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STRUCTURAL INTEGRITY ASSESSMENT OF STEAM GENERATOR TUBES USING A NEW EPRI STATISTICAL APPROACH

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ABSTRACT

A fundamental step in tube plugging management of a Steam Generator (SG), in a Nuclear Power Plant (NPP), is the tube structural integrity evaluation. The degradation of SG tubes may be considered one of the most serious problems found in PWRs operation, mainly when the tube material is the Inconel 600. The first repair criterion was based on the degradation mode where a uniform tube wall thickness corrosion thinning occurred. Thus, a requirement of a maximum depth of 40% of the tube wall thickness was imposed for any type of tube damage. A new approach considers different defects arising from different degradation modes, which comes from the in-service inspections (NDE) and how to consider the involved uncertainties. It is based on experimental results, using statistics to consider the involved uncertainties, to assess structural limits of PWR SG tubes. In any case, the obtained results, critical defect dimensions, are within the regulatory limits.

In this paper this new approach will be discussed and it will be applied to two cases (two defects) using typical data of SG tubes of one Westinghouse NPP. The obtained results are compared with 'historical' approaches and some comments are addressed from the results and their comparison.

INTRODUCTION

In a Pressurized Water Reactor (PWR) the Steam Generator (SG) tubes represent the major and also the thinnest part of the primary pressure boundary. Furthermore, due to their severe operational conditions, common in almost all heat exchangers, the tubes are more sensitive to damage and aging from several modes of degradation. The degradation of SG tubes may be considered one of the most serious problems found in PWRs operation, mainly when the tube material is the Inconel 600. The degradation may cause leakage and consequences for safety requiring actions such as tube plugging. On the other hand, this action is undesirable from economic reasons because decreases the plant efficiency. So, regarding the safety and economic aspects, the adequate management of tube degradation and plugging is an important issue for the plant operation. A fundamental step in tube plugging management of a Steam Generator (SG), in a Nuclear Power Plant (NPP), is the tube structural integrity evaluation.

Historically, the first repair criterion was based on the degradation mode called wastage, where a uniform tube wall thickness corrosion thinning occurred. Thus, a requirement of a maximum depth of 40% of the tube wall thickness was imposed for any type of tube damage.

A statistical approach, according to EPRI (Electric Power Research Institute), considers different defects arising from different degradation modes, which comes from the in-service inspections (Non-Destructive Examination - NDE), under the various reactor operational conditions and how to consider the involved uncertainties.

This approach is based on experimental results performed for several and different tube defect morphologies using statistics to consider the involved uncertainties, to assess structural limits of PWR SG tubes. To define criteria for tube repair such as plugging it is necessary to evaluate the maximum allowable defect size under each applicable operational condition. To assess allowable defect size of a tube one should consider (a) the tube dimensions, (b) the mechanical properties of tube material, (c) the applied loads, (d) the morphology of the defect and its location, (e) the ability of NDE to detect and to size the defect, (f) the defect growth between inspections and (g) the correlation that characterize the response of the tube with defect to the applied loads. Besides the more sophisticated statistics methods as the Monte Carlo method it is allowed simplified (and more conservative) statistical methods as well.

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In any case, the results are within the regulatory limits.

In this paper the EPRI approach will be discussed and it will be applied to two cases (two defects) using typical data of SG tubes of one Westinghouse NPP and some comments will be addressed from the results and their comparison.

APPROACHES FOR STRUCTURAL INTEGRITY EVALUATION

The main objectives of the SG tubes structural integrity management are: to keep the probability of tube rupture at a very low level and to keep the plant efficiency as high as possible. The first one is for safety reasons and, therefore, entails defining actions capable of offsetting the increased risk caused by damage of the tubes. The other one is for economic and availability reasons, and to limit the number of plant shutdowns caused by out-of-specifications primary to secondary leakage.

The first SG tubes repair criterion, already mentioned, was based on the wastage degradation mode where a uniform tube wall thickness thinning occurred due to corrosion. When other degradation modes showed up later on, with highly localized defect morphologies such as pits and cracks, the historical "40% structural limit" appeared strongly conservative. Studies were made to reduce this conservatism and pushed the development towards new criteria: the specific defect management that is applicable to each particular mode of tube degradation mechanism.

Tube plugging criteria. The development and implementation of the NDE techniques to detect and monitor defects, before they reach critical size, allowed the development of tube plugging criteria to define which damaged tubes can remain in service. The SG tube plugging criteria verify if the defect poses a threat to either the tube structural integrity or to the leak tightness. To demonstrate compliance with code and standards two characterizations of the structural condition of the SG tubes are required: the Condition Monitoring and the Operational Assessment. The CM and OA limits refer to the values of measured parameters that can be related to the strength of a degraded portion of the tube, for comparison with established performance criteria.

With the CM one determines the fitness for operation at the end of the operating interval just completed by evaluating compliance with structural and leak rate performance criteria. The OA demonstrates that applicable structural and leak rate performance criteria will be met through the next operating interval of the SG. In other words, the results of the CM analysis just performed with the inspection data are compared with the results predicted by the OA performed previously in the last inspection. If there is no good agreement between the CM and the OA the used criteria to establish the defect acceptability should be reviewed.

Procedure and uncertainties. Usually the criterion establishes a critical size for the defects as its length (L) or depth (h).· To find this critical size, for each type of defect, experiments are done to correlate the defect to the tube strength under pressure in concert with NEI (1997) and EPRI (2000). The structural limit (SL) comes from this correlation and corresponds to the required value of the burst pressure, for a tube with average or nominal material properties. So, the structural limit does not include adjustments made to account for the statistical distributions of the relational, tube material, and defect size measurement uncertainties. However, there may be multiple structural limits to account for different degradation morphologies and loading conditions.

The involved uncertainties are: the relational or prediction function uncertainty, the material strength uncertainty, and the NDE measurement uncertainty, the growth rate of the existing flaws, and the initiation and growth of new flaws. So, from this structural limit, adjustments should be done to account for the relational, the material, and the measurement uncertainties to arrive at a condition monitoring (CM) limit. Additional adjustments for detection of existing and initiation of new flaws and for future growth need to be made to arrive at an operational assessment (OA) limit.

The NEI (1997) refers to the maximum flaw size determined to be consistent with specified safety factor performance criteria. That is, all tubes should retain margins of safety against gross failure and/or burst of the tubing which are consistent with the safety factor margins implicit in the stress limit criteria of the ASME (1989) for all service level loads.

Statistical versus deterministic approach. To establish the CM or the OA limit a deterministic approach or a statistical approach can be used depending on the degree of conservatism one can allow from the evaluation and depending on the level of uncertainty in the involved factors.

Generally speaking, the deterministic approach can be applied to those defects which morphology is simple enough that it can be sized (e.g. in length and in depth) by an NDE examination technique. A characteristic defect dimensions is then compared to the corresponding calculated critical value, taking appropriate operational conditions and safety margins into account. The statistical approach can be applied when complex defect morphology does not allow a dimensional characterization. In this case an overall measure of the degraded tube residual strength (such as burst pressure) is then statistically correlated to some feature of an NDE signal; a lower bound of this correlation allows one to define a signal limit, with a proper safety factor.

Obviously, a range of approaches between these two extreme situations may be obtained according to the statistical combination of the uncertainties and the degree of conservatism adopted.

TYPICAL DEFECTS

This section shows some specific defects, the involved parameters, etc. and the next one will show how the EPRI (2000) tube plugging criteria can be applied to them. Typically the defects can be classified as **Axial Cracking, Circumferential Cracking** or **Volumetric Degradation**. In the first type we have, among others, Throughwall Cracking, Part Throughwall Cracking, Hardroll and Transition Axial Cracking-PWSCC, etc. In the third type can be named: Uniform 360° Thinning, Axially Oriented Degradation with Limited Circumferential Extent, Pitting, etc. The term freespan implies that there are no displacement restrictions of any type in the vicinity of the defect.

Some Typical Defects. *Freespan Throughwall Axial Cracking*. The idealized geometry is that of a single crack, parallel to the axis of the tube and throughwall everywhere along its length as illustrated in Fig. 1.

Freespan Part Throughwall Cracking. The cracking may be internal (ID) or external (OD). The idealized geometry is that of a single crack, parallel to the axis of the tube. A typical geometry of the degradation is illustrated in Fig. 2.

Expansion Transition Axial Cracking. The crack occurs near the expansion transition of the tube into a tubesheet. This case can contemplates multiple cracks, nearly parallel to the axis of the tube and throughwall or part-throughwall. Some limited circumferential contribution might be present as illustrated in Fig. 3.

Axial Thinning with Limited Circumferential Extent. In this case the defect is a thinning or volumetric degradation that is predominantly axial in a nature and limited to <135° in the circumferential direction. The Fig. 4 is a typical illustration of this defect.

Circumferential Cracking with Restricted Lateral Tube Motion. This case deals with circumferential cracks in tubes when the lateral motion of the tube is restrained by a tube support structure. The geometry is illustrated in Fig. 5.

Bobbin Voltage Alternate Repair Criteria (ARC), ¾" Thick, Drilled Tube Support Plates. This ARC analyzes the ODSCC (Outer Diameter Stress Corrosion Cracks) that occurs in the SG tubes at the positions of the tube support plates (TSP). There is no direct structural parameter involved, in this case. The voltage from the eddy current examination of the tube is used to analyze the indication instead of the measured depth or length of the indication. As the TSP covers the degradation, the tube is precluded from burst during normal operation due to restricted radial displacements (Fig. 6).

Pitting. The pitting is a very localized patch of wall thinning with comparable axial and circumferential lengths with a small penetration in the outside surface of the tube. Figure 7 shows a typical geometry of pitting.

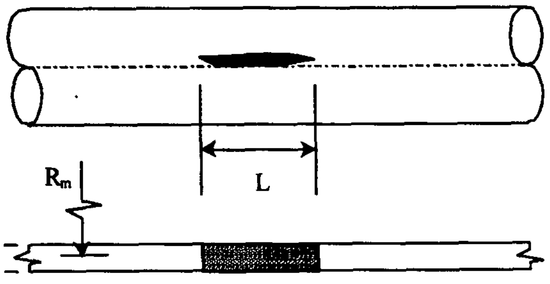

Figure 1. Throughwall Axial Cracking

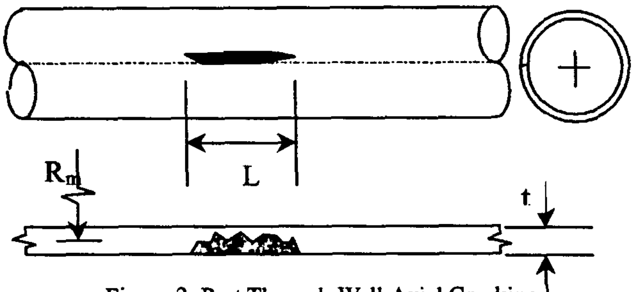

Figure 2. Part Through-Wall Axial Cracking

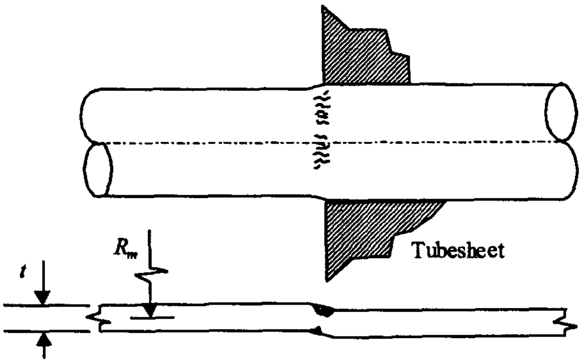

Figure 3. Expansion Transition Axial Cracking

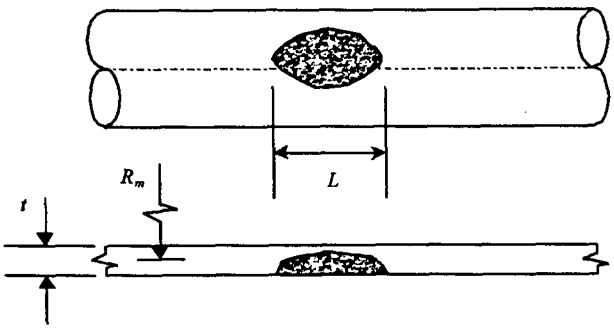

Figure 4. Volumetric Degradation with Limited Circumferential Extent

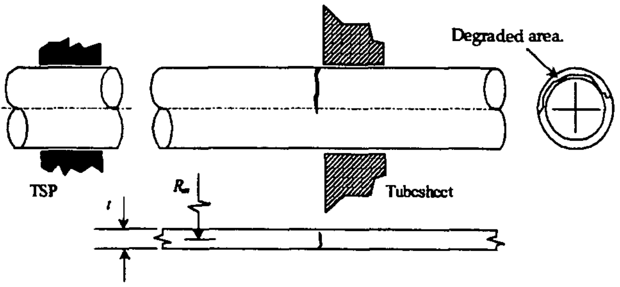

Figure 5. Circumferential Crack

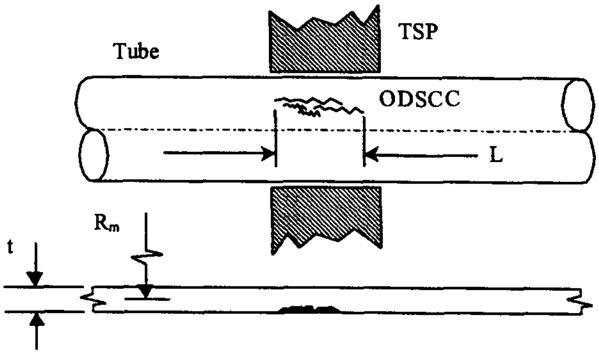

Figure 6. Bobbin Voltage TSP ARC

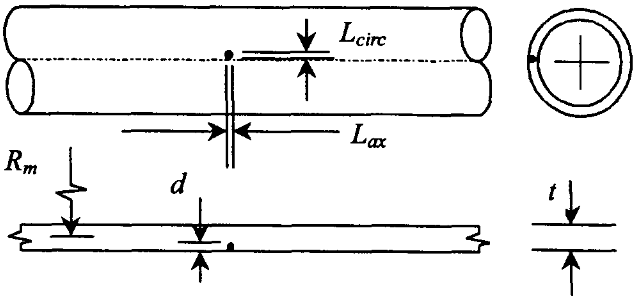

Figure 7. Pitting

Structural parameters. The structural parameters are (a) the length of the crack, L; (b) the structural average depth, d, or the relative crack depth, h; and (c) the strength of the material, $S_y + S_u$ (Yield Strength and Ultimate Tensile Strength). For uniform depth cracks, the structural length and structural average depth are as given in the figures. If the crack has a depth that varies along the crack length an average depth should be used.

BURST EQUATIONS

For every defect a burst pressure equation was obtained experimentally (EPRI, 2001), from tubes with machined defects and from pulled tubes with actual defects by fitting the results to obtain an average burst pressure as function of average structural parameters. Besides the other uncertainties, this fitting procedure introduces the relational or prediction function uncertainty already mentioned. The uncertainties usually are assumed to be normal distributed with a median error value, usually null, and a standard deviation σ. The uncertainties associated with the tube dimension are already considered in the correlation.

To illustrate how the equations look like, three cases will be shown: the ***Freespan Throughwall Cracking***, the ***Freespan Part Throughwall Cracking*** and the ***Axial Thinning with Limited Circumferential Extent*** cases where PB is the burst pressure. All equations were taken from (EPRI 2001), In the showed equations σ means standard deviation and σ_M is the standard deviation of the material strength value (Sy+Su).

Freespan Throughwall Cracking. The equation (1) presents the exponential correlation of the normalized burst pressure PN versus the normalized crack length λ for this type of defect. $b_1 = 0.061319$, $b_2 = 0.53648$ and $b_3 = -0.2778$ are correlation coefficients. $\sigma_{PN} = 0.01715$ is the basic standard deviation error in the regression (this value should be corrected to take into account the influence of the crack length in an iterative fashion). Re-writing the equation one obtains the critical crack length L_C indicated in eq. (2) for a given P_B value. The LC value that met the criteria, as defined in the next session, is the Condition Monitoring value (L_{CM}).

Freespan Part Throughwall Cracking. The equation (3) shows the correlation associated with this type of defect, where the parameter Φ is a correction to take into account if the cracking is external (OD), when Φ=1.0, or internal (ID). As can be seen in eq. (4), in case of internal cracking the solution is interactive once Φ depends on L. $\sigma_c = 0.0705$ is the standard deviation of the equation coefficient 1.104 (this is the 'correlation uncertainty'). The coefficient C = 1.104 is a mean value from burst test results on pulled tubes and calculations documented in EPRI (2000). This coefficient was developed as 1.0 (Flesch and Cochet, 1990) for predicting the internal pressure that would result in tearing of the remaining radial ligament.

Axial Thinning with Limited Circumferential Extent. The equation (5) shows the correlation for this type of defect. This correlation is similar to the eq. (3) once both defects and formulations are very similar. In this case, the defect is assumed to be external the uncertainty in the correlation σ_B = 282 psi is associated with the constant 291.

$$P_N = b_1 + b_2 e^{b_3 \lambda}, \quad P_N = \frac{P_B R_m}{\left(S_y + S_u\right)t}, \quad \lambda = \frac{L}{\sqrt{R_m t}} \tag{1}$$

$$L_{CM} = \frac{\sqrt{R_m t}}{b_3} \ln\left[\left(\frac{P_B R_m}{(S_y + S_u - Z\sigma_M)t} + Z\sigma_{P_N} - b_1\right)\Big/ b_2\right] - Z\sigma_{NDE} \tag{2}$$

$$P_B = \Phi 0.58\left(S_y + S_u - Z\sigma_M\right)\frac{t}{R_i}\left[(1.104 - Z\sigma_C) - \frac{L + Z\sigma_L}{L + Z\sigma_L + 2t}\left(h + Z\sigma_h\right)\right] \tag{3}$$

$$\Phi = \frac{1}{1 + \frac{t}{R_i} h \frac{L}{L+2t}} \quad \text{(for } \textit{ID cracking}\text{)} \tag{4}$$

$$P_B = 0.58\left(S_y + S_u - Z\sigma_M\right)\frac{t}{R_i}\left[1 - \frac{L + Z\sigma_L}{L + Z\sigma_L + 2t}\left(h + Z\sigma_h\right)\right] + 291 - Z\sigma_B \tag{5}$$

CRITERIA TO ESTABLISH THE CM AND OA VALUES

Condition Monitoring (CM). The CM structural limit of a given crack type is the limiting set of measured parameters (crack depth, h, or relative crack depth, d = h/t, and crack length, L) meeting a given minimum burst pressure P_B with a probability of 0.90 at 50% confidence. If one wants a more restrictive value (more conservative value) it can use the probability of 0.95 at 50% confidence. The burst pressure P_B the cracked tube should stand is defined as the maximum value between 3.0*ΔP during normal operation and 1.43*ΔP in accident condition). In other words: P_B = max(3.0*ΔP normal operation, 1.43*ΔP accident condition) where ΔP is the pressure difference between the primary and the secondary. So, P_B is a plant characteristic, not a variable. As an example, let's consider the Throughwall Cracking. Roughly this criteria means that, for a tube with a crack with length L_{CM}, in 90% (95%) of the occasions the cracked tube will not burst under P_B.

Obviously, in this example, the tube will leak. Another verification should be performed to verify if the overall leakage is within the plant specifications (this discussion on leakage is out of the paper scope. The repair limit is based on the results of an operational assessment however there can be no operational assessment for existing indications that exhibit leakage. The current disposition of these indications is plug-on-detection.)

Usually the equations are written to give a critical parameter, as L or h, as function of the others parameters, for a fixed value of P_B, like the equation (2). The following discussion will consider this fact and the probability of 0.90 at 50% confidence.

Considering the uncertainties. Some alternatives are presented (EPRI 2001) to take into account the uncertainties involved in the relations. Relatively accurate and conservative results for the combination of uncertainties may be obtained by expressing all uncertainties in terms of effective depth uncertainties, for instance, assuming normal distributions and taking the square root of the sum of the squared uncertainties. This simplified approach to consider the uncertainties was no used in this work.

Simplified statistics. Another simplified way to take into account the uncertainties is to consider the 90th (or the 10th) percentile of the distribution associated with every parameter. This can be done, assuming normal distribution for a given parameter, considering Z = 1.282 in the equations.

Monte Carlo statistics. The rigorous combination of all uncertainties may be developed numerically by Monte Carlo simulations. In this case, Z is a random value taken from a normal standard distribution (mean value = 0 and standard deviation = 1). For every random Z value a chosen critical crack parameter (L, for instance) is obtained that attend the burst pressure. If the process is repeated a great number of times, let's say 10000 times, a distribution of the chosen critical crack parameter is obtained from random values of all parameters. If L is, for instance, the chosen critical crack parameter, the desired Condition Monitoring value (L_{CM}) will be the 10th percentile of the critical L values distribution

The showed examples, in the following part of this paper will consider and compare these two approaches to consider the uncertainties.

Operational Assessment (OA). The Condition Monitoring value, minus an appropriate allowance for growth would then define the OA limit value. From the EPRI criteria (2001) the crack growth value to define the OA should be the value that represents the 95th percentile of the predicted defect growth distribution. All degradation dimensions at the beginning of cycle are required to lie below the OA limit curve.

APPLICATIONS

Two applications will be presented: *the Freespan Part Throughwall Cracking* (supposing an internal 'ID' crack) and the *Axial Thinning with Limited Circumferential Extent* defect.

These defects supposedly were found in tubes with nominal diameter ¾" and wall thickness TW = 0.043" (1.09 mm). The tube material strength, $(S_y + S_u)$ = 146.6 ksi (1010 MPa) with standard deviation σ_M = 6.2 ksi (42.7 MPa). 10000 Monte Carlo simulations were performed considering the specified burst pressure value P_B = 4.2 ksi (28.9 MPa). These are typical values of a Westinghouse NPP with about 600 MW output power.

The estimated NDE technique errors are Relative Depth Measurement Error = 0 %TW with standard deviation σ_h = 15 %TW and Length Measurement Error = 0.0" with standard deviation σ_L = 0.10" (2.54 mm).

To obtain the results, the equations were re-written to express h as function of the crack length L and all other parameters. For every crack length L, the Monte Carlo simulations were performed considering the specified burst pressure value P_B and no crack growth.

Figure (8) presents the obtained results for the *Freespan Part Throughwall Cracking* in terms of three curves: the 'Structural Limit' (using the nominal values for all parameters), the 'Simplified Statistics' (using the 90th percentile for every parameter, Z = 1.282) and the 'Monte Carlo Statistics' (using normal standard random Z values).

For the *Axial Thinning with Limited Circumferential Extent* defect the results are presented in Figure 9 with the same three curves as per the precedent application.

COMMENTS AND CONCLUSIONS

In a previous paper (Mattar Neto & Miranda, 2001) the developed program to obtain the CM curves from the EPRI (2001) equations were verified with good results. The same programming was used here to analyze the two defects.

The curves in Fig. 8 show that an axial defect 1" long (part-throughwall) can stand a depth of about 50% of the tube thickness (in the simplified statistics) or about 60% of the tube thickness (in the more sophisticated Monte Carlo statistics). If the defect is 3" long it can stand a depth of about 57% of the tube thickness (using Monte Carlo). This is a reasonable gain respect to the 'old' 40% structural limit. In the second case, Axial Thinning with Limited Circumferential Extent defect, the Monte Carlo statistics allows almost the same values. Obviously, these values will change as the assumed uncertainties change their values in an actual analysis.

It is possible to say that the presented EPRI approach, using statistical procedures to assess the structural integrity og SG tubes represents a leap relative to the historical approach based on the maximum depth of 40% of the tube wall thickness. There is a reduction in the implied conservatism respect to the "old" approach: In any case, the results are within the regulatory limits.

In the presented results the crack growth was not considered due to the lack of data. In an actual tube integrity evaluation the crack growth should be considered to obtain the OA limit value. This paper was related only with the assessment of the CM limit value. An important, if not crucial, issue in this new approach is the characterization and evaluation of the NDE uncertainties.

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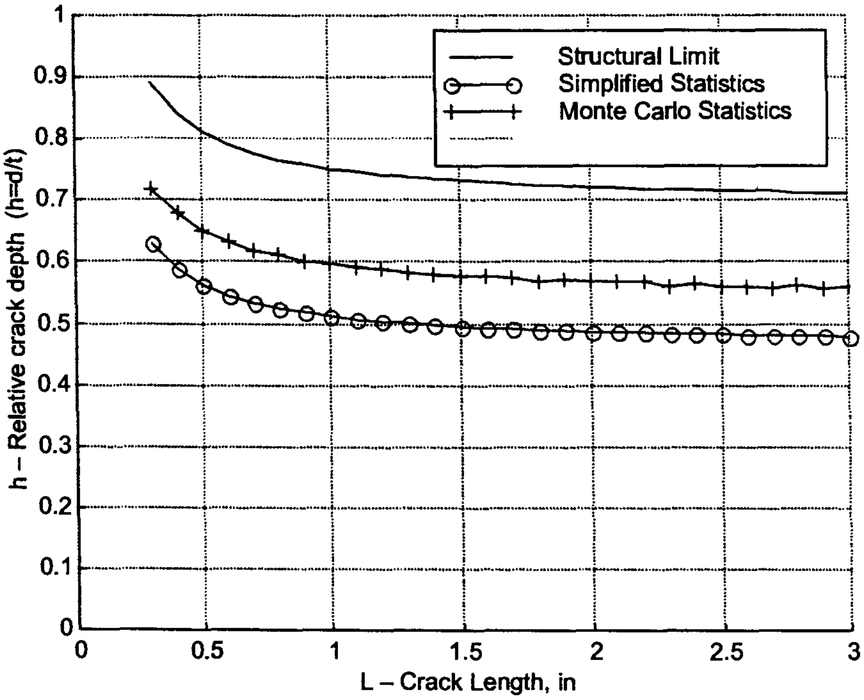

Figure 8. Freespan Part Throughwall Cracking (internal crack)

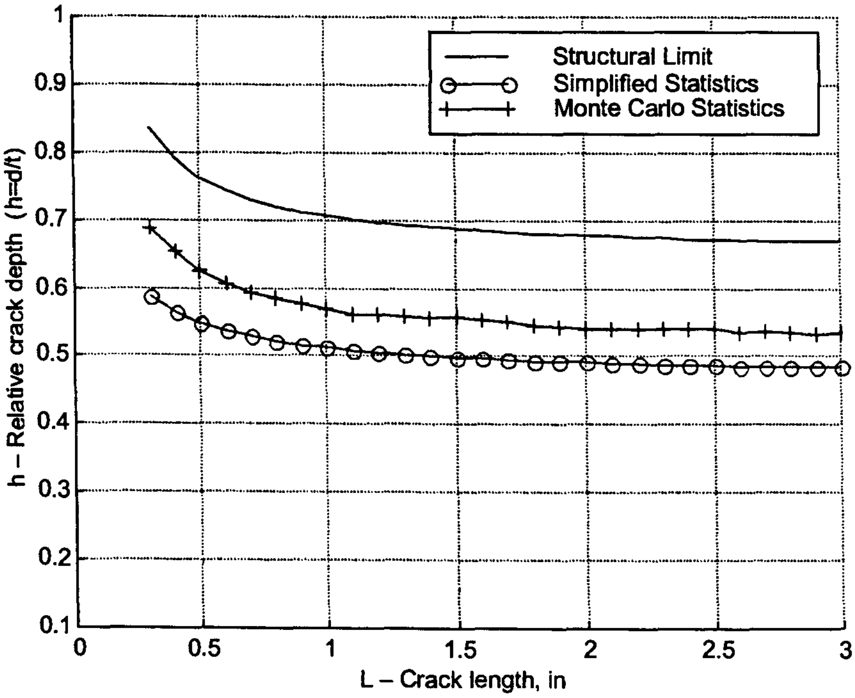

Figure 9. Axial Thinning with Limited Circumferential Extent