IJE TRANSACTIONS B: Applications Vol. 26, No. 5, (May 2013) 543-552

International Journal of Engineering

Journal Homepage: www.ije.ir

Failure Probability and Remaining Life Assessment of Reheater Tubes

E. Poursaeidi *, A. Moharrami, M. Amini

Department of Mechanical Engineering, University of Zanjan, P. O. Box 45371-38791, Zanjan, Iran

PAPER INFO

Paper history:
Received 19 December 2012
Accepted in revised form 24 January 2013

Keywords:
Structural Reliability Analysis
Failure Probability
Remaining Life Assessment
Reheater Tubes
RALA software

ABSTRACT

In this study, a real and significant industrial problem in a steam power plant was investigated. Reheater tubes in boilers are under creep and the fireside corrosion mechanism that cause some of them to fail. Since the estimation of probability of failure (PoF) and remaining life (RL) is expensive and time consuming by the deterministic methods, in this work they were evaluated using structural reliability analysis and distribution analysis based on in-site tests and selecting an appropriate limit state function (LSF). The criterion used for this purpose is based on the creep lifetime model and uncertainties**.** Sensitivity analysis was also carried out in this research. The considered relationship among three affecting parameters on boiler tube failure including time, creep and fireside corrosion leads to evaluating RL besides PoF as well as obtaining PoF and RL simultaneously by selecting an appropriate time-based LSF. Most accurate results were achieved based on obtained PoF and RL values which cause to provide more reliable results for economic planning of future inspection periods. This leads to significant cost savings and operational safety improvements. A new software package, named RALA was developed via programming in Matlab. The obtained results are in good agreement with all data gained from the practical experiments in the power plant based on the previous studies.

doi: *10.5829/idosi.ije.2013.26.05b.11*

Nomenclatures

C	Material constant	x^*	Design point in the physical space
$f_x(\boldsymbol{x})$	Joint probability density function of basic random variables $\boldsymbol{x}$	α_i^*	Sensitivity factor
$g(\boldsymbol{x})$	Failure function or limit state function or performance function	β	Reliability index
k_j	Main curvatures of the quadratic hyper-surface at the design point	σ_{ax}	Axial stress
K	Wall thinning rate	σ_H	Hoop stress
M	Total independent samples	σ_r	Radial stress
M^*	Number of samples among them satisfying $g(\boldsymbol{x}) \le 0$	σ_{ref}	Reference stress
n	Stress sensitivity coefficient	σ_U	Material ultimate strength
N	Number of simulations	σ_y	Material yield stress
P	Internal pressure	σ^*	Von mises stress
P_F	Failure probability	Φ	Cumulative standard normal distribution function
P_L	Current load	$\boldsymbol{X}$	Random variables in physical space

* Corresponding Author Email: epsaeidi@znu.ac.ir (E. Poursaeidi)

P_U	Rigid plastic collapse load for the component
r	Radial distance
r_i	Inner radius
r_o	Outer radius
T	Temperature
t_{nr}	Service rupture life in presence of corrosion (real operating conditions)
t_{op}	Operating time in service
t_r	Rupture time of tube without wall thinning
$\boldsymbol{u}$	Random variables in standard normal space
$\boldsymbol{u}^*$	Design point in the normal space
w_i	Initial tube wall thickness
w_f	Final tube wall thickness

Abbreviations

CDF	Cumulative Distribution Function
FORM	First Order Reliability Method
FOSM	First Order Second Moment
LMP	Larson-Miller Parameter
LSF	Limit State Function
MCS	Monte Carlo Simulation
PDF	Probability Density Function
PoF	Probability of Failure
RALA	Reliability Analysis and Life Assessment
RBDO	Reliability Based Design Optimization
RL	Remaining Lifetime
SORM	Second Order Reliability Method

1. INTRODUCTION

Internally pressurized tubes are considered as essential and critical elements in heat-exchanger applications, such as reheater tubes in boilers. Tubes in such applications may cause the material to encounter the creep regime, creep deformation and even fracture with severe consequences due to their vulnerabilities against temperature excursions. According to the obtained estimation, creep fractures in boiler tubes are responsible for 10% of all power plant breakdowns. Generally, creep is in responsible for 30% of all tube failures in boilers and reformers [1].

The residual creep life assessment of boiler components has a great significance from technical, safety, and economic standpoints. It also has sufficient ability to inhibit the unexpected and unforeseen stops which may be associated with severe damage and may not be capable of compensating in some cases. Therefore, many dissimilar analytical methods along with several criteria and standard codes have been established according to the obtained results of destructive and non-destructive tests and substitute inspections. The obtained results of these tests and inspections in the analytical methods consist of doubts and uncertainties due to the errors in the inspection tools, operator miscalculation, or ordinary simplifications mistake in the analytical estimations.

However, the dispersion of the sampling domains from the diverse aspects of a number of elements, a variety of components, and complicated service conditions is considered as a key factor in developing probabilistic methods of PoF and life assessment. For instance, many significant parts of a boiler with hundreds of kilometers of tubes in critical regions with very high temperatures tend to have corrosion at high temperature, oxidation, and erosion due to contact with hot gas flow and ignition products. The sampling problem is considered as the first and the significant problem under such conditions.

Furthermore, in-plant measurements of tube wall thinning are accomplished by grinding off the oxide to bare metal and measuring the thickness of the wall utilizing conventional ultrasonic tests, which is time-consuming and strictly limits the number of tubes that can be sampled. Additionally, only a slight segment of the tube is scrutinized; thus, if this is not the most severely damaged section, an extremely optimistic life assessment can result [2].

Based on the development of reliability engineering and probabilistic fracture mechanics, engineers and researchers can apply the reliability analysis and assessment methods for the structures containing defects. Probabilistic estimation of RL and PoF for corroded pipelines has been extensively used in the last decade. For example, the FORM, SORM, and different versions of simulation methods have been applied in the safety assessment of steam generator tubes with the axial through-wall crack due to stress corrosion cracking by Cizelj, Mavko, and Riesch-Oppermann [3]. Their probabilistic fracture mechanics model takes into consideration the scatter in tube geometry, material properties and stable crack propagation. Ahammed and Melchers [4] have described a probabilistic method for assessing the suitability of corroded pipelines under pressure loading. They have developed a probabilistic limit state model from the available deterministic failure equations. Then reliability is estimated by the advanced FOSM method. Guohua and Shuho [5] have studied the reliability assessment for pressure vessels containing defects using the FOSM method and the MCS. Ahammed [6] considered a methodology for the assessment of RL of a pressurized pipeline with active corrosion defects. The level II advanced FOSM was employed for carrying out reliability analysis. Furthermore, Caleyo, Gonzalez, and Hallen [7] investigated the probabilistic methodology for the estimation of the RL of pressurized pipeline containing active corrosion defect. The FOSM iterative reliability method, the Monte Carlo integration technique, and the first order Taylor series expansion of the LSF are used to estimate the PoF associated with any corrosion defect over time. Lee et al. [8] estimated the PoFs of wall-thinned pipes in nuclear systems using FORM, SORM, and MCS, and proposed limited operating conditions under different types of loadings, such as internal pressure, bending moment, and their combined loading . An integrated approach of RL assessment and reliability evaluation on the first stage of reheater tubes system was presented by Bakic et al. [9]. They collected a large set of data at the first stage of reheater tube system at a unit power plant and developed a method for estimating RL and reliability of reheater tubing system subjected to corrosion deterioration over time. Poursaeidi and Alimadadi [10] studied RL of super heater tubes of the boiler of a power plant using the MCS, based on non-destructive in-site tests.

In this work, a large set of data was achieved using the final reheater tubes of a 250-MW (Rajaee power plant, unit 4, Qazvin, Iran) with about 84000 hours service. The obtained data was utilized for statistical analysis of boiler tubes outages, inspection of the data and development of a method for estimating RL and reliability of reheater tubes which was subjected to corrosion deterioration over time. The PoF is evaluated according to the in-site tests (statistical data) along with selecting an appropriate limit state function or LSF (mechanical model) using FORM, SORM, and MCS methods. RL assessment is also carried out using the distribution analysis of the LSF based on MCS. The study also presents experimental data about the probabilistic distributions of the variables involved in the reliability analysis at hand.

This paper proposes a new measure of reliability to a significant practical problem through the time to creep-related failure of the reheater tubes. Moles and Westwood's relationship [2] was applied to investigate the reheater tubes in a statistical approach that is noteworthy. Consequently, the affecting parameters on boiler tube failure including time, creep and fireside corrosion were related to each other considering Equation (7). This leads to evaluating RL besides PoF as well as obtaining PoF and RL simultaneously by selecting an appropriate time-based LSF and applying aforementioned methods. Most accurate results were achieved based on obtained PoF and RL values which cause to provide more reliable results for economic planning of future inspection periods. This leads to significant cost savings and operational safety improvements. The above-mentioned approach which was performed in this study for obtaining of RL besides PoF has not been investigated in any other similar work up to now.

2. RELIABILITY MODEL

2. 1. PoF Estimation The statistical theory of reliability in structural mechanics copes with the description of PoF, P_F, in structural elements via scattering the applied loads and structural resistance properties. The behavior of structure failure is expressed by a function of failure $g(\boldsymbol{x})$, determining by basic random variables $\boldsymbol{x} = (x_1,x_2,\ldots,x_n)$ which indicates two distinct characteristics known as applied loads and structural resistance parameters including dimensions and material properties. For reliability analysis, system parameters are treated as random variables considering the type of distribution, mean, and standard deviation which were assumed to be known for each parameter. Failure is defined based on the values of $g(\boldsymbol{x})$, wherein $g(\boldsymbol{x}) < 0$ denotes failure while no failure occurs at $g(\boldsymbol{x}) > 0$, and $g(\boldsymbol{x}) = 0$ determines the so-called failure surface (a hyper-surface in the n-dimensional space of the basic random variables) which separates the failure domain from the safe domain. Therefore, as it is described in Equation (1), PoF can be computed from the integration of the joint PDF of respective basic variables over the region of $g(\boldsymbol{x}) < 0$:

$$P_F = P[g(\boldsymbol{x}) < 0] = \int_{g(\boldsymbol{x})<0} f_x(\boldsymbol{x})\, d\boldsymbol{x} \tag{1}$$

where $f_x(\boldsymbol{x})$ represents loads, material properties, and geometry.

The analytical solutions of the failure integral (Equation (1)) are restricted to special cases. Two different techniques known as reliability index technique including FORM and SORM, and simulation technique including MCS are generally applied for estimation of PoF. The algorithms description of FORM, SORM, and MCS will be mentioned briefly below.

An approximated PoF in FORM approach can be obtained via a linearization of the LSF at a design point or MPP ($\boldsymbol{x}^*$) as it is described in the following well-known expression (Equation (2)).

$$P_F \approx \Phi(-\beta) \tag{2}$$

The sensitivity of PoF towards the scattering of each basic random variable is expressed in Equation (3).

$$\frac{\partial \beta}{\partial u_i} = \frac{\partial}{\partial u_i}\sqrt{\sum_{j=1}^{n} u_j^2} = \frac{u_i^*}{|u|} = \alpha_i^* \tag{3}$$

In SORM approach, an approximated failure surface can be determined by a quadratic hyper-surface associated with the curvature of non-linear LSF around the design point or MPP. Calculation of probability with second order approximation is performed by a simple closed-form solution according to Equation (4).

$$\boldsymbol{P_F} \approx \Phi(-\beta)\prod_{\boldsymbol{j}=1}^{\boldsymbol{n}-1}\left(1+\beta\, \boldsymbol{k_j}\right)^{-\frac{1}{2}} \tag{4}$$

MCS can be also used to estimate the PoF. For structural reliability analysis consisting of a random vector $\boldsymbol{x} = \{x_1, x_2, \ldots, x_n\}$ along with joint density $f_x(\boldsymbol{x})$. The PoF defined by LSF, $g(\boldsymbol{x})$, can be evaluated from M independent samples $x_1,\ldots,x_M$ created from the function of density $f_x(\boldsymbol{x})$. An approximated PoF is evaluated by Equation (5) if there are M^* samples over the region of $g(\boldsymbol{x}) \leq 0$.

$$P_F = P[g(\boldsymbol{x}) \leq 0] \cong \frac{M^*}{M} \tag{5}$$

2. 2. Failure Function In this section, the probabilistic model of boiler tube in reliability analysis is presented. The LSF is represented by a set of random variables described by the distribution type and other parameters such as mean and standard deviation.

As mentioned before, Reheater tubes were investigated using Moles and Westwood's relationship (Equation (7)) in a statistical approach which is worth mentioning. Consequently, the affecting parameters on boiler tube failure including time, creep and fireside corrosion were related to each other considering Equation (7). This leads to evaluating RL besides PoF as well as obtaining PoF and RL simultaneously by selecting an appropriate time-based LSF using structural reliability analysis methods such as FORM, SORM, and MCS.

In reheater tubes, major thinning of the tube wall of about 30% or more can cause the premature creep failures. Generally, the thinning originates from additional corrosion at high temperature exposures, while in some cases the rates of fireside corrosion at designing temperatures will be increased due to the aggressive species in the fuels. Corrosion is an irreversible process of material degradation. Due to detrimental effects exerted on the operating material characteristics, especially in the boiler tube system, it is one of the most important issues in the operation of thermal plants and is considered the root cause of many outages. It is important to apply a method for reliability evaluation of the thermal power plant boiler tubes with corrosion damages besides our life assessment model.

The description of correlation among the predicted total service rupture life, t_{nr}, of a tube and the following three basic variables is defined as:

1. creep rupture life without wall thinning $t_r = t_r(w_f, r_i, \sigma_y, \sigma_U, P, T, n)$,
2. rate of wall thinning $K = K(w_i, w_f, t_{op})$, and
3. stress sensitivity of the creep rate, n.

As it is represented in Equation (6), the failure function $g(\boldsymbol{x})$ regarding with lifetime; safety margin is defined by the difference between the service rupture life, t_{nr} and the operating time in service, t_{op}.

$$g(\boldsymbol{x}) = t_{nr}(\boldsymbol{x}) - t_{op} \tag{6}$$

The corrosion of fireside can reduce the thickness of wall in the case of reheater tubes and consequently results in rise in stress and reduction in rupture life. A relationship for evaluation of RL under wall thinning conditions have been derived using Moles and Westwood [2] equation considering a linear rate of corrosion and the applicability of the linear damage rule (Equation (7)).

$$t_{nr} = \frac{1}{K}[1 - (1 + K(n-1).t_r)^{\frac{1}{1-n}}] \tag{7}$$

Wall thinning rate, K is defined by the following expression:

$$K = \frac{w_i - w_f}{w_i t_{op}} \tag{8}$$

SS321H was utilized in final reheater tubes of Rajaee power plant (SA213-TP321H American standard steels). LMP of SS347 with similar properties with SS321H was applied to compute creep life of the virgin tubes, t_r. The diagram of LMP-SS347 is demonstrated in Figure 1, Davis [11].

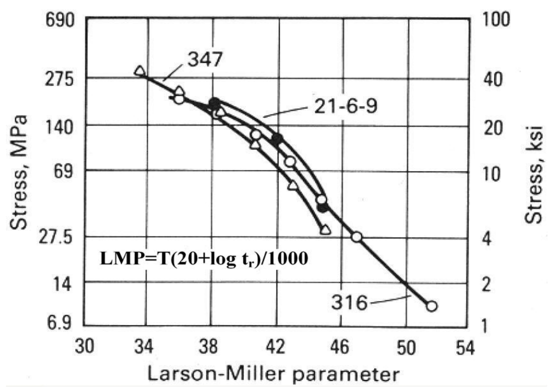


Figure 1. LMP diagram, Results for 1000 hours test

TABLE 1. A Summary of Uncertainties Data in Reheater Tubes in Each Case.

Variable	Case I			Case II			Case III		
	Mean	Standard deviation	Type of distribution	Mean	Standard deviation	Type of distribution	Mean	Standard deviation	Type of distribution
w_i (mm)	3.4	0.08	Normal	3.4	0.08	Normal	3.4	0.08	Normal
w_f (mm)	1.94	0.1	Normal	2.1	0.15	Normal	2.35	0.11	Normal
r_i (mm)	15.65	1.1	Normal	15.65	1.1	Normal	15.65	1.1	Normal
σ_y (MPa)	131	15	Log-normal	131	15	Log-normal	131	15	Log-normal
σ_u (MPa)	395	23	Log-normal	408	25	Log-normal	420	22	Log-normal
P (MPa)	3.7	0.09	Normal	3.7	0.09	Normal	3.7	0.07	Normal
T ($^\circ C$)	630	28	Normal	605	25	Normal	584	22	Normal
n	6.3	0.64	Normal	6.2	0.58	Normal	5.9	0.61	Normal

LMP is defined as follows, Viswanathan [12]:

$$LMP = T(C + \log t_r)/1000 \tag{9}$$

where T is temperature in $^\circ R$, and C is the material constant that varies from 17 to 23. Based on Equation (9), the calculation of t_r with considering the material constant at $C = 20$ can be presented as Equation (10).

$$t_r = 10^{\left(\frac{(1000LMP)}{(1.8T+492)} - 20\right)} \tag{10}$$

where T is temperature in $^\circ C$. LMP can be expressed by Equation (11). This equation was obtained from point fitting of the LMP diagram presented in Figure 1.

$$LMP = 46.879\,574 - 0.070\,781\,443\sigma_{ref} + 0.00009513063\sigma_{ref}^2 \tag{11}$$

σ_{ref} is given by, Viswanathan [12]:

$$\sigma_{ref} = \frac{P_L}{P_U}\sigma_y \tag{12}$$

It can be presented as, Sim [13]:

$$\sigma_{ref} = \frac{\sigma_y}{\sigma_U}\sigma^* \tag{13}$$

σ^* can be obtained from the following equation, due to Roberts et al. [14]:

$$\sigma^* = \frac{\sqrt{2}}{2}[(\sigma_H - \sigma_r)^2 + (\sigma_H - \sigma_{ax})^2 + (\sigma_r - \sigma_{ax})^2]^{\frac{1}{2}} \tag{14}$$

where σ_H, σ_{ax} and σ_r are expressed as, Baily [15]:

$$\sigma_H = P\frac{(2-n)[(\frac{r_o}{r})^{(\frac{2}{n})} + 1]}{n[(\frac{r_o}{r_i})^{(\frac{2}{n})} - 1]}, \quad \sigma_{ax} = P\frac{(1-n)[(\frac{r_o}{r})^{(\frac{2}{n})} + 1]}{n[(\frac{r_o}{r_i})^{(\frac{2}{n})} - 1]},$$

$$\sigma_r = P\frac{[(\frac{r_o}{r})^{(\frac{2}{n})} + 1]}{[(\frac{r_o}{r_i})^{(\frac{2}{n})} - 1]} \tag{15}$$

2. 3. Life Assessment Model According to Equation (6), the LSF is considered as a lifetime model defined by the difference between the service rupture life, t_{nr} and the operating time in service, t_{op} Based on MCS method, RL can be estimated by using the distribution analysis of the LSF in a stochastic manner. Accordingly, a realistic estimation of RL can be performed using PDF and CDF curves of LSF. Based on an iterative evaluation, a logical model of the system is analyzed in the case of MCS. Dissimilar values of distributed parameters utilizes in each run by software. Parameter values are selected in a random manner, but with probabilities governed by the appropriate distribution functions.

Correlation of results obtained from the reliability evaluation method and life assessment model gives a better knowledge of the current material state of tubes as well as a more accurate assessment of their behavior during future exploitation. Therefore, an integrated approach of remaining life assessment and reliability evaluation on the reheater tubes (a real industrial case) is presented in section 3. Assumptions of this kind are very important for risk-based maintenance programs.

3. INDUSTRIAL CASE STUDY

In this section, an industrial problem of a steam power plant is investigated. These tubes are under the creep and the fire-side corrosion mechanism that lead to failure of some of the tubes. Since the estimation of PoF and RL with high degree of reliability is costly and time-consuming in the case of common deterministic methods, the evaluation of PoF is performed using structural reliability analysis methods (FORM, SORM, and MCS) based on in-site tests and an appropriate LSF and RL assessment is carried out via the distribution analysis of LSF based on MCS method.

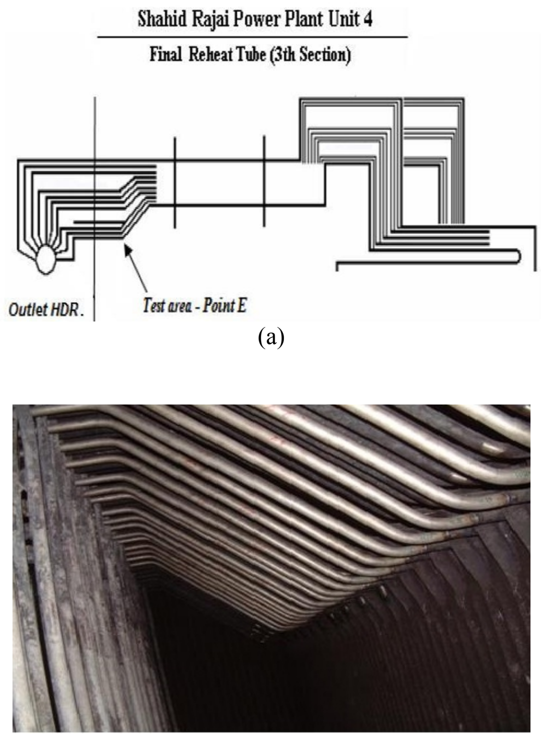
3. 1. Experimental Tests As mentioned before, the criterion was selected based on the model of the creep lifetime and tube uncertainties data in this research. The tubes uncertainties are related to their material properties, geometry, loading, manufacturing tolerances, and service conditions.

A series of experimental tests were designed due to the observation of non-uniformity of wall thinning in the final reheater tubes. Required experiments have been done in the previous study by Poursaeidi et al. [16]. Results of these experiments are depicted in Table 1 with operating time in service, t_{op} = 84000 hours, which contains statistical data for w_i , w_f , r_i , σ_y , σ_u , P , T and n .Tube uncertainties data in each case are summarized in Table 1.

3. 2. Reliability Analysis and Life Assessment Software Package (RALA software) In this study, a new software package, named RALA was developed via programming in Matlab to apply for the evaluation of structural reliability analysis and lifetime assessment. The evaluation of PoF is performed using FORM, SORM, and MCS while RL assessment is carried out via the distribution analysis of LSF based on MCS method. Furthermore, RALA software can solve different problems with the appropriate LSF definition and its required random variables data.

3. 3. Reliability Analysis and Life Assessment Model A schematic of the final reheater tubes of Rajaee power plant is presented in Figure 2. According to Figure 2, Point **E** is considered as a critical section for the evaluations of RL and PoF due to its high temperature and high wall thinning in comparison with the other sections in reheater tubes. This point is investigated on three different tubes, namely, No. 8, 40, and 64. As illustrated in Table 1, the values of random variables which are dedicated to each tube are different and named as case I, case II, and case III in the case of No. 8, 40, and 64 respectively.

3. 3. 1. PoF and RL Evaluation The PoF values for each case are calculated by various methods and listed in Table 2. The choice of the target reliability results from engineering practice and society acceptability. The admissible safety level depends on the consequences of failure. In the Rajaee power plant, admissible failure probability level is considered, 10^{-4} . Thus, according to this safety level, case I is failed.



(a)

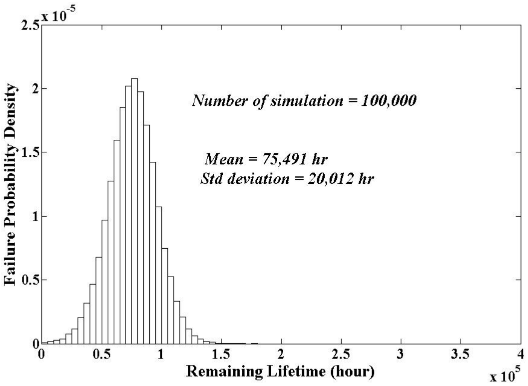
(b)

Figure 2. (a) A schematic of the final reheater tube and (b) an image of final reheater tubes of Shahid Rajaee power plant, unit 4.

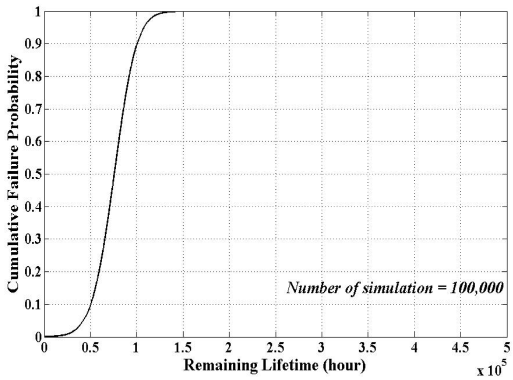
TABLE 2. The Values of the PoFs Calculated by Various Methods in Each Case

Method	Case I	Case II	Case III
FORM	5.7542×10^{-4}	7.3459×10^{-7}	1.4837×10^{-12}
SORM	5.9512×10^{-4}	8.0318×10^{-7}	1.6029×10^{-12}
MCS	5.8741×10^{-4}	7.9788×10^{-7}	1.5715×10^{-12}

Figures 3a, 4a, and 5a demonstrate the RL distribution versus remaining life based on the creep lifetime model obtained from the simulation of 100000 random inputs for cases of I, II, and III respectively. For instance, as presented in Figure 4a, the mean and standard deviation values of RL are 110347 and 27654 hours for case II respectively. Figures 3b, 4b, and 5b indicate the CDF of RL for each tube wherein RL can be obtained for certain reliability.

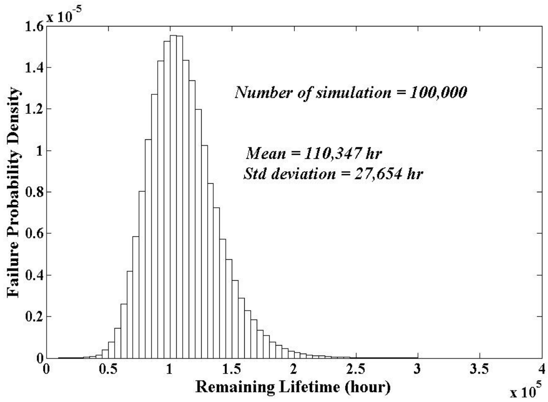


(a)

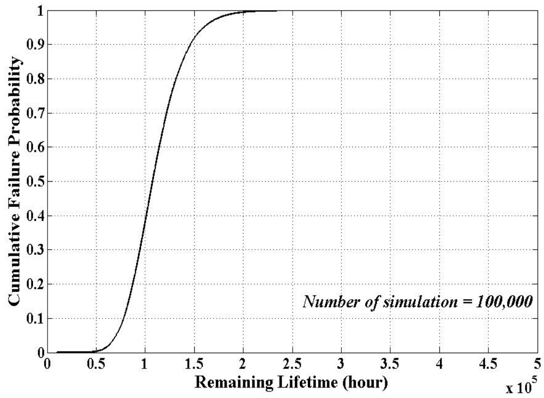


(b)

Figure 3. (a) Tube RL distribution, and (b) CDF of RL under uncertainties, (Case I).

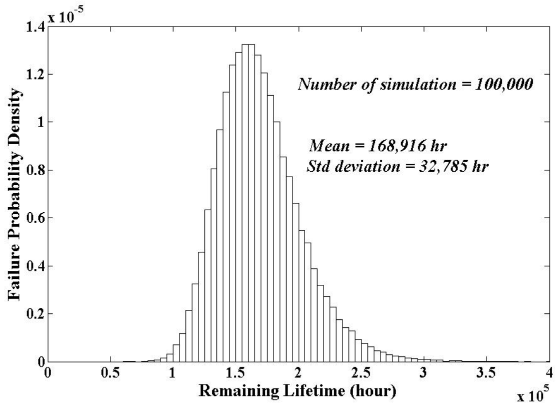


(a)

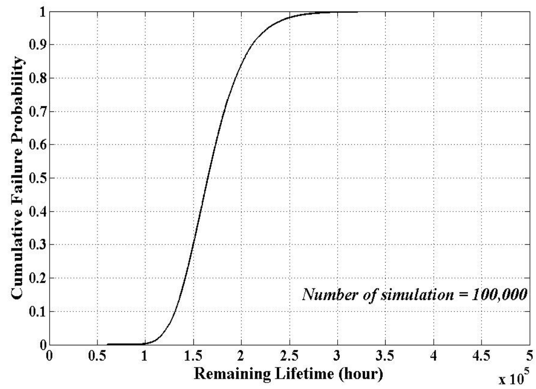


(b)

Figure 4. (a) Tube RL distribution, and (b) CDF of RL under uncertainties, (Case II).



(a)



(b)

Figure 5. (a) Tube RL distribution, and (b) CDF of RL under uncertainties, (Case III).

The admissible failure rate of 10^{-4} leads to a lifetime of 0, 27470, and 82100 hours for cases I, II, and III respectively (see Table 3). Consequently, according to obtained results, tubes No. 8 and 40 must be replaced by another one because tube No. 8 has already failed and tube No. 40 would have failed before the next overhaul. It should be noted that overhaul periods are every 4 years (approximately 35000 hours) in the Rajaee power plant.

Based on these results, a practical conclusion can be formulated by orienting the cost-safety balance. In another words, these results can be used in the time and economic planning of future inspection periods, which can lead to significant savings in costs.

3. 3. 2. Sensitivity Analysis Computing sensitivity factors provides the sensitivity of the safety-index with respect to random variables, which have two major purposes.

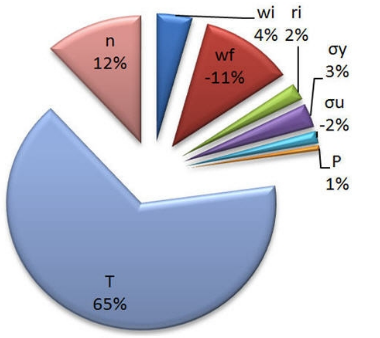
(1) These sensitivity factors show the contributions of random variables to the PoF and RL. The sensitivity factors of eight basic variables are presented in Figure 6 for every case. In fact, the analysis shows that the influence of temperature and wall thinning with model of uncertainties on the pipe safety is larger than other random variables. For example, Figure 6b shows that the effect of T and w_f on the PoF which are 60% and 17% respectively, is greater than other random variables. The reasons for the significant influence of temperature and wall thinning with presented model of uncertainties are the dominate creep and corrosion mechanisms. This phenomenon is in good agreement with our experimental data obtained from the power plant.

The diagrams of CDF for every case are illustrated in Figure 7 to have a better clarification of the effect of sensitivity analysis on CDF. As a matter of fact, the effect of temperature and wall thinning on the PoF and RL is presented in Figure 7. The CDF curves shift to the left side with increasing temperature and wall thinning as depicted in this figure. Furthermore, the effect of the mentioned parameters on PoF is observed in Table 2 and RL in every case for different values of reliability is shown in Table 3.

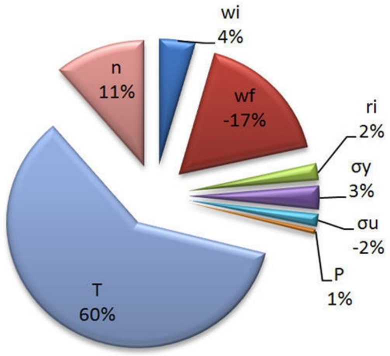
(2) The sign of the sensitivity factors indicates the relationship between the LSF and the physical variables. A negative sensitivity factor means that the LSF increases while the random variable increases, and a positive α_i^* means that the LSF decreases as the random variable increases.

TABLE 3. The Values of RL According to PoF Values in Each Case

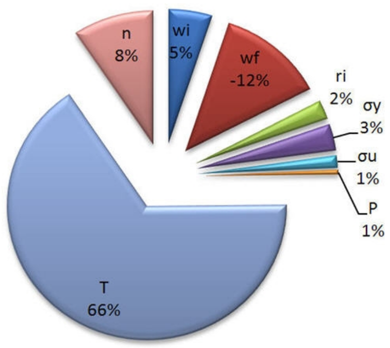
PoF	Remaining Lifetime (hour)		
	Case I	Case II	Case III
10^{-2}	25430	56470	108000
10^{-3}	4319	39880	92960
10^{-4}	0	27471	82100



(a)



(b)



(c)

Figure 6. Sensitivity factors of basic variables in every case; (a) case I, (b) case II, and (c) case III.

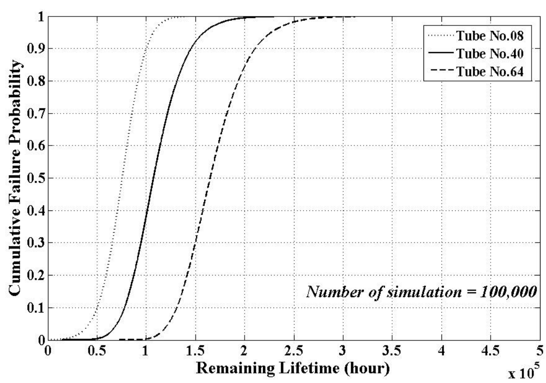


Figure 7. A comparison between CDF diagrams in each case.

4. CONCLUSION

In this paper, the structural reliability analysis and remaining life assessment have been taken into consideration based on in-site tests and an appropriate LSF. Key findings include the following:

One of the major outcomes of this study is the use of a proper time-based LSF. Including the LSF into Equation, in the form of Equation (6) in this work, time parameter has directly entered into LSF in addition to geometry, material properties, loading and operating conditions parameters. This operation causes that the PoF is obtained by the mentioned methods of FORM, SORM, MCS. Furthermore, RL of tubes is obtained by distribution analysis of the LSF based on MCS which leads to more practical and logical results.

Sensitivity analysis of tubes show that the influence of operating temperature and wall thinning in PoF is more than the other existing variables in LSF which presents the primacy of creep and corrosion mechanisms, considered in LSF, in PoF of tubes.

In this research, a new software package called RALA is developed which collects the statistical data and the parameters of uncertainties of LSF related to the variables of geometry, material properties, loading and operating conditions, as input and then provides the related information of PoF and RL of tubes as output.

A practical conclusion of this study could be found in the use of obtained results of PoF and RL of tubes in designing, service and maintenance that helps a lot in safety, financial saving and also balance between cost and safety.

The outcome for PoF and RL of tubes and sensitivity factors in this paper have satisfactory compliance with acquired data from practical experiments of authors based on previous studies and works in this power plant and other power plants which have been investigated.

In continuing this study and as the later work, investigation and application of reliability based design optimization methods (RBDO) can be analyzed to come up with an optimal and safe design of system at lower costs.

5. ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my colleagues, Ms. M. Razi and Ms. M. Arablou for their fruitful discussions.

6. REFERENCES

1. Jones, D., "Creep failures of overheated boiler, superheater and reformer tubes", ***Engineering Failure Analysis***, Vol. 11, No. 6, (2004), 873-893.
2. Moles, M., Westwood, H. and Hydro, O., "Residual life estimation of high temperature superheater and reheater tubing", Canadian Electrical Association, (1982).
3. Cizelj, L., Mavko, B. and Riesch-Oppermann, H., "Application of first and second order reliability methods in the safety assessment of cracked steam generator tubing", ***Nuclear Engineering and Design***, Vol. 147, No. 3, (1994), 359-368.
4. Ahammed, M. and Melchers, R., "Reliability estimation of pressurised pipelines subject to localised corrosion defects", ***International Journal of Pressure Vessels and Piping***, Vol. 69, No. 3, (1996), 267-272.
5. Guohua, C. and Shuho, D., "Study on the reliability assessment methodology for pressure vessels containing defects", ***International Journal of Pressure Vessels and Piping***, Vol. 69, No. 3, (1996), 273-277.
6. Ahammed, M., "Probabilistic estimation of remaining life of a pipeline in the presence of active corrosion defects", ***International Journal of Pressure Vessels and Piping***, Vol. 75, No. 4, (1998), 321-329.
7. Caleyo, F., Gonzalez, J. and Hallen, J., "A study on the reliability assessment methodology for pipelines with active corrosion defects", ***International Journal of Pressure Vessels and Piping***, Vol. 79, No. 1, (2002), 77-86.
8. Lee, S.-M., Chang, Y.-S., Choi, J.-B. and Kim, Y.-J., "Failure probability assessment of wall-thinned nuclear pipes using probabilistic fracture mechanics", ***Nuclear Engineering and Design***, Vol. 236, No. 4, (2006), 350-358.
9. Bakic, G. M., Sijacki-Zeravcic, V. M., Dukic, M. B. and Andelic, B. M., "Probability of failure of thermal power plant boiler tubing system due to corrosion", ***FME Transactions***, Vol. 35, No. 1, (2007), 47-54.
10. Poursaeidi, E. and Alimadadi, M., "Utilizing the montecarlo simulation in life evaluation of superheater tubes", in Proceedings of International Conference on Mechanical & Manufacturing Engineering, Bahru, J., Editor, Malaysia, (2008), 21- 23.
11. Davis, J., "ASM specialty handbook", ***Stainless Steels, (Materials Park, OH: ASM International, 1996)***, Vol. 290, (2001).
12. Viswanathan, R., "Damage mechanisms and life assessment of high-temperature components", ASM International (OH), (1989).
13. Sim, R. G., "Creep of structures", University of Cambridge. (1968).
14. Roberts, B., Ellis, F. and Bynum, J., "Remaining creep or stress-rupture life under nonsteady temperature and stress", ***ASME, Transactions, Journal of Engineering Materials and Technology***, Vol. 101, (1979), 331-336.
15. Bailey, R., "Creep relationships and their application to pipes, tubes, and cylindrical parts under internal pressure", ***Proceedings of the Institution of Mechanical Engineers***, Vol. 164, No. 1, (1951), 425-431.
16. Poursaiedi, E., Amini, M. and Moharrami, A., "Remaining life evaluation of boiler and turbine critical components of rajaee powerplant-unit 1", ***Report, Rajaee Powerplant Management***, (2007).

Failure Probability and Remaining Life Assessment of Reheater Tubes

E. Poursaeidi, A. Moharrami, M. Amini

Department of Mechanical Engineering, University of Zanjan, P. O. Box 45371-38791, Zanjan, Iran

PAPER INFO

Paper history:
Received 19 December 2012
Accepted in revised form 24 January 2013

Keywords:
Structural Reliability Analysis
Failure Probability
Remaining Life Assessment
Reheater Tubes
RALA software

چکیده

در این مطالعه، یک مشکل صنعتی واقعی و پُراهمیت در یک نیروگاه بخار بررسی شده است. لوله‌های ری‌هیتر در بویلرها تحت مکانیزم‌های خزش و خوردگی سمت آتش هستند که موجب از کار افتادگی برخی از آنها می‌گردد. از آن جا که تخمین احتمال از کار افتادگی (PoF) و عمر باقی‌مانده (RL) در روش‌های قطعی پرهزینه و زمان‌بر است، در این کار آنها با استفاده از آنالیز قابلیت اطمینان سازه‌ای و آنالیز توزیع بر اساس تست‌های انجام شده در محل و انتخاب یک تابع حالت حدی مناسب (LSF) ارزیابی شده‌اند. معیار استفاده شده برای این منظور بر پایه مدل عمر خزشی و عدم قطعیت‌ها می-باشد. همچنین آنالیز میزان حساسیت نیز در این پژوهش مطالعه و انجام شده است. رابطه در نظر گرفته شده بین سه پارامتر مؤثر در از کار افتادگی لوله‌های بویلر شامل زمان، خزش و خوردگی سمت آتش منجر به ارزیابی RL علاوه بر PoF و نیز به دست آوردن همزمان PoF و RL از طریق انتخاب یک LSF مناسب وابسته به زمان می‌شود. بر اساس مقادیر به دست آمده PoF و RL صحیح‌ترین نتایج حاصل می شوند که منجر به ارائه نتایج اطمینان‌تر برای برنامه‌ریزی اقتصادی در دوره‌های بازرسی آتی می‌گردد. این امر موجب صرفه‌جویی‌های قابل توجهی در هزینه و نیز بهبود ایمنی عملکرد می‌شود. یک بسته نرم افزاری جدید با نام RALA با استفاده از برنامه نویسی در Matlab ایجاد شده است. نتایج به دست آمده سازگاری خوبی با تمامی داده‌ها و اطلاعات کسب شده از تجربیات عملی در نیروگاه بر اساس مطالعات قبلی، دارند.

doi: *10.5829/idosi.ije.2013.26.05b.11*