Probabilistic Fracture Mechanics Analysis to Justify Inservice Inspection Intervals for the Helms Penstock Field Welds

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Abstract

Inservice inspection of welds in hydroelectric facilities is performed to maintain assurance that adequate margin exists against postulated failure scenarios. Inservice inspections can be very costly and time consuming, especially when performed from the inside of tunnel liners or penstocks. Performance of appropriately timed inservice inspections can help reduce the cost of unnecessary inspections. Failures can be prevented by performing inspections that consider the fracture mechanics aspects of the material being evaluated. Deterministic fracture mechanics (DFM) methods are typically used to ascertain allowable flaw sizes. Inspection programs based on the need to detect DFM-based allowable flaws are very conservative since they must consider lower bound conservative input. Probabilistic fracture mechanics (PFM) techniques are an acceptable alternative to DFM methods in order to determine inspection intervals.

A case study is presented in this paper that describes the use of both DFM and PFM techniques in establishing an inservice inspection program for a buried penstock. This case study provides an excellent example of the benefits of performing PFM to demonstrate the acceptability of extending inservice inspection intervals while maintaining acceptable levels of safety.

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Introduction

This paper presents the application of PFM techniques to the evaluation of penstock circumferential field welds (FWs). The objective of the paper is to demonstrate the effectiveness of the PFM method in justifying shorter inspection intervals than would be required if DFM methods were used. A specific example of the use of PFM is presented using the penstock FWs of Pacific Gas & Electric Company's Helms Pumped Storage Project. Three of the field welds near the powerhouse were the focus of this study.

The penstock field welds at Helms are currently inspected in accordance with an established inspection plan based on DFM methods. This inspection plan calls for inspections that require dewatering of the tunnel on a ten-year interval. The dynamic fluid head is approximately 2340 feet (1014 psi pressure). The deterministic fracture mechanics analyses predict extremely small critical flaw sizes. The primary reason for the small critical flaw sizes is the conservative values used for material fracture toughness and weld residual stress. Testing for these quantities showed a wide degree of scatter, and the analyses used conservative bounding values coupled with safety factors.

Although observed crack growth (based upon results from successive inspections) is very small, a ten-year inspection interval requirement continues to be applied because of the extremely small critical flaw sizes and personnel criticality of the subject welds. Due to the extensive effort required to perform inspections, a sophisticated probabilistic approach can be used to justify less frequent inspections. A twenty-year inspection interval was selected for this evaluation. The PFM approach is used to evaluate specific flaw indications at the Helms facility considering the twenty-year inspection interval.

Analysis Methodology

Most fracture mechanics evaluations use deterministic fracture mechanics methods resulting in conservative results, since limiting assumptions are typically made for key parameters. However, some important parameters used in the DFM analyses of FWs are known to vary significantly, and can be assumed to behave in a random manner. Both the material fracture toughness and weld residual stress are known to demonstrate significant scatter based on actual measurements. Following is a presentation of the PFM methodology and required inputs for a PFM analysis of penstock FWs.

Monte Carlo Technique

The Monte Carlo analysis technique is a numerical probabilistic analysis approach that is amenable to statistical problems governed by a large number of random variables, for which closed form solutions are impossible or impractical. It has been used extensively in probabilistic fracture mechanics analyses, and other highly complex, probabilistic risk assessments in various industries. The essence of the approach is to assign mean values and statistical distributions to all of the important variables affecting the problem. Solution algorithms for the problem are set up (generally in the form of a computer program) in exactly the same manner as one would if each variable were a known, deterministic parameter. The algorithms are then exercised repetitively, a large number of times, randomly selecting a different value for each random variable from its respective distribution, for each repetition (or iteration). In probabilistic fracture mechanics, each iteration results in either a failure or a non-failure, and the probability of failure (POF) is simply the total number of failures divided by the total number of iterations performed. In terms of this evaluation, failure is defined as a crack with stress intensity factor greater than the material fracture toughness or if the crack propagates through the wall thickness.

Stress Analyses

Stress analyses are required to determine the actual stress at the locations of interest. These stresses may be determined using available strength of materials solutions or more sophisticated methods, such as finite element analysis. All appropriate loading conditions, such as daily pumping and generating cycles, and monthly load rejections, must be considered in order to obtain the appropriate stress levels for critical flaw size and crack growth calculations. The primary input from the stress analyses for input to the fracture mechanics evaluation is the membrane and bending stress values at the locations of interest. These applied stresses are treated as deterministic values in the subsequent PFM analyses.

Fracture Mechanics Analyses

The fracture mechanics solutions for the appropriate crack configuration are used in the PFM analysis. Solutions for surface (inside and outside), and subsurface flaws can be obtained from the literature.

Weld Residual Stresses

Weld residual stress usually shows a significant amount of variability as demonstrated by experimental measurements. In deterministic fracture mechanics analyses, bounding weld residual stress is typically used. PFM methods account for the variability of the weld residual stress as demonstrated in FW measurements.

Fracture Toughness

Similar to the behavior of weld residual stress, the material fracture toughness demonstrates significant data scatter. DFM techniques use the bounding fracture toughness in calculations of allowable flaw sizes. PFM methods consider the significant scatter of the material fracture toughness.

Plant Specific Analyses

The discussion above presented the general methodology of the PFM approach to assessing fracture in a penstock field weld. Following is a description of a plant specific analysis performed for the Helms Pumped Storage Project.

Methodology

The Monte Carlo method was used to evaluate the probability of failure for the field welds in the Helms penstocks. Since the calculation of crack growth to failure involved the time domain, the computation time would be very significant if a large number of iterations is required to quantify the risk, especially when the risk could be very small. In order to minimize the computational time, a modified approach of the Monte Carlo method was derived, and software was developed to perform the calculation. It involves a combination of DFM and PFM methods to develop relationships in matrix form between the various key parameters, with consideration for the random distribution of the material fracture toughness, K_{Ic}, residual stress and crack growth rates. This modified approach is described below.

The stress intensity factor and crack growth results were calculated deterministically for a few chosen standard deviations, σ (zero, $\pm 3\sigma$, and $\pm 4.8\sigma$), of the random variables which were K_{Ic}, weld residual stress and fatigue crack growth rate. These results were put into matrix form for use in the probabilistic failure analyses of the penstocks.

In each Monte Carlo iteration, instead of calculating the stress intensity factor and performing the crack growth analysis through the time domain, these results were interpolated directly from these matrices. For each of the Monte Carlo iterations, a random number was generated for each random variable. The corresponding standard deviation was calculated. This standard deviation was used to perform the interpolation for the desired results using the appropriate matrix.

Figure 1 demonstrates the procedure. After determining the standard deviation for the material K_{Ic}, crack growth rate and residual stress for a given iteration (based on a selected random number for each random variable in each iteration), the initial stress intensity factor is determined. Next, the stress intensity factor at the end of the desired operating time is determined. For the previously randomly selected K_{Ic}, the allowable flaw size is determined. Lastly, the time for the crack to grow from an initial flaw size to the allowable flaw size is determined.

The procedure described above and in Figure 1 is similar to performing a full Monte Carlo evaluation. The advantage is that the procedure reduces the amount of calculations, and thus the amount of time to obtain meaningful probability of failures. Thus, this modified approach could be considered as a series of DFM calculations with developed relationships (in matrix form) between the key parameters which could be used to form the basis of the PFM calculations.

The computer program **pc-CRACK** was used to perform the deterministic fracture mechanics analyses for the surface and subsurface cracks (which considered the variation of the key parameters). Industry available surface and subsurface crack solutions under membrane and bending stresses were used. The operating stress cycles for the field welds were obtained by finite element analyses.

The penstock has a 126 inch inside diameter, with the nominal wall thickness varying from 2.625 inches to 3 inches. The penstock is made from A-516, Grade 70 material. The welds analyzed are located at the bottom end of the penstocks.

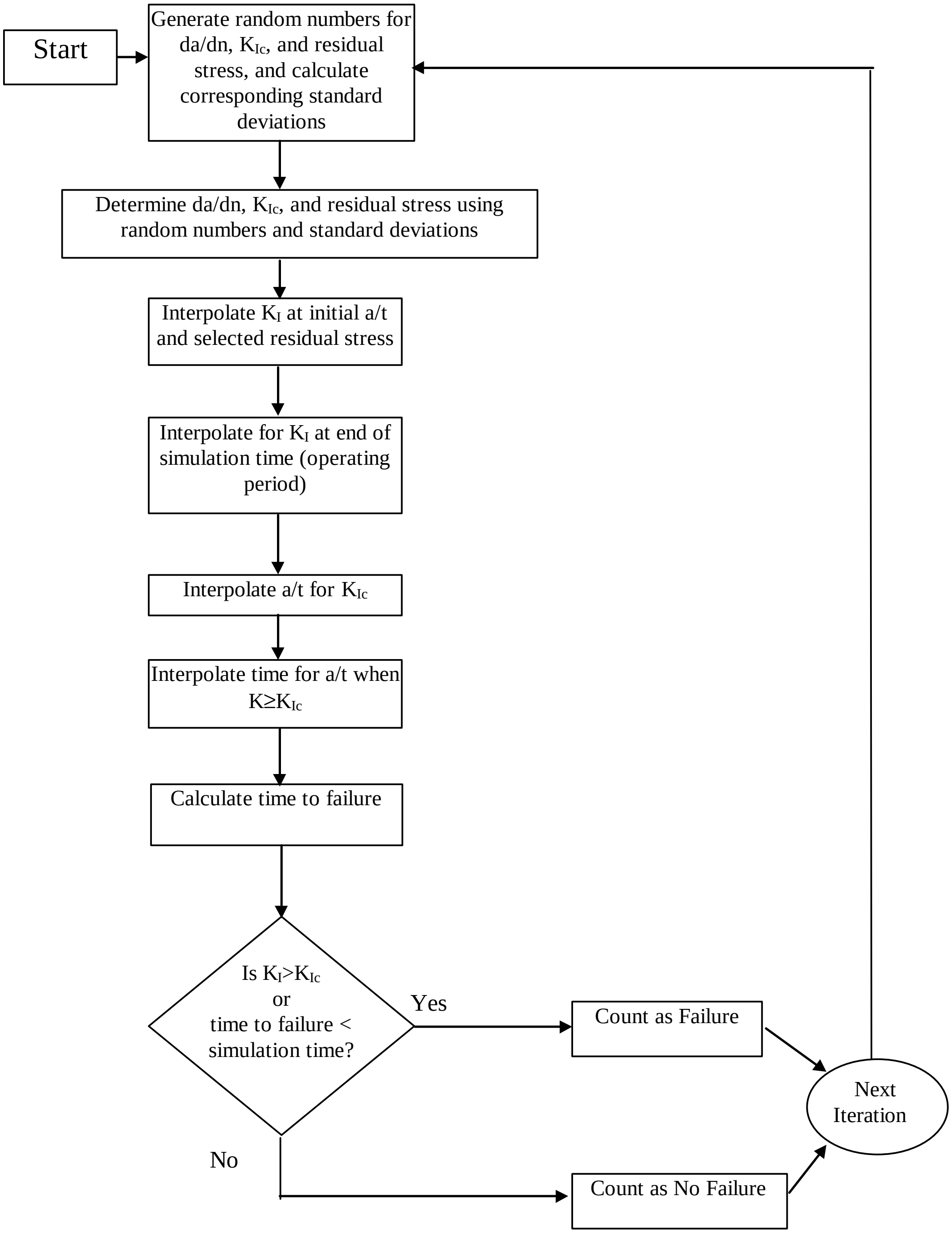

Figure 1. Flow Chart Describing Calculation Procedure

Corrosion was considered by conservatively reducing the thickness throughout the calculation and correcting the stresses for the decreased wall thickness.

The random variables, residual stress and fracture toughness, were assumed to be defined by a normal distribution. Based on plant specific data, the following input data was generated:

Residual Stress: 42.1 ksi Average Axial Stress
16.1 ksi Standard Deviation for Axial Stress

49.7 ksi Average Hoop Stress
27.6 ksi Standard Deviation for Hoop Stress

Fracture Toughness: 82.96 ksi$\sqrt{\text{in}}$ Average
13.4 ksi$\sqrt{\text{in}}$ Standard Deviation

Based on inspection results from Helms, an initial crack size of 0.04 inches was used for an outside surface crack based on the sensitivity of the inspection technique used in the 1997 inspection of the penstocks. For the subsurface crack, the initial half-crack size was 0.064 inches, with a material yield stress at 50 ksi, and eccentricity ratio of 0.45 (eccentricity ratio = distance from center of wall/center of indication). These were the representative inputs for the two subsurface indications detected in the 1997 inspection. An industry crack growth law in air environment was used for both the surface crack and the subsurface crack in the crack growth calculation. The simulation time for crack growth was twenty years. The simulation of the variability of the fatigue crack growth was accomplished by scaling the operating cycles. It was assumed that the distribution of crack growth rate at a given applied stress intensity factor had a spread of about one order of magnitude of crack growth rate. This distribution was assumed to correspond to ±3 standard deviations with a normal distribution.

For each iteration, the interpolation of the matrices would give results on the stress intensity factor at the initial crack size, final a/t and stress intensity factor at the end of the simulation time due to crack growth, and a/t and time corresponding to K_{Ic}. The stress intensity factor at the end of the simulation time was compared to the material toughness to determine the failure status for that particular iteration. If the stress intensity factor at the end of the simulation time is greater than the material fracture toughness, that iteration is counted as a failure. Then the time required for the flaw to reach the critical flaw size, based on K_{Ic}, was interpolated from the appropriate matrix.

One hundred million Monte Carlo iterations were used.

Results

Outside Diameter Surface Cracks

The probability of failure for a twenty year period for an assumed initial crack depth of 0.04 inches was determined to be 3.18×10^{-6}. For comparison, the probability of failure for the same period for an assumed initial crack depth of 0.06 inches was 2.08×10^{-5}. This illustrates that even with a 50% increase in crack depth, the probability of failure remains low.

Results of the evaluation demonstrated that failure occurs only at the beginning of the analyzed operating period. This demonstrates that crack growth does not play a role in the failure probability. Failure occurs only when in the random selection of variables results in a combination of low fracture toughness and high weld residual stress. Thus, the cumulative probabilities of failure curves are essentially constant since failures occur only at the beginning of the operating time.

Sub-surface Cracks

The probability of failure was calculated to be 1.8×10^{-7} for an operating period of twenty years. Similar to the results for the surface crack, any indication with half-crack size of 0.064 inches would fail by fracture due to the combination of high weld residual stress and low fracture toughness. Again, this demonstrates that crack growth does not play a role in the failure probability.

Summary and Conclusions

An approach using PFM methods has been outlined for application to inspection interval periods for penstock circumferential field welds. The method was applied to a specific case of indications at the Helms project. The probabilities of failure for the outside surface cracks (0.04 inches deep) and the detected subsurface indications of the Helms penstocks were evaluated. The evaluation was performed by using a modified Monte Carlo approach to eliminate the computational time for the crack growth calculation. Three random variables, residual stress, crack growth rate and fracture toughness, were used in the probabilistic evaluation. The initial crack sizes were based on UT inspection results and capabilities.

For the outside diameter surface crack, the cumulative probability of failure is 3.18×10^{-6} for an initial crack size of 0.04 inches, after twenty years of operation since the last inspection. For the subsurface crack, the cumulative probability of failure is 1.8×10^{-7} for an initial half-crack size of 0.064 inches, after twenty years of operation.

Based on the evaluation results, the probability of failure of the observed indications is essentially independent of time. This is because any failure is predicted to occur at initial operation and not as a result of crack growth with time. Failure of the welds is predicted only when a very low fracture toughness and high residual stress are used based on the random number selection. Thus, any failure would occur at the beginning of the operating period and no failure is predicted (for the 0.04 inch deep indication) for the surface flaws and embedded flaws. These results indicate that inspection does not provide added assurance of reliability of the field welds. Since the probability of failure using a twenty-year inspection interval is the same as that for a ten-year inspection interval. Thus, extension of the current ten-year inspection interval to twenty years is justified, and does not reduce the reliability of the penstock field welds. It should be noted that since the results were found to be independent of time, an inspection interval greater than twenty years could be justified.

In conclusion, the PFM method is a valuable and technically sound approach to determine the risk involved in changing inspection intervals when key parameters are known to vary randomly. This method applied to the Helms project has demonstrated the significant conservatism in the DFM approach.

Measurement Conversions

Unit	m	Pa
1 Inch	0.0254	-
1 Foot	0.3048	-
1 Pound per square inch (psi)	-	6,894.757