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A CASE STUDY ON GENERATION OF ACCEPTANCE CRITERIA IN FEEDWATER SUPPLY TUBE BENDS

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ABSTRACT

Inspection of components utilizing advanced examination techniques is becoming standard practice in the power industry. One of the critical aspects during this type of inspection is to have on hand criteria for acceptance or rejection of flaws found during these inspections. The examinations typically include the use of advanced ultrasonic techniques such as Linear Phased Array (LPA), Focused Annular Phased Array (APA), and Time of Flight Diffraction. These techniques can detect and size flaws that are often "Fit for Service" for at least one additional outage cycle. However, schedule limitations during an outage often do not permit for extensive analysis time. Repair decisions need to be made immediately and having criteria available for these decisions are critical.

The following is a case study for the generation of acceptance / rejection criteria for power boiler feedwater supply tube bends.

The determination of "allowable flaw sizes" is needed to determine which of these supply tube bends need to be removed during the outage. The acceptance criteria in this work is based on the criteria of API 579-1 / ASME FFS-1 "Fitness for Service Standard" [1] to evaluate the rate of growth of the flaws found. Discussion is also made as to the sensitivity of the examination methods used to detect the flaws expected and how this relates to the acceptance criteria generated.

NOMENCLATURE

APA – Annular Phased Array
BR – Bend Radius of Tube
C, n – Crack Growth Rate constants
da – Change in flaw depth
dN – Change in Number of cycles
ΔK – Change in Stress Intensity Factor
FAD – Failure Assessment Diagram
FFS – Fitness for Service
K_{Ic} – Critical Stress Intensity Factor
K_I – Stress Intensity Factor
K_r– Stress Intensity Factor Ratio (K_I / K_{Ic})
LPA – Linear Phased Array Ultrasonics
L^P_r – Load Ratio based on Primary Stress
NDE – Non-Destructive Evaluation
P - Pressure
R – Radius of Tube
σ_{1max} – Maximum Principal Stress in Bend
t – Thickness of Tube

INTRODUCTION

Disposition of components identified to contain defects during a maintenance outage is often of critical importance in getting units back on-line. Replacement components are typically not readily available and could involve significant delays in outage schedules.

The following is a case study on the use of API 579-1 / ASME FFS-1 Fitness for Service (FFS) [1] for the generation of acceptance criteria for feedwater supply tube bends. A typical configuration of this type of bend is used here for the case study. The bends considered are:

Tubes – 4 ½ inch diameter x 0.375 inch min wall thickness
Bend Radius – approximately 4 x tube diameter (18 inches)
Operating Pressure – 2080 psi at sat. temperature of 641°F
Material – SA-210 Grade C Carbon Steel [3],[4]
Yield Strength is 40 ksi at room temperature
Yield Strength is 29.6 ksi at 641°F
Tensile Strength is 70 ksi at room temperature

Cracking in these bends is often a result of either fatigue or corrosion fatigue. The corrosion is often caused by the water itself and the severity of the corrosion is dependent on the cycle chemistry of the unit.

Recent advancements in the use of advanced ultrasonic techniques such as Linear Phased Array (LPA) have resulted in the ability to detect and size flaws in the tubes that may have been previously undetectable. The evaluation of these flaws is critical, because, in many instances, these results may not have been encountered in the past.

This case study is from a unit which has an estimated 20 shutdowns per year. The supply tube bends are inspected on five year intervals.

METHODOLOGY

Fatigue life of tubes can be divided into two parts. First, the crack needs to initiate and then the crack needs to propagate. The initiation typically occurs at the internal diameter of tubes either due to high stress at the internal surface or due to corrosion initiated fatigue cracking. Fatigue crack initiation in water-touched tube surfaces usually is associated with aligned corrosion pits or axial-oriented draw die marks from tube fabrication. The acceptance criteria determined should be sufficiently conservative to allow for reliable operation until the next outage in which they will be inspected. Therefore, the final phase of failure of the tube is of primary interest in this evaluation. This would be the last phase of crack propagation in the tubes.

The methodology presented here is to utilize Part 9, Assessment of Crack-Like Flaws, of the FFS document [1] for the evaluation of cracking found in supply tube bends.

The general procedure for this type of assessment is to perform a crack growth evaluation for the flaws. The cracks found at the inner surface of feedwater tubes are generally reported by length and depth. The flaw used in this evaluation is an infinitely long ID surface connected crack in a cylinder. An infinitely long flaw will grow faster under a given load condition to a semi-elliptical crack or pit and therefore is a conservative approximation for the cracks generally found in the internal of feedwater tubes.

The crack is assumed to grow through the wall until the point where plastic collapse of the remaining ligament is reached or critical crack size is achieved. These two conditions are evaluated using the Failure Assessment Diagram (FAD) [1] approach.

An estimation of future operation is necessary to determine the amount of crack growth expected before the next inspection interval. The amount of crack growth due to this operation, when subtracted from the critical crack size, is then used as the "maximum allowable crack size" at the time of the present inspection.

STRESS ANALYSIS

For this case study, the stresses that drive the flaw are due to pressure only. It is assumed that the tubes do not experience significant thermal transients during startup or shutdown events.

The maximum principal stress or hoop stress is the driving force in the propagation of the cracks in this case. The tubing used to make the bends in question is considered to be "thin walled". Roark's Handbook [2] shows that the equation for stress for the bends is:

$$\sigma_{1\max} = \frac{P * R}{2 * t} * \frac{2 * BR - R}{BR - R}$$

$$\sigma_{1\max} = \frac{2080 * 2.25}{2 * 0.375} * \frac{2 * 18 - 2.25}{18 - 2.25}$$

$$\sigma_{1\max} = 13{,}371\, psi$$

The hoop stress in the bend is not constant around the circumference. The equations shown here are for the peak hoop stress which occurs at the intrados of the tube.

CRITICAL FLAW SIZE ASSESSMENT

The critical flaw size is determined using the Failure Assessment Diagram procedure in the FFS document [1]. A FAD is a plot of the stress intensity at the root of the crack normalized with the critical stress intensity factor for the material plotted versus the ratio of the stress in the remaining ligament of the wall divided by the yield strength for the ligament.

Figure 1 shows the failure assessment diagram for the tube in question. The crack will grow until the final collapse of the wall is achieved at 0.207 inches deep. Traditional fracture mechanics states that the critical crack size is when the stress intensity at the root of the crack (K_I) equals the critical stress intensity (K_{Ic}). In other words, that would be where $K_r = 1.0$. However, the figure shows for the case of the feedwater tube, the failure occurs at a $K_r = 0.37$ and the result is that the tube will have net section collapse in lieu of brittle failure.

ACCEPTANCE CRITERIA ASSESSMENT

It is necessary to conservatively predict the crack growth rate of the cracking in the tubes. Once the rate of crack growth is established and the time between outages in which the tubes are examined is known, the maximum size of crack that can remain in the tube between inspections can be determined.

The crack growth rate curve is based on the Paris law formulation [1] for crack growth of

$$\frac{da}{dN} = C(\Delta K)^n$$

Where the crack size is “a”, “N” is the number of cycles, “C” and “n” are crack growth rate constants for the particular material in question. The FFS document has many crack growth rate constants available for different environments. The constants for the case of light water reactor environments were used here for the case study. Selection of the proper crack growth rate constants for a particular environment is a critical factor for achieving a sufficiently conservative result in establishing allowable crack sizes.

Figure 2 is a plot of the crack growth rate through the wall of the tube. The horizontal axis has been adjusted to equal the wall thickness. The figure shows that cracks will grow at a very slow rate when small and then accelerate quickly as the end of life is near.

The establishment of the acceptable crack size is a matter of determining the size of crack that is less than the predicted size of failure by the FAD. A margin of 10 on the number of cycles is suggested here to allow for conservatism. Therefore, based on the unit experiencing approximately 100 startup / shutdown cycles every five years, the critical crack size for the present inspection is determined at 1000 cycles prior to predicted failure. Therefore, the current critical crack size is 0.131 inches as shown in Figure 2.

SUMMARY AND DISCUSSION

The critical crack size was determined using Fitness for Service methodology. This same methodology has been successfully implemented many times for the purpose of determining an allowable flaw size for cracking in boiler and feedwater tubes. Determination of this type of acceptance criteria will allow for expedient disposition of NDE flaws during the outage, with minimal upfront costs. Flaws that are not acceptable per the conservative approach similar to that described in this case study, can be analyzed further with a more specific assessment of each individual location or the component can be repaired or replaced.

When determining the acceptance criteria for a particular inspection, actual geometry involved in the inspection, NDE technique used, resolution of the NDE technique being performed, as well as specific material information for the tubes involved need to be considered. The expected operation of the unit also needs to be considered in conjunction with the time between inspections.

In the type of inspection performed here, typically the flaws are reported with both a length and a depth. The procedure could be repeated for the flaw model of a “through wall radial-axial flaw” to determine a conservative length of a flaw. Both dimensions of flaws would then be “bounded” as acceptance criteria.

The Fitness for Service [1] document also has solutions for elliptical radial-longitudinal flaws in a cylinder. The growth of these flaws will be slower than that of either the “infinitely long radial-axial flaw” or the “through wall radial axial flaw”. Therefore, as a first approximation of the growth of flaws for the purpose of generation of acceptance criteria for inspections, the most conservative flaw models are recommended.

Many factors go into the rate of crack growth. Cycle chemistry of the unit is one major influence on the rate of crack growth in corrosion-fatigue situations. Proper understanding of the water chemistry and how it factors into this type of analysis is important when trying to predict the crack growth rates.

It is also recognized that not all bends in a system may be inspected in a given outage or on the time period used here. The methodology presented in this paper is a case study using the Fitness for Service principals of fracture mechanics to determine the size of flaw that would be acceptable for an inspection. This methodology can be used for specific components and based on specific inspection frequencies. The actual inspection frequency for a given component is typically determined utilizing risk based methodology, which is beyond the scope of the work being performed here.

REFERENCES

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[3] ASME Section II Part D, Materials – Properties (Customary), New York, NY, 2007.

[4] ASME Section II Part A Materials - Ferrous Material Specifications (Beginning to SA-450), New York, NY, 2007.

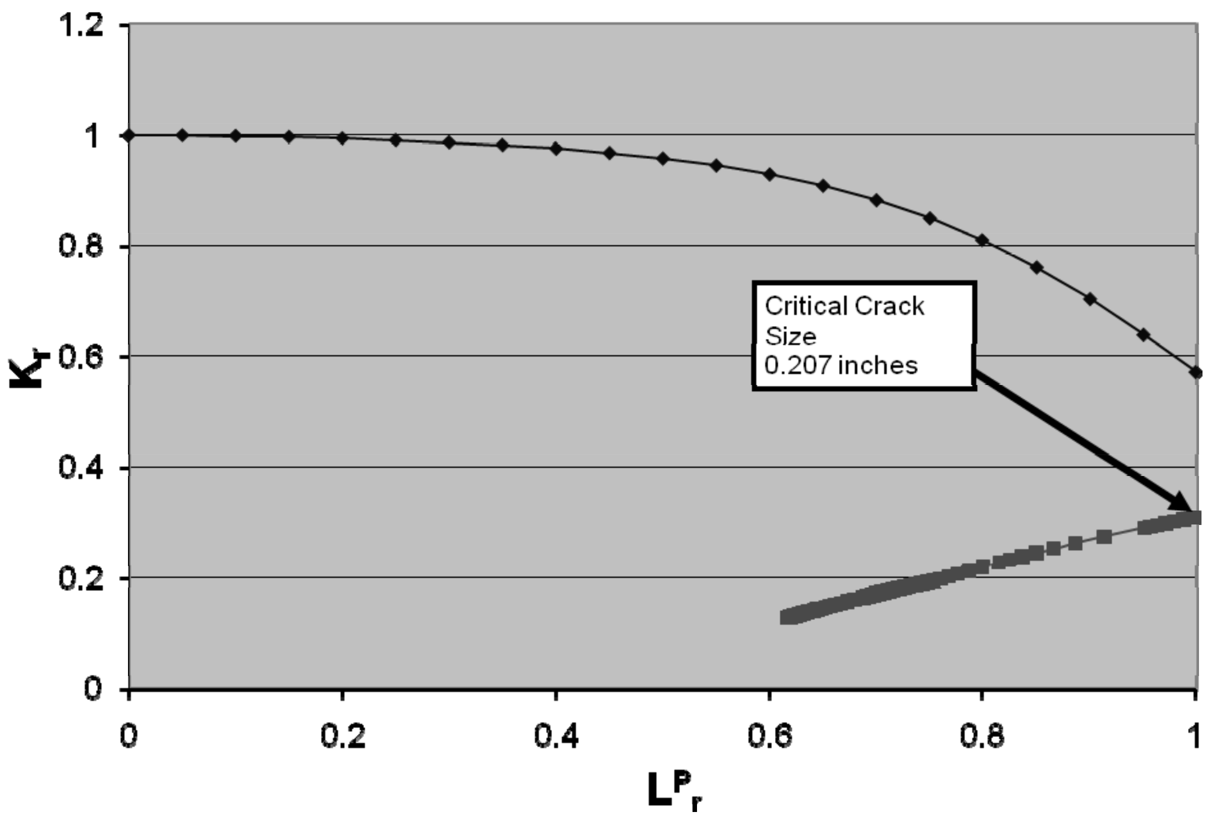

FIGURE 1 – FAILURE ASSESSMENT DIAGRAM FOR TUBE – INFINITE RADIAL – LONGITUDINAL CRACK

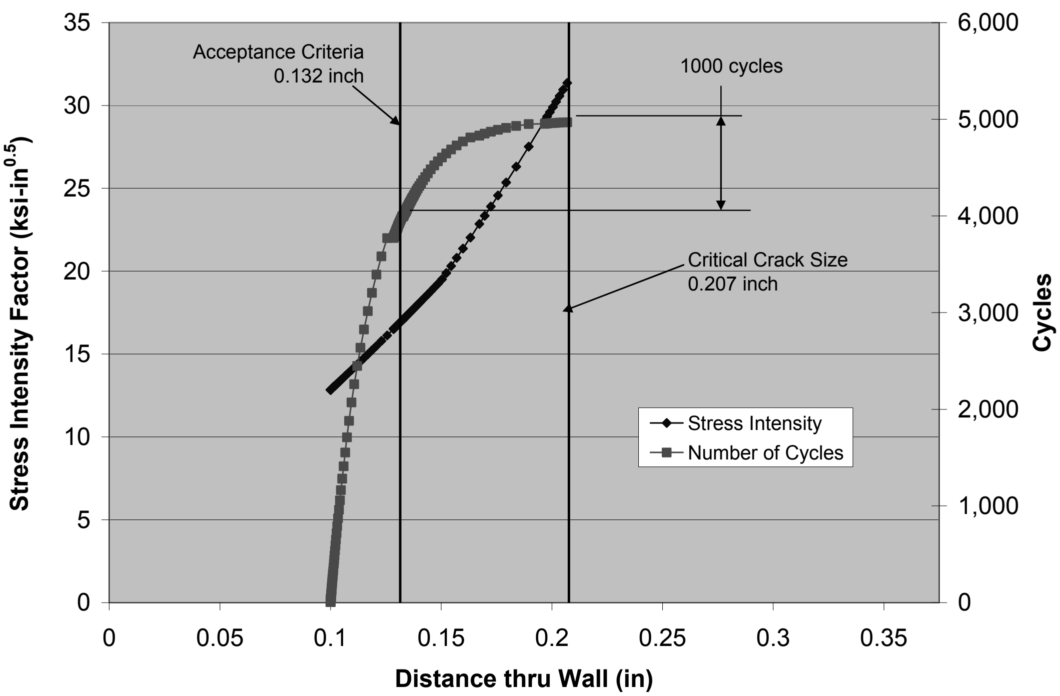

FIGURE 2 – CRACK GROWTH STUDY OF SUPPLY TUBE BEND