EVALUATION OF THE STRUCTURAL RELIABILITY OF CRACKED STEAM GENERATOR TUBES BASED ON THE FAILURE DIAGRAM ASSESSMENT

Thais M. W. Ouverney

Alexandre S. Francisco

Renato S. Horta

Luciano P. Moreira

thaismacedow@hotmail.com

afrancisco@metal.eeimvr.uff.br

renato.s.horta@gmail.com

luciano@metal.eeimvr.uff.br

Universidade Federal Fluminense

Avenida dos Trabalhadores, 420, 27250-125, Volta Redonda, RJ, Brazil

Abstract. *In the structural reliability evaluation of steam generator (SG) tubes subjected to crack-like flaws, it is possible to perform analyses based on the plastic collapse, as well as on elastic-plastic fracture mechanics and even on linear elastic fracture mechanics. Due to the austenitic microstructure of the tube materials, very high fracture toughness values are found in these materials, and most of the integrity criteria are based on limit load analysis, where plastic collapse is the prevailing mode of failure. In spite of the failure mechanism in SG tubes be mostly dominated by plastic collapse, a weak effect of elastic-plastic fracture takes place in the failure. One way for addressing this effect is evaluating the structural reliability based on the Failure Assessment Diagram (FAD), which is a two-criteria approach that considers the linear elastic fracture mechanics and the plastic collapse as two extreme forms of cracked component failure, while for elastic-plastic material, the failure will occur in an intermediate state. The recent tendency in safety assessment of structures containing defects is to consider the uncertainty of structural parameters. In the present paper, we perform a structural reliability evaluation of SG tubes based on the FAD approach by using the Monte-Carlo simulation. An engineering case is evaluated in order to compare the traditional limit load analysis with the FAD approach, considering Alloy 600, Alloy 690, and Alloy 800 materials.*

Keywords: *Structural reliability, Fracture mechanics, Monte-Carlo simulation*

1 INTRODUCTION

Steam generator (SG) is a critical equipment for the safety and operational performance of nuclear power plants. In pressurized water reactors, it is responsable for the heat tranfer from the primary circuit to the secondary one. SG is basically a heat exchanger in which the tube bundle is subjected to internal pressures, moderate temperatures, and agressive environments. This set of adverse conditions provides the occurrence of a degradation mechanism in the SG tubes, known as stress corrosion cracking. After a crack initiates, it may propagate through the tube wall along the time.

Thus, as far as a crack size does not reach its allowable limit, the respective tube is maintained in service, without compromising the regular operation of the SG. In this way, SG is a typical equipment that can be operated in a failure-tolerance condition. The use of a structural integrity assessment approach to derive crack acceptance criteria for SG tubes is an adequate practice. It allows the maximum tolerable size of tube cracks to be assessed on a fitness-for-service basis (Cheaitani, 2007). Fitness-for-service assessments are quantitative evaluations that are performed to demonstrate the structural integrity of in-service tubes containing cracks. Such assessments are referenced by API and ASME code and standard for evaluating the structural integrity of SG tubes, where inspections reveal cracks in the material (API, 2007).

An appropriate approach to derive crack acceptance criteria for SG tubes is the failure assessment diagram (FAD). The FAD can provide a convenient, technically based procedure to provide a measure for the acceptability of SG tubes containing cracks when the failure mechanism is driven by two forces: elastic fracture and plastic collapse. The elastic fracture driving force is represented by the thoughness ratio, and the plastic collapse, by the load ratio. These two parameters are represented on a vertical and horizontal axes, where a failure assessment curve determines the acceptability.

A good practice in fitness-for-service assessment of SG tubes containing cracks is to consider the uncertainty of the quantities involved in the FAD parameters. The reliability analysis and probabilistic fracture mechanics provide the methodology in which the uncertainties can be taken into account for assessing more realistically the structural integrity. Engineers and researches have taken seriously such probabilistic approach a long time ago (Guohua and Shuho, 1996). Lee (2007) has investigated the crack initiation and propagation process called delayed hydride cracking (DHC), and observed that a probabilistic safety assessment method is more appropriate for the assessment of overall pressure tube safety.

In the present work, a study was carried out on the evaluation of the structural reliability of SG tubes containing cracks, using the Monte-Carlo simulation. The FAD was chosen as the criterion to determine the acceptability of the SG tubes. In addition, the limit load analysis is also used to evaluate the structural reliability. The limit load analysis is a criterion chosed when the plastic collapse is the only failure mechanism of the structure. Due to the austenitic microstructure of the SG tube materials, very high fracture toughness values are found in these materials, and the crack acceptance criteria are based on limit load analysis. To check the effect of this metalurgical behavior, the Alloy 600, Alloy 690 and Alloy 800 were considered in order to compare the results of failure probability using FAD and limit load analysis.

The results of failure probability for the SG tubes show that the FAD presents the less conservative criterion. And the Alloy 690 is the material more adequate for using in SG tubes, since it presents levels of failure probability in compliance with the regulatory code.

2 FITNESS-FOR-SERVICE CRITERIA

The fitness-for-service assessment criteria can be used to evaluate SG tubes containing cracks. If the results of a fitness-for-service assessment indicate that the equipment is suitable for the current operating conditions, then the equipment can continue to be operated at these conditions provided suitable monitoring/inspection programs are established. The structural assessment based on the last inspection is performed in condition monitoring.

The crack acceptance criteria used for the evaluation of cracks can be the ”40%criterion”, the limit load analysis, and the FAD, as described below.

2.1 Minimum wall thickness

One of the most widely implemented crack acceptance criterion in use is the minimum wall thickness proposed in the 70s, the so-called 40% criterion. It establishes that the allowable depth of a crack should be less than 40% of the tube wall thickness (ASME, 1995). Although the 40% criterion is still widely used in the nuclear industry, it is often applied without a clear understanding of the limitations related with the assumptions made for its formulation.

This criterion results in excessive conservatism and an excessive number of SG tubes should be repaired or plugged. To overcome these drawbacks, some codes permit the use of alternative criteria subjected to previous acceptance by the regulatory authorities.

2.2 Limit load analysis

In order to reduce the number of SG tubes unnecessarily removed from service, even though they would continue to satisfy the existing regulatory guidance for adequate structural integrity, in recent years new revised fitness-for-service assessment were developed.

The new crack acceptance criterion is based on limit load (LL) analysis, which assumes that the plastic collapse is the prevailing failure mode due to the very high ductility of SG tube materials. A first disadvantage of this criterion is that for a particular cracked geometry and loading condition, different definitions for limit load estimation are available. On the other hand, the choice of a particular flow stress for the material under study has influence on the LL estimation. Therefore, although LL analysis seems to be simple in practice, it needs extensive supporting experimental data and still further research would be needed in order to validate their applicability (Bergant et al., 2015).

The main loading that leads the SG tube to the failure is the pressure difference across the tube wall. Considering a partial through-wall axial crack, located outside a SG tube, between two support plates or between the first support plate and the tube sheet, EPRI (2001) establishes a LL criterion given by the following equation:

$$p_b = 0.58(\sigma_y + \sigma_u)\frac{t}{R_i}[\phi - \frac{(a/t)^2}{a/t + a/c}], \tag{1}$$

where p_b is the burst pressure, σ_y is the yield strength, σ_u is the ultimate strength, t is the tube wall thickness, R_i is the inlet tube radius, ϕ is a correlation coefficient, c is the half crack length, and a is the crack depth.

A LL assessment curve can be defined in a diagram, where the aspect ratio a/c and the relative crack depth a/t are the coordinate axes at this diagram. If the coordinate of an assessment point is below the LL assessment curve, the tube is suitable for continued operation. A schematic that illustrates the safety margin for a crack-like flaw using this diagram is shown in Fig. 1.

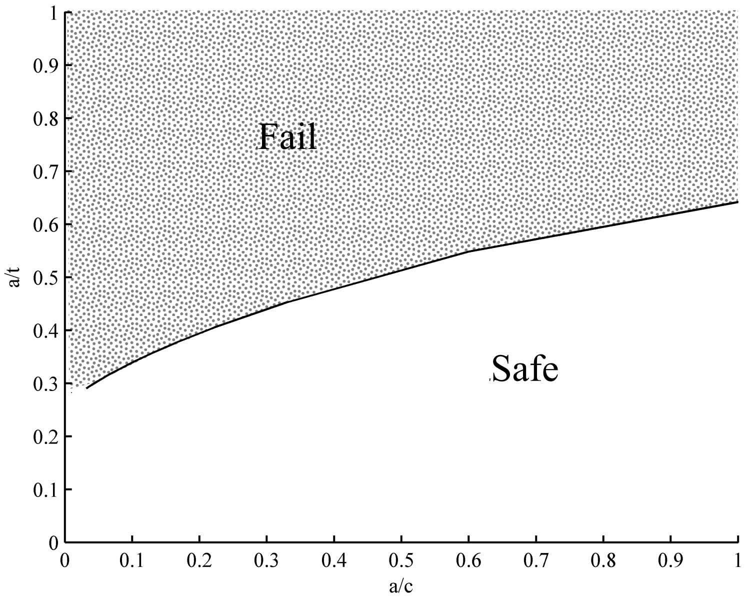

Figure 1: Safety margin using the limit load analysis

2.3 Failure assessment diagram

The FAD criterion was adopted because it provides a convenient, technically based method to provide a measure for the acceptability of a SG tube containing a crack-like flaw when the failure mechanism is measured by two driven forces: linear elastic fracture and plastic collapse. Linear elastic fracture usually controls failure for small cracks in SG tubes fabricated from a brittle material, and plastic collapse typically controls failure for large cracks if the SG tube is fabricated from a material with high toughness. In a fitness-for-service assessment of crack-like flaws, the results from a stress analysis, stress intensity factor and limit load solutions, the material strength, and fracture toughness are combined to define the FAD parameters: the toughness ratio, Kr, and the load ratio, Lr. These parameters are determined as follows:

$$K_r = \frac{K_I}{K_{mat}} \tag{2}$$

and

$$L_r = \frac{\sigma_{ref}}{\sigma_y}, \tag{3}$$

where K_I is the applied stress intensity factor, K_{mat} is the fracture toughness, σ_{ref} is the reference stress, and σ_y is the yield strength.

The FAD parameters define the coordinates of an assessment point in the FAD whose position relative to a FAD assessment curve determines the safety margin of the component. This curve represents the failure locus, and if the assessment point is below the curve, the SG tube is suitable for continued operation (Anderson, 2005). Considering a partial through-wall axial crack, located outside an SG tube, between two support plates or between the first support plate and the tube sheet, the guide API (2007) has proposed the following FAD assessment curve:

$$K_r = (1 - 0.14L_r^2)[0.3 + 0.7exp(-0.65L_r^6)]. \tag{4}$$

A schematic that illustrates the safety margin for a crack-like flaw using the FAD is shown in Fig. 2. Both the limit load analysis and fracture mechanics are encompassed by the structural integrity assessment using the FAD.

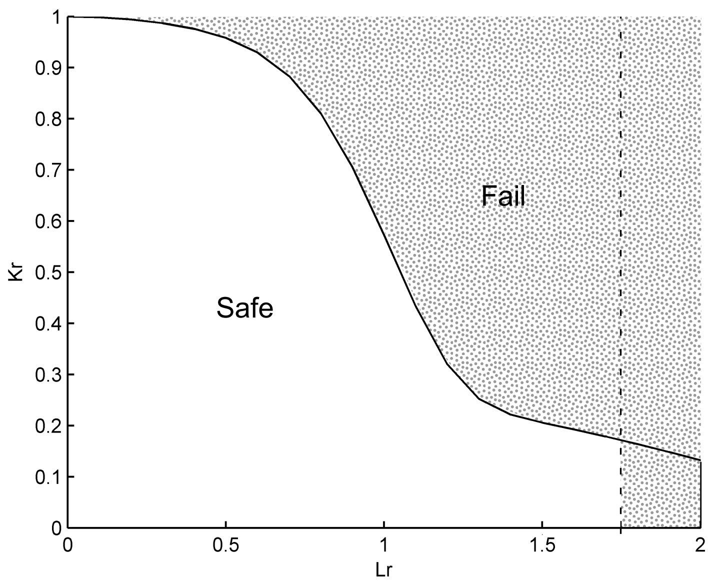

Figure 2: Safety margin using the FAD analysis

3 RELIABILITY METHOD

Reliability methods have been established to take into account, in a rigorous manner, the uncertainties involved in the analysis of an engineering problem. The failure probability is used to quantify risks and therefore evaluate the consequences of failure. In this approach, the governing parameters of the problem are modeled as random variables. Basic random variables can be grouped in a random vector **X**.

For reliability analysis, the space **D** of basic random variables may be divided into the failure and the safety regions. The failure region is defined by $\mathbf{D}_f = \{\mathbf{x}|g(\mathbf{x}) \leq 0\}$, where $g(\mathbf{x})$ represents the failure limit-state function. Notice that $g(\mathbf{x}) = 0$ is the boundary between failure and safety regions, and it is called the limit-state surface. The failure probability is determined by the following integral (Melchers, 1987):

$$P_f = Pr\{g(\mathbf{X}) \leq 0\} = \int_{\mathbf{D}_f} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}, \tag{5}$$

where $f_{\mathbf{X}}(\mathbf{x})$ is the joint probability density function of the basic random variables.

For the LL procedure, the failure limit-state function is given by

$$g(\mathbf{x}) = 0.58(\sigma_y + \sigma_u)\frac{t}{R_i}[\phi - \frac{(a/t)^2}{a/t + a/c}] - p, \tag{6}$$

where p is the applied pressure, and the components of the vector $\mathbf{x} = (\sigma_y + \sigma_u, \phi)$ are the basic random variables that represent all the relevant uncertainties influencing the failure of the SG tubes.

For the FAD procedure, the failure limit-state function is given by

$$g(\mathbf{x}) = (1 - 0.14L_r^2)[0.3 + 0.7exp(-0.65L_r^6)] - K_r. \tag{7}$$

where the components of the vector $\mathbf{x} = (K_{mat}, \sigma_y)$ are the basic random variables.

One of the most accurate method for calculating the failure probability is the Monte Carlo simulation, checking if the failure limit state function is violated.

4 RESULTS AND DISCUSSION

In order to perform the structural critical assessment on the SG tubes, two fitness-for-service criteria are investigated in this work: LL and FAD. The applicability of each criterion depends on the tube material, geometry and loading condition of the SG tubes. For this purpose, the impact of the crack geometry is observed by using relative crack depth $a/t = 0.4$ and 0.8, with aspect ratio $a/c = 0.25$. Alloys 600, 690 and 800, mill-annealed, are used to investigate the effect of SG tube material on the structural integrity. The mechanical properties of the materials are given in Table 1 (Granta Design, 2015).

Table 1: Mechanical properties for studied alloys.

$Alloy$	σ_y (MPa)	σ_u (MPa)	K_{mat} (MPa$m^{1/2}$)
600	$221 - 262$	$517 - 586$	$349 - 386$
690	$280 - 480$	$630 - 845$	$314 - 347$
800	$205 - 415$	$515 - 725$	$412 - 456$

A partial through-wall axial crack is assumed to be present outside the SG tube, between two support plates or between the first support plate and the tube sheet. The crack and tube geometries are illustrated in Fig. 3. Working pressure difference is applied on the inner surface of the tube as the unique loading condition. The data of the tube geometry and loading condition are found in Table 2. The resistance of the SG tubes is assured when the structural integrity attends to safety requirements. According to NEI (2005), the tubes should support to three times the pressure difference across the tube wall, in normal conditions.

Assuming that the plastic collapse is the prevailing failure mechanism, the structural criterion should be based on the limit load analysis. Fig. 4 shows the coordinates of assessment points for relative crack depths $a/t = 0.4$ and 0.8, and for Alloys 600, 690 and 800.

The traditional minimum wall thickness ($a/t = 0.4$) is excessively conservative for all the alloys. When the crack reaches the relative crack depth $a/t = 0.8$, the Alloy 600 is pratically

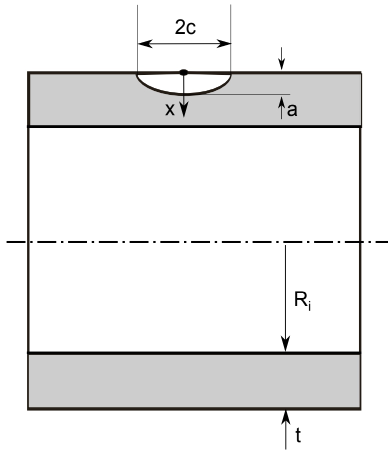

Figure 3: A schematic diagram of the crack outside the tube.

Table 2: The tube geometry and loading condition.

R_i (mm)	t (mm)	p (MPa)
8.4327	1.0923	9.42

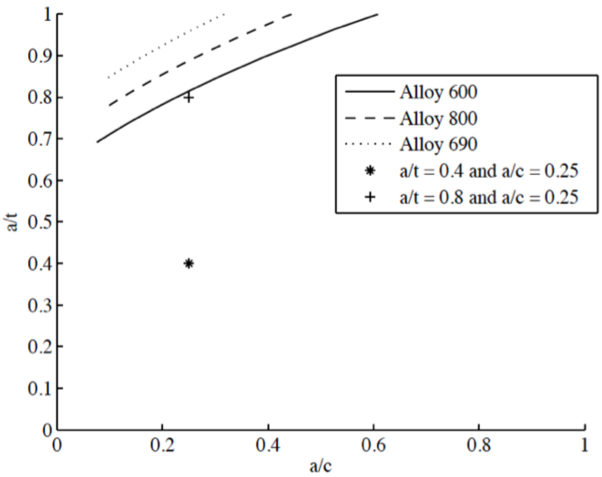

Figure 4: LL procedure at $p = 28,26$ **MPa.**

not suitable for continued operation. On the other hand, the Alloy 690 provides the more conservative assessment for the SG tube material. In Fig. 5, the LL procedure is carried out for Alloy 690 at distinct pressure differences. With the relative crack depth $a/t = 0.8$, the Alloy 690 became unsuitable for continued operation at the pressure differences $p = 50.00$ and 61.55 MPa.

Depending on the SG tube material, the failure mechanism might be in minor extent based on the elastic-plastic fracture. In this way, the FAD procedure would be applied as a comprehensible criterion for predicting the structural failure of the cracked SG tubes. Fig. 6 shows the coordinates of FAD assessment points for relative crack depths $a/t = 0.4$ and 0.8, and for Alloys 600, 690, and 800.

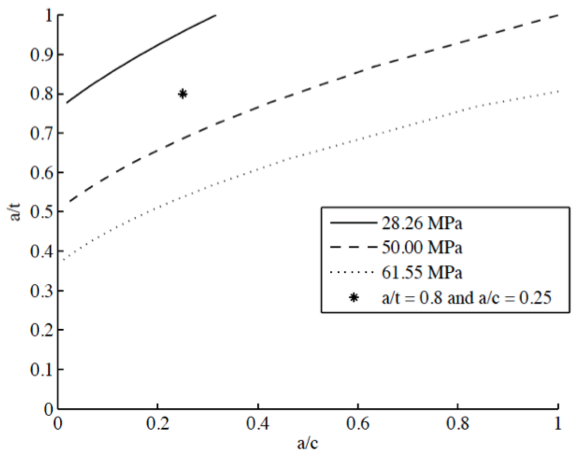

Figure 5: LL procedure for the Alloy 690 and $a/t = 0.8$, at distinct pressure differences.

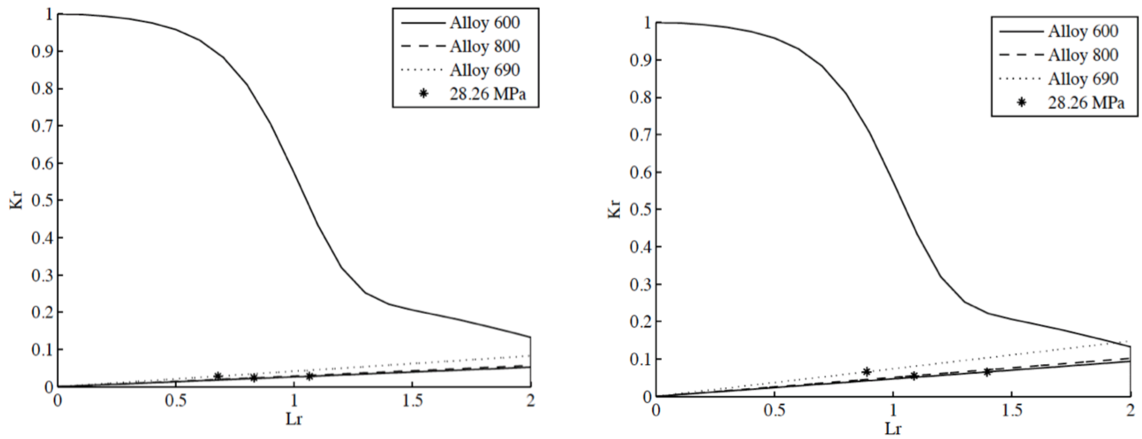

Figure 6: FAD procedure for $a/t = 0.4$ (left) and $a/t = 0.8$ at $p = 28, 26$ MPa. (right).

According to the FAD procedure, the SG tube is suitable for continued operation for the all the considered crack geometries and tube materials, at the pressure difference $p = 28.26$ MPa. The Alloy 690 also provides the more conservative assessment for the SG tube.

For a given crack geometry, when the pressure is increased, the assessment points in the FAD move following a straight line, called loading line. The intersection of this line and the FAD assessment curve determines the failure mechanism of the SG tube. When plotted assessment points are mostly located under the line of $K_r/L_r = 0.2$, it implies that the plastic collapse dominates the failure mechanism (Kim et al., 2007). Then, for the all the considered crack geometries and tube materials, the failure mechanism predicted by the FAD is close to plastic collapse. This means that a solely limit load analysis would be adequate to assess the structural integrity of the SG tube.

In Fig. 7, the FAD procedure is carried out for Alloy 690 at distinct pressure differences. With relative crack depth $a/t = 0.8$, at pressure difference 61.05 MPa, the SG tube of Alloy 690 became unsuitable for continued operation. Despite the loading line for the Alloy 690 has a low slope, it is next to the line of $K_r/L_r = 0.2$. Therefore, both the limit load analysis and elastic-plastic fracture mechanics could be chosen for the structural integrity assessment.

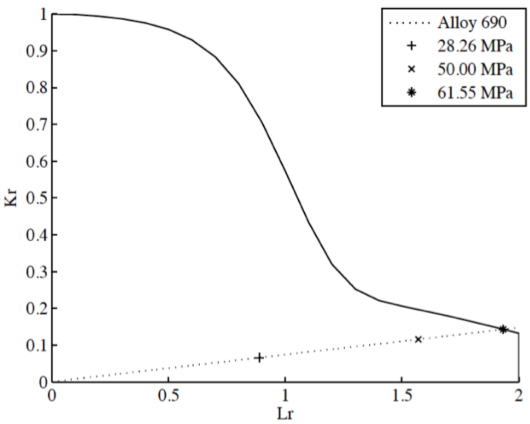

Figure 7: FAD procedure for the Alloy 690 and $a/t = 0.8$, at distinct pressure differences.

The possibility of using both the limit load analysis and elastic-plastic fracture mechanics as the crack acceptance criteria for the SG tube is plausible, when considering that the uncertainty of the FAD parameters exists. Under this condition, there is variability in the relative position of the FAD assessment points and curve. Then, fitness-for-service assessments of SG tubes containing cracks are best performed by probabilistic approaches. The reliability analysis and probabilistic fracture mechanics provide the methodology in which uncertainties can be taken into account for assessing more realistically the structural integrity.

In probabilistic approaches, the governing parameters are modeled as random variables. In this work, the random variables involved are the following: correlation coefficient, yield strength, ultimate strength and fracture toughnes. As shown in Table 1, the data of yield strength, ultimate strength and fracture toughness are available in a range of values. For the statistical characterization of these mechanical properties, the sample mean is assumed to be the average of the minimum and maximum values, and coefficient of variation is equal to 0.13. The statistical data of these variables is outlined in the Table 3 for each alloy. Data of the correlation coefficient is presented in the Table 4, valid for all the alloys.

Table 3: Statistics of the mechanical properties.

$Variable$	$Distribution$	$Alloy\,600$	$Alloy\,690$	$Alloy\,800$
σ_y	normal	$\mu_{\sigma_y} = 241.5$	$\mu_{\sigma_y} = 380.0$	$\mu_{\sigma_y} = 310.0$
σ_u	normal	$\mu_{\sigma_u} = 551.5$	$\mu_{\sigma_u} = 737.5$	$\mu_{\sigma_u} = 620.0$
K_{mat}	log-normal	$\mu_{K_{mat}} = 367.5$	$\mu_{K_{mat}} = 330.5$	$\mu_{K_{mat}} = 434.0$

Table 4: Statistics of the correlation coefficient.

$Variable$	$Distribution$	$Statistics$
ϕ	normal	$\mu_\phi = 1.104$
		$\sigma_\phi = 0.0705$

In order to investigate the effects of the uncertainties on the crack acceptance criteria, comparisons of failure probability using the limit load analysis and FAD methodology are performed. The failure probability is determined by the integral of the Eq. (5), in which the failure limit-state function depends on the failure acceptance criterion. The integral is solved by using the Monte-Carlo simulation. The failure probability of SG tube is computed for relative crack depths $a/t = 0.4$ and 0.8, and for Alloys 600, 690 and 800, at the pressure difference $p = 28.26$ MPa.

First, considering the LL procedure, failure limit-state function is given by Eq. (6). The results of the failure probability are listed in Table 5. It is seen that the failure probability is rather low for the relative crack depths $a/t = 0.4$. This example shows the conservatism of the "40%criterion". For the Alloy 690, the failure probability remains at low level even for relative crack depths $a/t = 0.8$. According to EPRI (2006), the SG tube should fail at pressures less than three times the pressure difference across the tube wall, with probability of 5%. Therefore, such safety requirement is satisfied by using the LL procedure for the Alloy 690. On the other hand, for the Alloys 600 and 800 it is found high level of failure probability.

Table 5: Failure probability for the LL procedure.

Alloy	$a/t = 0.4$	$a/t = 0.8$
600	0.0005	0.4350
690	0.0000	0.0397
800	0.0000	0.1750

Next, considering the FAD procedure, the failure limit-state function is given by Eq. (7). The results of failure probability are shown in Table 6. The failure probability are in general decreased in the FAD procedure in comparison with the LL procedure, except for the relative crack depth $a/t = 0.4$. In the LL and FAD procedures, the the higher value of failure probability is for the Alloy 600, since it has the lower sum of yield strength and ultimate strength.

Table 6: Failure probability for the FAD procedure.

Alloy	$a/t = 0.4$	$a/t = 0.8$
600	0.0403	0.2200
690	0.0008	0.0013
800	0.0003	0.0166

As the Alloy 690 presents the lowest level of failure probability, the LL and FAD procedures are carried out with this material relative for the crack depth $a/t = 0.8$, at distinct pressure differences. The results in In Table 7 show that the failure probability increases as the pressure differences is increased, reaching almost the certain event of failure with $p = 61.55$ MPa, for both the LL and FAD procedures.

Table 7: Failure probability for the Alloy 690 and $a/t = 0.8$, at distinct pressure differences.

	P_f	
$Pressure$ (MPa)	LL	FAD
26.28	0.0397	0.0013
50.00	0.8517	0.6415
61.55	0.9893	0.9864

CONCLUSIONS

The evaluation of the structural integrity of SG tubes containing crack-like flaws is performed in this work. A partial through-wall axial crack is located outside the tube, and working pressure difference is applied on the inner surface of the tube as the unique loading condition. Deterministic and probabilistic failure analyses are performed considering two crack geometries, two fitness-for-service criteria, and three tube alloys.

With regard to crack geometries, both the deterministic and probabilistic failure analyses show that for relative crack depth $a/t = 0.4$, the SG tube is in a safe condition. The results indicate that the so-called 40% criterion is excessively conservative for the Alloys 600, 690, and 800, using the LL and FAD procedures.

The deterministic failure analysis demonstrates that the results from the LL procedure are more conservative than ones from the FAD procedure. The same evidence can be observed by the probabilistic failure analysis using both the fitness-for-service criteria. But the FAD procedure is the more adequate tool for assessing the structural integrity of flawed SG tubes, since it provides a more comprehensive and accurate assessments.

The Alloy 690 presents the best results of structural integrity assessment in deterministic and probabilistic failure analyses, in compliance with the guide EPRI (2006), in which SG tubes should fail at pressures less than three times the pressure difference across the tube wall, with probability of 5%. Therefore, the Alloy 690 is the material that offers more structural strenght to flawed SG tubes, in addition to be less susceptible to mechanisms of degradation such as the stress corrosion cracking.

ACKNOWLEDGEMENTS

The authors wish to acknowledge CAPES which supported this work through the graduate scholarship program (Thais M. W. Ouverney and Renato S. Horta).

REFERENCES

Anderson, T., 2005. *Fracture Mechanics, Fundamentals and Applications*, pp. 413. CRC Press.

API 579-1/ASME FFS-1, 2007. Fitness-For-Service. American Petroleum Institute and American Society of Mechanical Engineers, Washington.

ASME, 1995. ASME Boiler and Pressure Vessel Code Section XI.

Bergant, M. A., Yawnyb, A. A., & Ipina, J. E. P., 2015. Structural integrity assessments of steam generator tubes using the FAD methodology. *Nuclear Engineering and Design*, vol. 295, pp. 457467.

Cheaitani, M. J, 2007. Case studies on ECA-based flaw acceptance criteria for pipe girth welds using BS 7910:2005. In *26th International Conference on Offshore Mechanics and Arctic Engineering, OMAE 2007, San Diego, California, 10-15 June*.

EPRI, 2001. Steam Generator Degradation Specific Management Flaw Handbook. Eletric Power Research Institute, Report 1001191.

EPRI, 2006. Steam Generator Integrity Assessment Guidelines, Revision 2. Eletric Power Research Institute, Report 1012987.

Granta Design, 2015. CES EduPack 2015 Aerospace database.

Guohua, C., & Shuho, D., 1996. Study on the reliability assessment methodology for pressure vessels containing defects. *International Journal of Pressure Vessel and Piping*, vol. 69, pp. 273277.

Kim, J. C., Lee, S. M., Chang, Y. S., Choi, J. B., Kim, Y. J., & Choi, Y. H., 2007. Development of an Integrity Evaluation System for Steam Generator Tubes in a Nuclear Power Plant. *Solid State Phenomena*, vol. 120, pp. 157-162.

Lee, J. S., Kwak, S. L., & Pyo, C. R., 2007. Failure Probability Estimation of Pressure Tube Using Failure Assessment Diagram. *Solid State Phenomena*, vol. 120, pp. 37-42.

Melchers, R. E., 1987. *Structural Reliability: Analysis and Prediction*. Ellis Horwood Limited, 1st edition.

NEI, 2005. Steam Generator Program Guidelines, Revision 2. Nuclear Energy Institute, NEI 97-06.