N fatigue data base and experience in design for fatigue, with major elements of crack propagation technology. It will also provide continuity and logical transition to the eventual inclusion of environmental and aging effects in design criteria for new plants.

USE OF ELASTIC-PLASTIC FRACTURE MECHANICS

We propose to use elastic-plastic fracture mechanics (J-integral) [Ref. 1] concepts to obtain improved S-N curves that incorporate more general crack propagation solutions applicable to the growth of stable fatigue cracks in low-cycle fatigue specimens including the strain hardening exhibited by both ferritic and austenitic steels. Apparent anomalies which have been reported for short fatigue cracks based on linear elastic fracture mechanics can potentially be resolved by J-integral-based methods for the materials and conditions of interest.

The general elastic-plastic crack propagation technology proposed herein will make it possible to accurately evaluate crack sizes in the unnotched low-cycle fatigue specimens starting with the measured failure cycles at each alternating strain level. The effects of thermal and strain aging and irradiation are accounted for by decreased ductility in the S-N curve approach. The low-cycle fatigue end of the S-N failure curve is controlled by the true strain at fracture which is directly related to the reduction of area measured in the tensile test. Changes in the ultimate strength of the material affect the high-cycle fatigue strength.

The stress intensity parameter ΔK is based on linear elastic fracture mechanics, and has been shown to be quite useful in correlating Mode I fatigue crack growth rates where nominal stress ranges do not exceed yield. However for situations involving gross plasticity, such as the low-cycle fatigue tests of interest herein, ΔK has little physical meaning. A more general parameter capable of accounting for large scale plasticity effects is needed for the evaluation of low-cycle fatigue specimens.

In order to more accurately analyze the fracture conditions in a component undergoing nonlinear elastic deformation, the energy available to drive the crack per unit extension, J, has been developed by Rice [Refs. 1 and 2]. For linear elastic Mode I behavior, J is equal to the energy release rate per unit crack extension, G. For nonlinear elastic conditions, J is the potential energy difference per unit of cract extension between two identically loaded bodies possessing slightly different crack lengths. The difference in strain energy, ΔU associated with slightly different crack lengths Δa is shown in Figure 1 and is equal to $J\Delta a$, so that $J = dU/da$ where:

$$J = \int_0^P \frac{\partial \delta}{\partial a}\Big|_P \, dP$$
$$J = -\int_0^\delta \frac{\delta P}{\partial a}\Big|_\delta \, d\delta \qquad (1)$$

where P and δ are the associated loads and deflections.

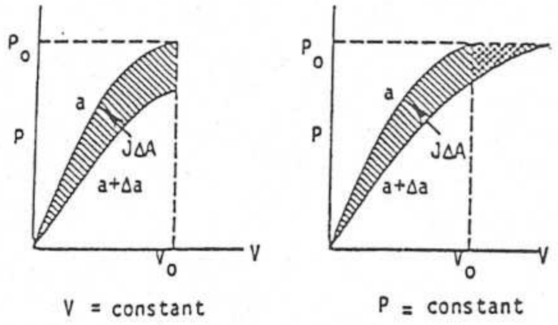

Fig. 1 Determination of J-Integral Based on Fixed Displacement V_o and Fixed Load P_o

Thus for either linear or nonlinear elastic behavior, J is the energy at the crack tip per unit crack extension, or the crack driving force. Under irreversible plastic straining, however, J is no longer equal to the energy available for crack extension. By defining J in the same way for nonlinear elastic and elastic-plastic conditions, J remains a measure of the intensity of the entire elastic-plastic stress-strain field surrounding the crack tip.

As illustrated in Figure 2, J is a line integral taken counterclockwise about an arbitrary contour, Γ, around the crack tip.

$$J = \int_\Gamma W dy - \vec{T} \frac{\partial \vec{u}}{\partial x} \, ds \qquad (2)$$

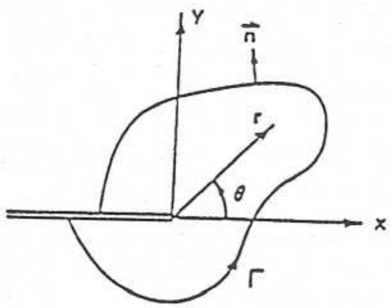

Fig. 2 Coordinate System and Arbitrary Line Contour at Crack Tip

where the strain energy density, W, is:

$$W = \sigma_{ij} d\varepsilon_{ij} \qquad (3)$$

σ_{ij} and ε_{ij}, are the stress and strain tensors, s is the arc length along Γ, $\vec{T}$ is the traction vector for the outward normal $\vec{n}$, and $\vec{u}$ is the displacement vector.

For the case of a closed contour, the line integral of Equation (2) is equal to zero. The line contour begins on one surface of the crack and ends on the opposite surface. For the deformation theory of plasticity, the value of the line integral has been shown to be independent of the path [Ref. 1]. Thus, the line integral can be taken sufficiently remote from the crack tip to obtain reliable stresses and strains for use in the solution, even though considerable yielding occurs. This technique provides a means of extending fracture mechanics concepts from linear elastic (K) behavior to elastic-plastic behavior.

From Equations (1, 2 and 3), J can be evaluated from load vs. displacement records for test specimens containing slightly different crack lengths. Begley and Landes [Refs. 3 and 4] have done considerable work developing the J-integral as an analytical tool for elastic-plastic cracks using this compliance characteristic. For the power law stress - plastic strain relationship, Hutchinson [Ref. 5], Rice and Rosengren [Ref. 6] showed that crack tip stress and strain singularities are functions of J.

Dowling and Begley [Ref. 7] used the range of ΔJ to characterize fatigue crack growth in compact-type (CT) specimens of A533B steel at room temperature under conditions of gross cyclic plastic deformation. Dowling later extended this crack propagation work to other specimen configurations and materials [Refs. 8 and 9] and to the growth of small cracks in low-cycle fatigue specimens [Ref. 10]. Mowbray [Ref. 11] showed that under certain simplifying assumptions, the J-integral approach leads to low-cycle fatigue relationships of the type used in Sections III and VIII of the ASME Code. El-Haddad, Dowling, Topper and Smith [Ref. 12] have shown that ΔJ could be used to characterize the growth behavior of short cracks in low-cycle fatigue.

Figure 3 shows the load deformation and stress-strain hysteresis loops in low-cycle, constant strain amplitude fatigue testing. Cyclic hardening or softening, depending on the metallurgical state of the material, occurs very early in life. Normally, a near-constant steady-state cyclic response is achieved after a number of cycles which is small compared to the number of cycles-to-failure. This

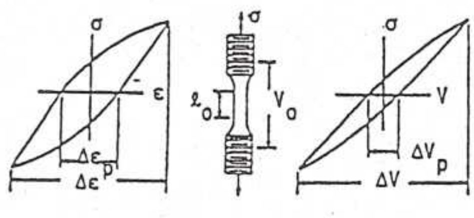

Fig. 3 Strain and Deflection Measurements in Low cycle Fatigue Tests

steady-state response is called the cyclic stress-strain curve and is the locus of the stabilized stress and deformation (converted to strain) values from a series of tests at different strain amplitudes (Figure 4). The plastic strains in the cyclic stress-strain curve can be represented by a power law so that the total strains are:

$$\varepsilon = \frac{\sigma}{E} + (\sigma/A)^n \quad (4)$$

The two terms correspond to the elastic and plastic components of the total strain:

$$\varepsilon_e = \sigma/E, \quad \varepsilon_p = (\sigma/A)^n \quad (5)$$

where
n = cyclic strain-hardening exponent
A = material constant

The cyclic stress strain curves can be used to approximate the J-integral for use in evaluation of experimental data. The use of the J-integral approach for the cyclic plastic conditions experienced in low-cycle fatigue testing, in fatigue crack propagation testing, and in operating nuclear power components is on a sound technical basis. It is therefore proposed to include reactor environmental effects into the fatigue design life assessment methods of Section III of the ASME Code using the Section XI crack propagation technology extended by the J-integral approach to include the large-scale plasticity effects encountered in low-cycle fatigue testing.

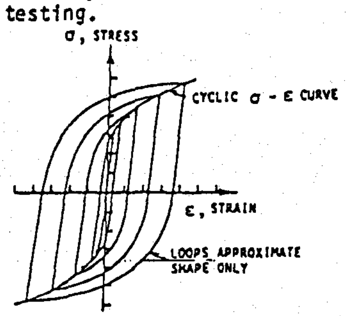

Fig. 4 Hysteresis Loops and Cyclic Stress-Strain Curves

We take A533B as a representative pressure vessel steel characterized by intermediate strength for which the cyclic stress-strain properties are taken from [Ref. 10] and shown in Figure 5. Constant amplitude deflection control across the fatigue specimen ends results in the strain amplitude in the test section being very nearly constant during most of the fatigue life. Figure 6 shows the strain range, $\Delta\varepsilon$, vs. cycles from the A533B tests of [Ref. 10]. Also the plastic strain range $\Delta\varepsilon_p$, was shown to be nearly proportional to the plastic deformation, Δv_p, over the entire range of measurement, as shown in Figure 7. This makes it possible to relate the amount of strain energy in continuum elements near the crack to the overall deformation conditions. Figure 8 shows the fatigue properties including the elastic, plastic and total strain amplitudes vs. cycles-to-failure. Figure 9 shows the compilation of the crack growth data plotted vs. ΔJ for large cyclic deformations in the center-cracked specimen. The

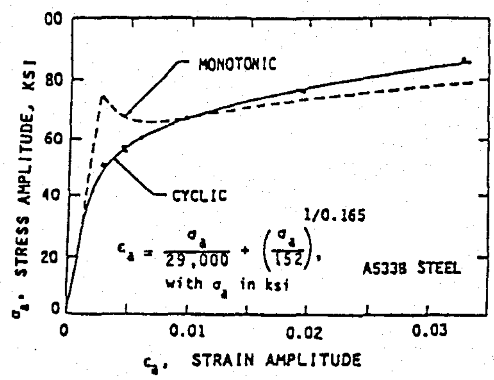

Fig. 5 Cyclic and Monotonic Stress Strain Curves

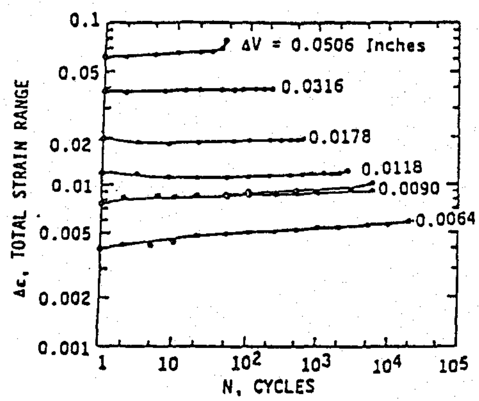

Fig. 6 Variation of Strain Range with Cycles Under Constant-Amplitude Deflection Control

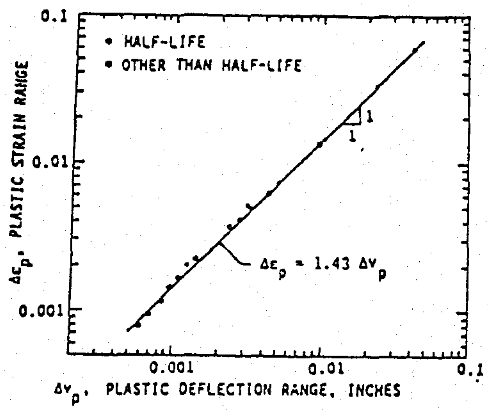

Fig. 7 Proportionality Between Plastic Strain and Plastic Deflection

correlation is quite encouraging.

The upper three curves in Figure 10 taken from [Ref. 13] give the ratio of K(equivalent) from J to K(elastic). It can be seen that the ratios are quite large for large strain amplitudes. The lower two curves give the plastic zone correction, which is quite inadequate, and is close to that used in the Q factor of Section XI of the ASME Code.

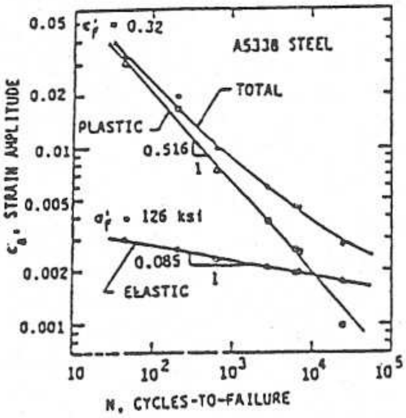

Fig. 8 Low-Cycle Fatigue Properties - Elastic, Plastic, and Total Strain Amplitudes Versue Life

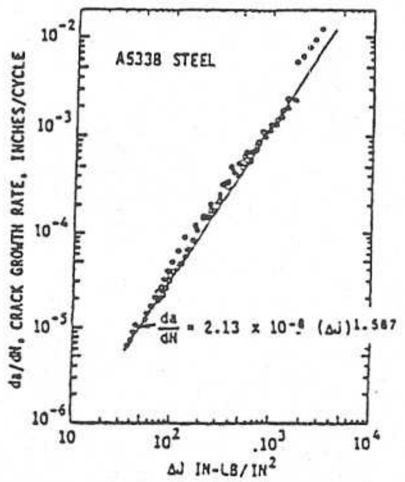

Fig. 9 Fatigue Crack Growth Rate Versus Cyclic ΔJ Data For Elastic-Plastic Tests on Center Cracked Specimens

Crack growth rates are given by:

$$\frac{da}{dN} = C_1(\Delta J)^n \qquad (6)$$

For reactor pressure vessel steel, $n = 1.587$. For failure in 1000 cycles, $\varepsilon_a = 0.74\%$ in air, and $K_{eq}/K = 2$. The error in life is therefore $2^{1.587} = 3$, which means that LEFM overestimates life by a factor of 3. On the steep part of the reactor water curves of Section XI, $n = 2.975$, and a factor of 2 error in K results in overestimating the life by a factor of about 8. This demonstrates the importance of using elastic-plastic fracture mechanics (J-integral) for crack propagation in unnotched fatigue specimens.

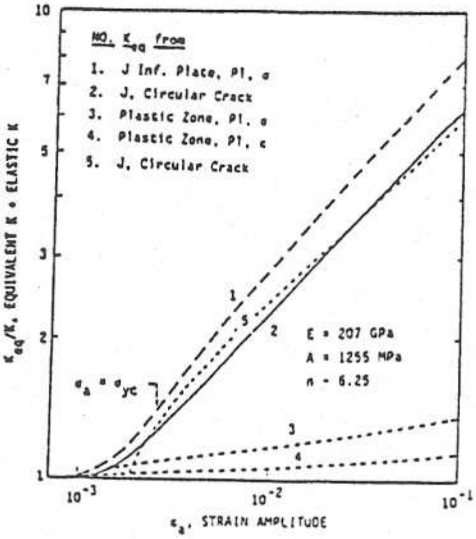

Fig. 10 Plasticity Modified K Based on J and on Plastic Zone Corrections, For Cracks in Infinite Bodies Remotely Stressed Normal to the Crack Plane.

CONSIDERATIONS FOR SMALL FATIGUE CRACKS

The initiation and growth of small cracks is of major importance. The small crack question becomes critical as it represents a regime where there is a possible "breakdown" in linear elastic fracture mechanics analyses. At the same time, sound solutions for this region are very much needed since initiation and growth of small cracks provide a missing link between the S-N classical approach design, and damage tolerant methodologies based on defined tolerant technologies which consider the imperfections and inspection results. This topic is of special importance in assessment of residual life since the time spent when the cracks are incubated or remain small accounts for the large majority of the component life in the high-cycle regime. Subthreshold extension of small cracks may lead to overprediction of life. However, their initial enhanced growth rates often decay to arrest, or in other cases, propagate to merge with the long-term crack behavior. Figure 11 from [Ref. 14] illustrates the complexities of developing growth correlations vs. the range of stress intensities, ΔK.

In studying the available data on small cracks it was observed that in order to obtain measurable crack growths, the tests were often conducted at relatively high nominal stresses and included considerable plasticity. This suggests that the actual driving force was significantly higher than what the LEFM principles predict. The elastic-plastic J value for a small crack in plane strain is given by:

$$J = \frac{(1 - \nu^2)(1.12)^2}{E}\frac{\pi}{Q}\sigma_1^2 a + h(n,g)\sigma_1\varepsilon_p a \qquad (7)$$

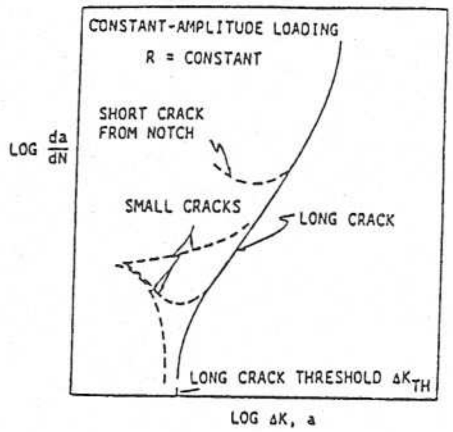

Fig. 11 Schematic Representation of the Typical Variation in Fatigue Crack Growth Rates da/dN, with the Nominal Cyclic Stress Intensity Factor ΔK, or Crack Length a, for "Long" and "Small" Cracks. ΔK_{TH} is the Nominal Threshold Stress Intensity Range Below Which Long Cracks Remain Dormant.

Dowling [Ref. 9], measured the growth of small cracks in low-cycle fatigue specimens of the A533B steel. Figure 12 shows the crack growth data which makes use of Equation (7) to calculate ΔJ for each test. Considering the difficulty measuring accurate sizes in smoothed unnotched low-cycle fatigue test specimens, the correlation of Figure 12 is considered quite good. These results confirm the validity of the ΔJ correlation for crack lengths 0.002 inches or larger in A533B pressure vessel steel.

While the use of elastic-plastic fracture mechanics resolves some of the anomalous crack growth behavior found using LEFM, the short crack problem and related crack initiation issues need further study. Short cracks in various materials have been observed to propagate below the threshold ΔK levels which have been found for long cracks.

AGING AND ENVIRONMENTAL EFFECTS

Crystalline defect theory and the use of electron microscopy have contributed immensely toward the understanding of the factors involved in the initiation of fatigue cracks. For practical purposes, it is useful to consider three phases of crack initiation:

1) the generation of persistent slip bands,
2) the initiation of permanent damage, and
3) the coalescence of micro-voids to form a crack.

Fatigue damage appears to begin as a sequence of small cavities oriented on the persistent slip bands. Such cavities increase in number and size, ultimately joining to form either a continuous microcrack or shallow surface intrusion. The stress and strain amplitudes and the number of active slip systems does not change the basic process of crack initiation, but only the rate and mode of cavity coalescence.

Environmental and aging effects on crack initiation are not well understood from a a mechanistic point of view, nor have they been well quantified by tests. We therefore take a pragmatic approach of using high-cycle fatigue life

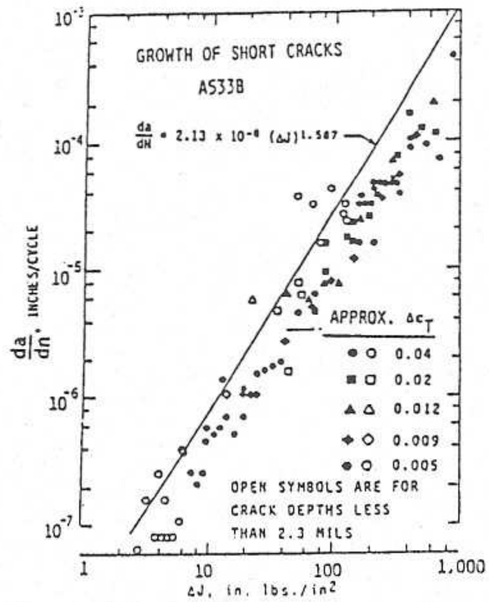

Fig. 12 Crack Growth Data for Short and Very Short Cracks Compared with "Best Fit" Line for Long Cracks

measurements, generalized by crack initiation models, to include such effects in the total fatigue life evaluations. Progress in the understanding and quantification of crack initiation can then be used to make further improvements in the S-N curves and in the related inspection program requirements.

As far as environmental effects on crack growth are concerned, the process is primarily electrochemically related. As such, the propagation rate is controlled by reaction rates on the crack tip and how these are affected by the passivation rate, liquid diffusion rate, and strain rate at or near the crack tip. Knowledge of the interaction between these controlling processes helps to quantify the testing conditions which will produce the most meaningful and useful results, and applications of a mechanistic understanding allows the data to be extended to a broader range of conditions than those tested.

Corrosion-assisted crack growth rates depend not only on the material, temperature and coolant chemistry, but on the strain rates, loading waveform, stress intensity range, temperature and flow conditions, maximum stresses and sequence of loading. The existing ASME Code Section XI Appendix A crack growth curves for reactor water environments do explicitly account for the mean stress by the R ratio dependence. These are the upper two curves in Figure 13, which are shown with the air environment curve previously described. In the S-N fatigue life technology of Sections III and VIII of the ASME Code, the fatigue curves are adjusted for the maximum effect of mean stress which is potentially more conservative than the Section XI treatment.

Strain rate is another important variable not explicitly included in the Section XI crack growth evaluation method. The Appendix A curves are based on test frequencies between 0.1 and 1 cycle per minute which were found to produce high growth rates in A533B. The rate of rupture of a passive film at the crack tip or the rate of metal surface exposure at the crack tip is related to the crack tip strain rate. Although it is recognized, it is not feasible to use crack tip strain rates directly in a life

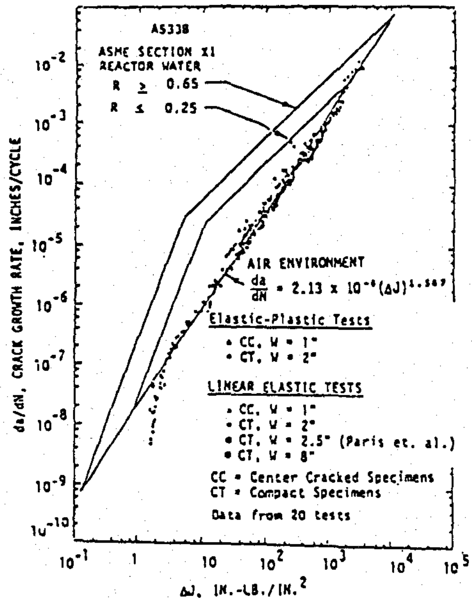

Fig. 13 Comparison of Fatigue Crack Growth Rates For Reactor Water Environment from ASME Section XI with Rates for Air Used Herein Based on ΔJ

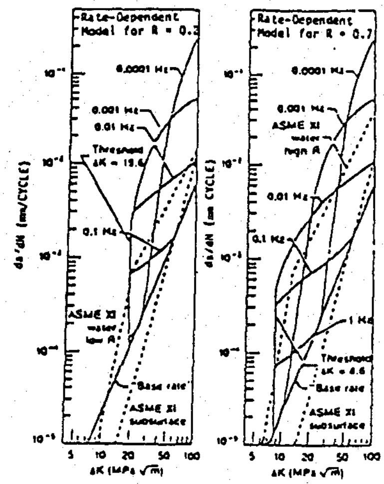

Fig. 14 J. D. Gilman (EPRI) Theoretical Time-Frequency Dependent Crack Growth Predictions for A533-1 Steel in Reactor Water Environment

assessment evaluation. Gilman [Ref. 15] and others have worked with rate dependent models which recognize that the corrosion-cracking component of crack growth is time-dependent rather than cycle-dependent. Such models are quite useful in predicting long-term behavior from short-term laboratory measurements of crack growth rates. [Ref. 15] results for A533B material for BWR and PWR environments are illustrated in Figure 14 along with the Section XI curves. These results indicate that the Section XI curves are sensible but there may be much higher crack growth rates at low-cyclic frequencies.

LIFE EVALUATION CURVES FOR WELDMENTS

The fatigue life of aged weldments may be expected to control the useful safe life of many components. Our approach is to treat the imperfections inherent in production welds of nuclear grade quality, including the effects of residual welding stresses. An extensive literature survey concerning weld discontinuities was completed for PVRC by Lundin [Ref. 16].

The elastic-plastic crack propagation methods developed for unnotched fatigue specimens can be extended to include cracks growing from imperfections such as porosity and inclusions in weldments. Low-cycle fatigue behavior of weldments will be quantified by considering the nucleation and growth of fatigue cracks from the imperfection into plastically deformed material. The role of imperfections in the failure response of weldments is complicated by the nonuniform nature of the residual stress distribution. In the case of residual stress, retained tensile residual stress must be assumed unless there is evidence justifying a less conservative approach.

The total fatigue life of a weldment can be considered to be equal to the number of cycles required to initiate a micro-crack at an imperfection to a size which reduces the remaining cross-section such that it will no longer support the cyclic load. The weldment then fails by ductile or brittle fracture. The low-cycle life of a weldment in a thick section is dominated by the crack growth phase. The high-cycle fatigue endurance strength is usually dominated by crack initiation and the early phase of crack growth where the crack is reorienting perpendicular to the maximum stress direction.

The complicating issue for weldments is the treatment of crack nucleation and short-crack growth in the presence of gross plasticity effects. To deal with this, we propose to use the J-integral formulation as applied to cyclic plasticity. The J-integral formulation will be used to study the growth of short and long cracks with cyclic plasticity. The needed ingredient required to extend the procedure to deal with weldments is the J-integral solution for cracks emanating from blunt notches which characterize weldment imperfections. Solutions for such models will be used in conjunction with crack-growth rate correlations to compute the fatigue life S-N curves for air and water environments. The S-N endurance data will anchor the curve at the high-cycle end. Design curves for weldments can then be generated by applying the appropriate factors. Metallurgical notch effects and geometric fatigue strength reduction factors are applied to the nominal stresses before entering the life evaluation curve.

ADDITIONAL ISSUES IN DEVELOPMENT OF IMPROVED FATIGUE LIFE EVALUATION TECHNOLOGY

There are a series of technical issues which can have a significant effect on the assessment of the residual life:

1. Factors used to Account for Scatter in Fatigue Data, Surface Finish Effects, Size Effects, and Environmental Effects.
   Environmental effects such as reactor water can be explicitly taken into account using S-N data obtained in the appropriate environment, or by using their known effects on crack initiation and growth rates to adjust the S-N curves using the J-integral approach proposed herein. The existing Code Design fatigue curve is based or

applying a factor of 2 on the total strain range, and a factor of 20 on cycles to each point on the "best fit" failure curve to account for data scatter, surface finish effects, size effects and environmental effects. The factor of 2 on strain range governs in the high-cycle regime and the factor of 20 on cycles governs the low-cycle regime. Since the data were obtained using completely reversed deflections, corrections were made in order to include "worst case" mean stress effects. Use of more involved methods in the development of fatigue curves should justify reevaluation of safety margins in order to eliminate undue conservatism.

2. Loading Sequence Effects
The ASME Code design criteria uses a linear cumulative damage rule, the inaccuracies of which have long been recognized. The sequence of loading is known to have a major effect on the damage accumulation. Of particular concern is the possible early crack initiation which could occur under large strain ranges occurring during shakedown early in life. Such cracks could propagate under the "endurance limit" of the unnotched material which was used as the basis for the design curves currently in the Code.

3. Extension to Very High Cycles
An effort is under way to extend the fatigue design curves for carbon and low-alloy ferritic steels beyond one million cycles in order to include flow-induced high-cycle thermal fatigue and mechanical vibrations. Mean stress and environmental effects are quite significant in the high-cycle regime. Little information is available and the test data for very high cycles are difficult to generate.

4. Crack Initiation Technology
Analytical methods of treating crack initiation are needed to formulate more effective inspection programs. Such methods will serve to identify the location of critical areas which are expected to include stress raisers in addition to weldments. The predicted cycles to crack initiation will provide a sound basis for specifying inspection locations and intervals.

5. Propagation of Multiple Cracks
It is not unusual to find a series of small cracks during in-service inspections. More accurate methods of accounting for interaction effects on their propagation behavior are needed.

6. Methods of Accounting for Severe Thermal Transients
Rapid thermal transients involving large temperature variations and complex heat transfer conditions may induce early crack initiation and significant fatigue damage. More accurate means of quantifying such damage would improve the residual life assessments.

7. Safety Margins for Instability for Cracks
The stability of fabrication, stress corrosion and fatigue induced cracks raise safety margin issues, particularly under complex conditions involving weldments, stress raisers, aging and/or irradiation effects, and level D loading.

8. The Loss of Toughness with Aging of Castings
Certain cast stainless steels are known to lose most of their toughness with thermal aging. Thus, they may be subject to brittle failure modes not covered by current safety margin criteria.

CLOSURE

The Pressure Vessel Research Committee in cooperation with ASME Code Committees has been quite effective in providing industry with improved criteria for the design, inspection and fabrication of structural components. Our approach is intended to focus research and development efforts in the emerging technology of Plant Life Extension in order to develop the desired life extension criteria using limited available national resources. The focus is on development of fatigue life evaluation methods based on use of S-N curves, modified in accordance with advanced fracture mechanics solutions and extensive stable crack growth rate test results now available. Although results obtained by traditional fatigue testing of smooth specimens has provided a sound technical design basis for shell structures, improved accuracy and reliability are needed for residual life assessments. Our approach makes maximum use of available world-wide data quantifying the effects of aging and environmental influences on the properties of the relevant structural materials. Effects on material strength, ductility, notch sensitivity, fatigue resistance will be integrated into a quantified criteria for evaluating the residual operating life which remains within ASME Code safety margins. Program to develop improved fatigue design criteria is given in the Appendix. The program has been approved by ASME Subgroup on Fatigue Strength and the Subcommittee on Design.

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PROGRAM TO DEVELOP IMPROVED CUMULATIVE FATIGUE DESIGN CRITERIA IN ASME BOILER AND PRESSURE VESSEL CODE

Background

The ASME Boiler and Pressure Vessel Committee is attempting to develop improved cumulative fatigue design curves and criteria which take advantage of the major developments which have occurred in the technology since the current criteria were written into the Code over twenty-five years ago.

The Seven Part Program Plan which has been developed for this purpose is described herein. The first two Parts are in Category I, Work In Progress by ASME Code committees. The last five Parts in Category II, Future Work, include environmental and aging effects.

In addition to the need for improved fatigue design criteria which include aging and environmental effects, the Code needs criteria for evaluating the safe residual life of all hardware. Such rules would make it possible to evaluate the operative life extension which continues to meet Code fatigue safety margins. In spite of recent advances, inspection technology is not yet totally reliable, and these are areas not accessible for inspection. S-N technology provides a proven means of evaluating residual safe operating life without depending on inspection results.

Category I: Work In Progress

Part 1: Updating of fatigue design curves for carbon, low alloy and high tensile steels to include updated fatigue data. (This requires extensive data evaluations, parameter analyses and sensitivity studies.)

Part 2: Extension of carbon, low alloy and high tensile steel fatigue curves beyong 10^6 cycles to include mechanical vibrations, thermal striations, thermal striping and mean stress effects studies and consideration of threshold crack initiation technology.)

Category II: Future Work

Part 3: Upgrade cumulative fatigue usage factor quantification methods. Include loading sequence, size, and surface finish effects where cracks initiated in low-cycle regime could propagate well below the endurance limit in the high-cycle regime. (This requires sensitivity, studies of crack initiation and subsequent propagation under varying stress range loading conditions.)

Part 4: Inclusion of reactor water environmental effects in the fatigue design curves for carbon, low alloy and high tensile steels. (This requires extensive elastic-plastic crack propagation analyses using available worldwide data for ferritic steel crack growth rates in reactor water.)

Part 5: Inclusion of reactor water environmental effects in the fatigue design curves for austenitic steels and nickel chromium, iron, and copper alloys. (This requires evaluation of worldwide data for austenitic stainless steel and crack growth rates in reactor water, and extensive elastic-plastic crack propagation analyses.)

Part 6: Development of fatigue design curves for ferritic and austenitic weldments including the effects of welding residual stresses, acceptable imperfections and metallurgical notch effects. (This requires extensive weldment fatigue data analyses, consideration of early crack initiation in the heat-affected zone (HAZ) due to metallurgical notch effects and residual stress effects. Extensive elastic-plastic crack propagation analyses must be carried out for cracks growing from acceptable imperfections with mean stress effects.)

Part 7: Development of fatigue life evaluation curves which include aging as well as reactor water environment effects for ferritic and austenitic steels and weldments. Such curves will provide a criterion for nuclear plant life extension beyond forty years. (This work builds on all six of the first six Parts of the effort described above. The effects of aging on the crack initiation and propagation elements of fatigue failure will be included in the curves, accounting for any reduced toughness and ductility, and the increased notch sensitivity of the materials and weldments.)

Part 8: Development of improved analytical procedures for performing fatigue analysis. (This