Fatigue and corrosion fatigue data analysis using FATDAC

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ABSTRACT

This paper describes FATDAC, an interactive fatigue and corrosion FATigue Data Analysis Code. FATDAC provides a variety of analysis techniques, including: (1) an optimization process which minimizes the numerical scatter in da/dN that arises from differentiation of (a,N) data, (2) a feature for combining data from many investigators while taking into account the varying amount of crack extension or life represented by each point, (3) weighted least squares techniques for fitting standard or user-defined models, (4) analysis of corrosion fatigue effects by state-of-the-art time domain analysis techniques, and (5) methods for handling outliers, confidence bounds or intervals, printing and plotting.

1 INTRODUCTION

For more complete understanding of corrosion fatigue phenomena it is desirable to combine fatigue data generated by different investigators under similar test conditions and analyze all data together. Before data pooling can be performed, however, differences between investigators in data acquisition and data reduction techniques must be addressed. The Δa or ΔN measurement intervals generally vary by investigator, and may vary for different tests by the same investigator. This problem has been magnified by computerized testing, which allows data to be collected at much smaller increments compared to manual techniques. Different data collection intervals result in different numbers of (a,N) points per specimen, so with standard data reduction techniques the number of (da/dN,ΔK) points will differ from test to test. This can cause problems when modeling, as specimens with many (da/dN,ΔK) points can dominate curve fits to a collection of data which includes many equally-valid specimens with fewer points. Other data reduction differences include the method of (a,N) differentiation (some methods introduce more scatter than others), the type of model fitted to (da/dN,ΔK), and the method of determining model parameters.

The need to analyze data pooled from many sources with minimum numerical error has been recognized by several organizations, including the Electric Power Research Institute (EPRI), the International Cyclic Crack Growth Rate Committee and the Metal Properties Council Task Force on Crack Propagation Technology. EPRI is funding projects to (1) create a unified data base of nuclear reactor materials, called EDEAC (EPRI Database for Environmentally Assisted Cracking) (Mindlin et al 1986), and (2) develop an advanced data analysis code FATDAC (FATigue Data Analysis Code), the subject of this paper.

The following list outlines the main FATDAC features, which are more fully described in subsequent sections:

1) (da/dN,ΔK) data may be calculated from the experimental (a,N) data using an optimization routine to minimize scatter, or through the conventional secant and seven-point polynomial methods.

2) Corrosion fatigue effects can be assessed by considering crack growth on a time domain basis, in either $\dot{a}_e$ vs. $\dot{a}_b$ or $\dot{a}_e$ vs. $\dot{\varepsilon}$ format.

3) A variety of models, including user-defined models, can be fit to the (da/dN,ΔK), ($\dot{a}_e$,$\dot{a}_b$) or ($\dot{a}_e$,$\dot{\varepsilon}$) data.

4) Confidence intervals or bounds can be developed for the (da/dN,ΔK) data or the associated models.

5) (da/dN,ΔK) points, or models fitted to the points, may be integrated for comparison with the original (a,N) data.

6) Outliers in (a,N), da/dN, or da/dt data may be identified either manually or through statistical or ASTM criteria, and they can be included or excluded in modeling as desired.

7) (da/dN,ΔK), ($\dot{a}_e$,$\dot{a}_b$), and ($\dot{a}_e$,$\dot{\varepsilon}$) data from many different tests can be merged into a single set. The data can be weighted by the amount of crack growth or life (cycles) represented by each point.

8) Many data sets may be automatically processed through the same path.

9) Output may be printed or plotted or saved in a permanent file.

2 DESCRIPTION OF FATDAC

FATDAC is an interactive, modular, menu-driven computer program developed for the analysis of fatigue and corrosion fatigue data. The structure of the code is shown in Figure 1. The source code is written in FORTRAN 77, and it is currently running under VMS 4.3 on a VAX 11/785 computer. FATDAC is specifically designed to interface with the EDEAC database, using the EDEAC accession numbers to identify each data set. However, the code also allows the user to analyze (a,N) or (da/dN,ΔK) data that are not included in this database.

2.1 (da/dN) Calculation

FATDAC calculates da/dN from (a,N) data developed in either constant load range or constant ΔK tests. If the test is of the constant ΔK type, line segments are fit over Δa or ΔK intervals in the (a,N) data by least squares, determining da/dN for each interval. For constant load

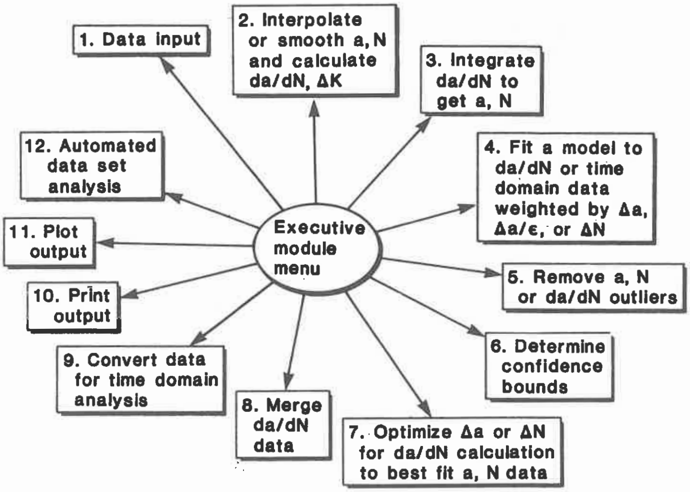

Figure 1. FATDAC modular program structure.

range tests, the user has three options. Conventional secant or seven-point polynomial methods as prescribed by the ASTM E647 standard (ASTM 1984) can be used, or an optimized method can be utilized. This latter technique allows the user to fit linear or exponential functions over optimally-sized Δa or ΔN intervals, calculating (da/dN,ΔK) by evaluating the derivatives at the points of average slope in each interval. The optimized technique generally produces superior results compared to the ASTM methods.

The size of the Δa or ΔN differentiation interval is a critical issue when attempting to reduce the numerical data scatter (Clark and Hudak 1974, 1979, Wei et al 1979, Ostergaard et al 1981). The differentiation interval must be large relative to the experimental error in crack length measurement, or the da/dN points will have excessive numerical scatter. Hence, these intervals are key variables for data analysis. Within FATDAC, the differentiation interval may be:

(a) defined by the (a,N) point spacing (the ASTM approach);
(b) chosen by the user; or
(c) optimized to minimize the deviations between the original (a,N) data and the curve produced by integrating the final (da/dN,ΔK) points.

2.2 Optimized Differentiation Intervals

The optimization technique is shown schematically in Figure 2. The user selects the type of differentiation interval (Δa or ΔN) and its allowable range (defaults are provided). FATDAC then selects a trial differentiation interval Δa or ΔN within the allowable range, and divides the (a,N) data into intervals of this size. Smoothing functions

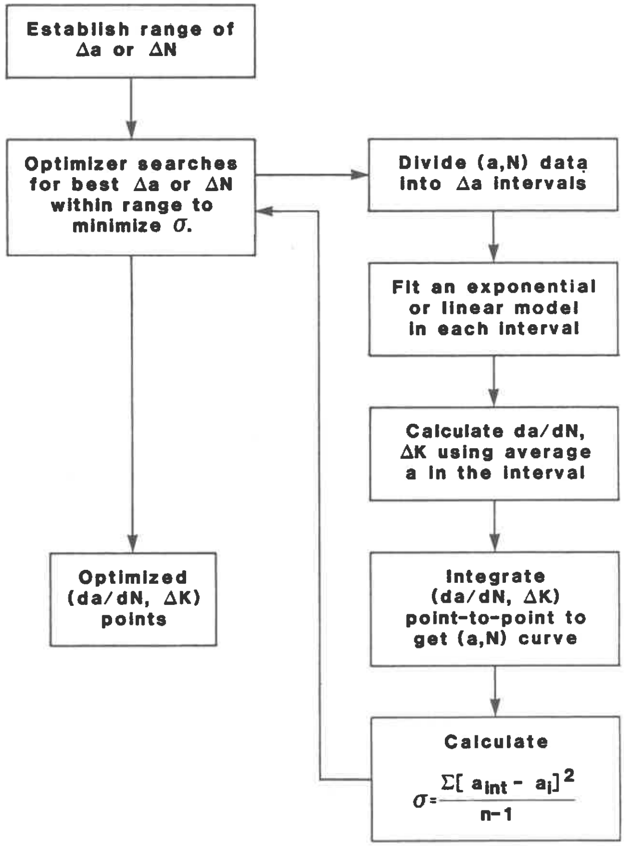

Figure 2. Logic of interval optimization for minimum deviation from (a,N) data

(linear or exponential) are fitted over each interval, and a (da/dN,ΔK) point is computed at the average slope in each interval. These (da/dN,ΔK) pairs are then integrated point-to-point to produce an (a,N) curve. A straight line on log-log coordinates is assumed between (da/dN,ΔK) points (in sequence) to allow integration steps to be independent of (da/dN,ΔK) point spacing. The sum of the squared deviations between the original (a,N) points and the integrated (a,N) curve is computed for the trial differentiation interval. This process is then repeated with new differentiation intervals chosen by the optimizer until the value of Δa or ΔN that minimizes the sum of squared deviations has been found.

Use of the optimized technique with Δa intervals on hundreds of pressure vessel steel specimens tested in air, Boiling Water Reactor (BWR), and Pressurized Water Reactor (PWR) environments, has shown that most constant load range data sets can be accurately represented by 5 to 10 (da/dN,ΔK) points. The resulting improvement in da/dN scatter, compared to secant or 7-point polynomial differentiation of the (a,N) data, can be significant, as illustrated in Figure 3 for a single pressure vessel steel specimen tested in air. The (a,N) data and the

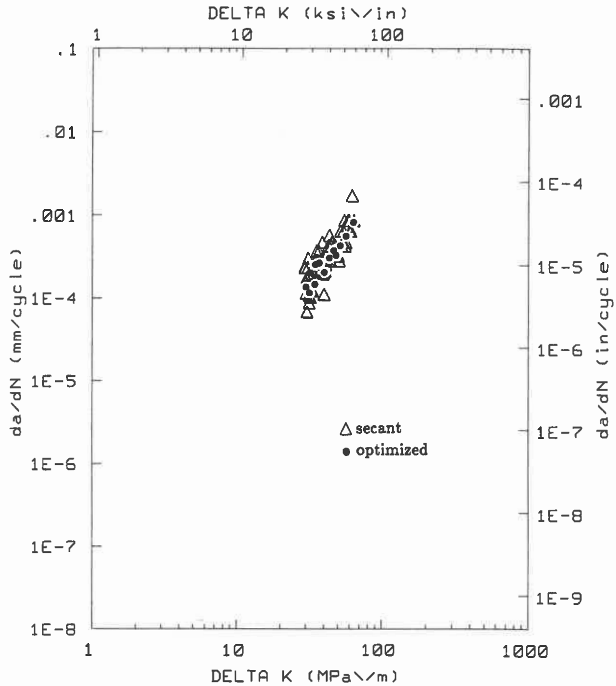

Figure 3. Comparison of scatter from secant and optimized differentiation.

integrated curve resulting from the optimized differentiation intervals are shown in Figure 4. It is clear in Figure 4 that the optimized technique is capable of smoothing through minor perturbations in the (a,N) data while accurately following the major changes in shape. As the experimental error in the (a,N) data increases, more scatter is observed in da/dN values from the secant and polynomial methods, increasing the advantage of optimizing the differentiation interval.

2.3 Time Domain Analysis

FATDAC allows for the analysis of corrosion fatigue data by both frequency domain (da/dN) and time domain (da/dt) methods. The particular time domain methods have been presented in recent work (Shoji and Takahashi 1983, Shoji et al 1981, Gilman 1985, Ford 1986 and Ford et al 1985). The basic approach is to compare the crack growth rate in the environment, $\dot{a}_e$, with a baseline rate $\dot{a}_b$. FATDAC calculates both of these time domain growth rates and allows the user to fit models to the $(\dot{a}_e,\dot{a}_b)$ data.

The baseline fatigue crack growth rate $(da/dN)_b$ is calculated from applied ΔK values using an appropriate crack growth model, such as a Paris fatigue model fitted to air or inert environment data. The time domain rate is then calculated from:

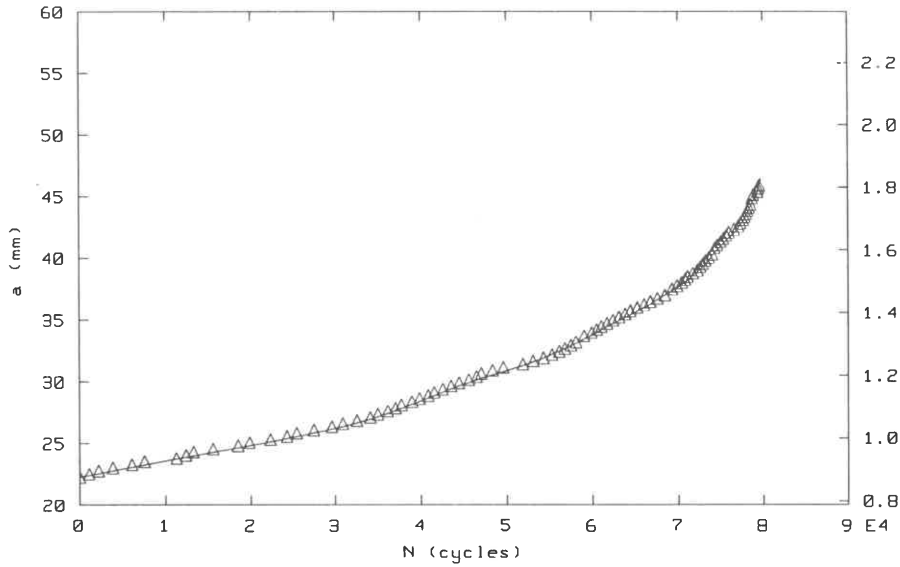

Figure 4. Original data and curve integrated from optimized points.

(1) $\dot{a}_b = (da/dN)_b(\frac{1}{t_r})$

where t_r is the period of the rising-load portion of the loading cycle. The environmental crack growth rate is determined by calculating $(da/dN)_e$ from (a,N) data taken in the corrosive environment, then converting to time domain $\dot{a}_e$ by using $(da/dN)_e$ in place of $(da/dN)_b$ in equation 1.

An example of this type of environmental rate calculation is shown in Figure 5. The bilinear shape is characteristic of tests exhibiting an environmental enhancement in crack growth rate relative to the base rate (which was crack growth rate in air in this case).

The strain rate approach developed by Ford (1985, 1986) and others shows promise for fundamentally understanding corrosion fatigue effects. This approach is based on theoretical relationships between crack tip strain rate, $\dot{\varepsilon}$, and the environmental crack growth rate. The strain rate approach is the underlying theory behind the $\dot{a}_e$ vs. $\dot{a}_b$ approach; the connection between the two approaches is $\dot{\varepsilon} = f(\dot{a}_b)$. In the strain rate correlations, the environmental (time-domain) crack growth rate is calculated as previously described, then FATDAC calculates $\dot{\varepsilon}$ using the models proposed by Ford (1986). An option is available for users to input their own crack tip strain rate models. The resulting strain rate and crack growth rate values can be modeled through a power law equation:

(2) $\dot{a}_e = A\dot{\varepsilon}^n$

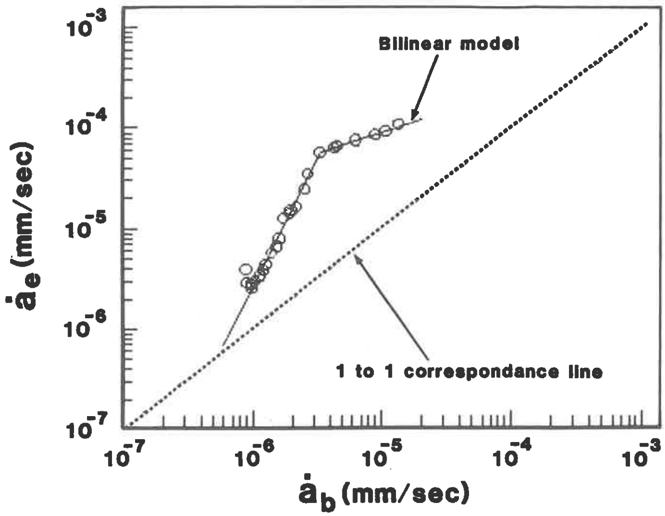

Figure 5. Total environmental rate vs base rate plot.

and plotted on $\dot{a}_e$ vs $\dot{\varepsilon}$ plot, as shown in Figure 6. The slope of such curves is typically less than unity, as it is here.

2.4 Modeling Capabilities

FATDAC currently is able to fit Paris, piecewise Paris (up to 5 segments), Walker, or user-defined models to (da/dN,ΔK), and additional models are under development. Time domain $\dot{a}_e$ vs $\dot{a}_b$ correlations can be fit with a linear or piecewise linear model, and $\dot{a}_e$ vs ε correlations can be fit with equation 2. The piecewise linear model is especially useful for modeling corrosion fatigue data, which can exhibit bi- or tri-linear behavior, and for modeling apparent ΔK thresholds.

Paris models are fit by linear least squares procedures, whereas the other models use a nonlinear least squares algorithm. All methods allow the minimization of either vertical or horizontal residuals, and the piecewise model also allows minimization of perpendicular residuals.

Fits in both the horizontal and vertical direction are statistically valid in that they both minimize residuals in a particular direction. Neither approach is fundamentally "correct" in fracture mechanics correlations, because both the abscissa and ordinate contain a combination of experimental and analytical error. In addition, when dealing with large collections of data, the numerical effects of scatter are more important to the result than any theoretical consideration of the proper direction for fitting. The authors have standardized on the use of horizontal residuals for (da/dN,ΔK) correlations where the slope is greater than two, and vertical residuals for ($\dot{a}_e$,$\dot{a}_b$) or ($\dot{a}_e$,ε) correlations where the slope is less than or equal to one.

When fitting models, FATDAC allows four data weighting options. The purpose of this weighting is to give equal weight to equal crack growth or number of cycles when fitting (da/dN,ΔK) or time domain models, regardless of the number of points determined experimentally or analytically. The weighting options available are:

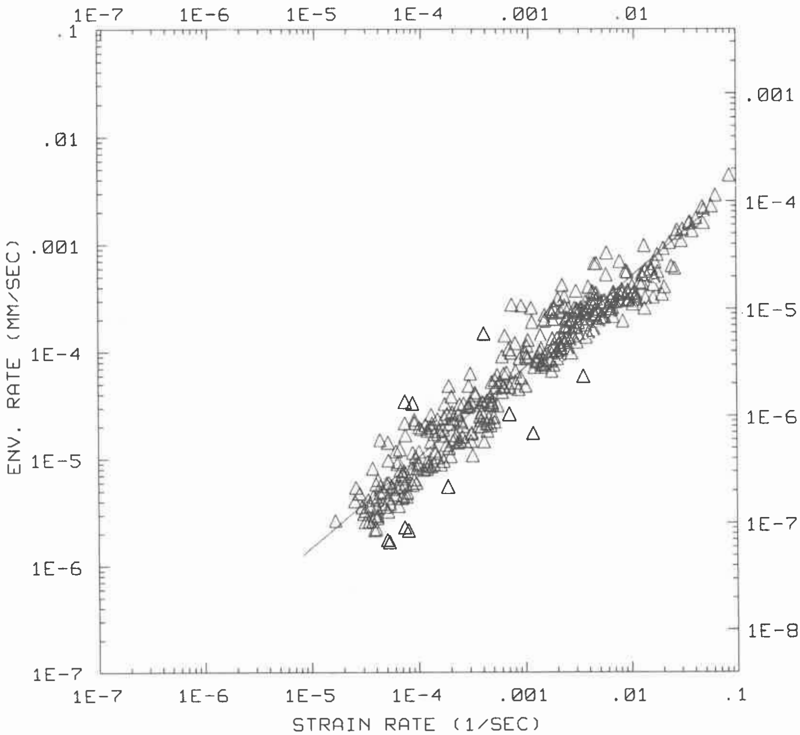

Figure 6. Environmental rate vs cyclic strain rate.

(1) uniform (each point has equal weight);
(2) by crack extension (Δa) corresponding to each ($da/dN, \Delta K$) point;
(3) by life expended (ΔN) per point; and
(4) by the ratio of crack extension to measurement precision ($\Delta a/\varepsilon$) per point.

2.5 Merging and Automated Path Capabilities

FATDAC facilitates combining and analyzing ($da/dN, \Delta K$) and time domain data from multiple data sets. Through this option, as many as 2000 points or 400 data sets may be combined, stored, analyzed, and saved as a permanent file. When storing these merged sets, the differentiation intervals (Δa) used in calculating da/dN, rise time for calculating da/dt, R ratio, frequency, temperature and other test variables are also stored along with the appropriate outlier status information.

When the user wishes to process many data sets by the same path through the code, the process of answering the same menu-driven questions over and over again becomes tedious and time consuming. Hence, the code can be programmed to automatically process a list of many data sets through the same path. As each set is analyzed, the results can be added to the merge file. Any logical combination of modules can be placed within this path, and the list of data sets to be processed can either be created while inside FATDAC or separately, using the system editor. Each defined path and data set list can be stored and retrieved whenever the automated analysis option is chosen. After all data sets have been processed, a list of any processing errors and the associated data sets are displayed at the terminal and stored in a permanent file. This allows automated processing of all but the exceptional specimens, which can then be analyzed in detail by choosing options from the menus.

2.6 Outlier Identification and Removal

In any data set, the user may question the validity of certain points and decide to ignore them in a particular phase of analysis. FATDAC has three options available for outlier identification, manual selection of points, Chauvenet's criterion, and ASTM criteria. Once a point is declared an outlier, it is not actually deleted from the data set, but rather is flagged as an outlier in FATDAC. When other modules are entered with the same data set, the user has the option of including or excluding outliers in the analysis.

Manual outlier identification can be applied to (a,N), (da/dN,ΔK), ($\dot{a}_e$,$\dot{a}_b$) and ($\dot{a}_e$,ε) data. It allows one or more individual points to be identified as outliers. Chauvenet's criterion (Young 1962:78) is a statistical method that identifies all points with low probabilities of occurrence as outliers. Since this method identifies points that are a specified number of standard deviations away from a fitted model, it is only available for (da/dN,ΔK) points after fitting a model. The ASTM criteria within FATDAC will identify points that violate the linear elastic fracture mechanics criterion, or points with less than a 10^{-5} mm/cycle crack growth rate, according to ASTM E647 (1983).

2.7 Other Features

Three types of confidence intervals or bounds, with confidence levels of 90, 95, 99, and 99.9 percent, are available:

(1) bounds on the (da/dN,ΔK) data (assuming a lognormal distribution in da/dN);
(2) bounds on the values of the slope and intercept (Paris model only); and
(3) hyperbolic bounds on the mean model line.

This last type of bound includes the effect of variations in both slope and intercept, but all three bounds are based on the usual simplifying assumption that all errors are in the vertical direction. None of these bounds account for the correlation between the fitted Paris model slope and intercept that is evident in low alloy steel and other materials. Because of the above assumptions, the confidence levels are approximate.

Two types of integration are available in FATDAC, point-to-point integration of (da/dN,ΔK) data, and integration of any (da/dN,ΔK) model. Point-to-point integration is performed on a, using a modified trapezoidal integration method, assuming the (da/dN,ΔK) points are connected in sequence by piecewise Paris models. The integration interval, Δa, can be either uniform or successively larger multiples of Δa_0 (i.e.: $\Delta a_2 = 1.01\Delta a_1$, $\Delta a_3 = 1.01\Delta a_2$...). The starting point for the integration can be the minimum value of crack length from the experimental data or any user-defined point. Model integration is performed by directly integrating the analytic model using a trapezoidal rule.

The printing and plotting routines allow real-time terminal display of the FATDAC analysis results. The plot option offers a full complement of plots (complete with symbol control) including optimization output, (a,N), (da/dN, ΔK), and time domain ($\dot{a}_e,\dot{a}_b$) and ($\dot{a}_e,\varepsilon$) points, models and bounds. Similar information is available through the print routine, whose output may also be sent to a permanent file for future recall. In addition to printing and plotting, FATDAC also can automatically document the path followed through the program.

3 EXAMPLE

An example illustrating several FATDAC capabilities is shown in Figure 7. This plot contains about 1150 da/dN data points from over 240 specimens of pressure vessel steel tested in air at various frequencies, R ratios, and temperatures, by investigators from all around the world. A 3-parameter model of the form used by Yuen et al (1974) was fitted to a four-fifths subset of the data,

$$(3)\quad da/dN = 7.87 \times 10^{-8} \left(\frac{\Delta K}{2.88 - R}\right)^{3.07} \quad \text{mm/cycle}$$

where ΔK is in MPa $\sqrt{m}$. The points have been normalized to the same condition as the model and confidence interval ($R = 0.1$) to display the degree of agreement. Certain points are solid to indicate that they are outliers because of linear elastic fracture mechanics criteria, manual selection or Chauvenet's criterion.

The ASME Section XI code line (1983) for evaluating subsurface flaws in pressure vessels is also shown in Figure 7. It is apparent that the slope of this code line,

$$(4)\quad da/dN = 4.77 \times 10^{-10}(\Delta K)^{3.276} \text{ mm/cycle}$$

where ΔK is in MPa $\sqrt{m}$, is steeper than the best-fit air data curve. Equation 3 was fitted using horizontal (ΔK) residuals, which gives it the steepest slope that can be justified by the data. It is apparent that some refinement in the code line is now possible. The development of equation 3 is documented in detail in Eason et al (1987) and described in a companion paper in this conference.

4 CONCLUSIONS

The FATDAC software has proven to be a convenient method for analyzing fatigue and corrosion fatigue data. It is capable of handling massive amounts of data with careful, consistent analysis of each individual specimen. Based on synthetic benchmarks and actual applications to hundreds of data sets, the optimized differentiation provided within FATDAC is generally more accurate in reproducing the (a,N) data and produces less scatter in calculated da/dN than the ASTM secant and 7-point polynomial methods.

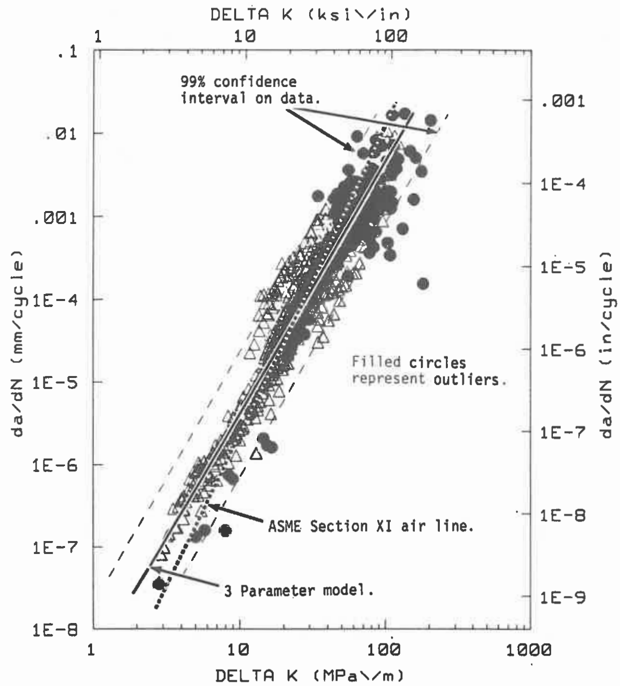

Figure 7. Data normalized to 3 parameter model at R = 0.1 with 99% confidence interval.

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