XXI ENMC
ENCONTRO NACIONAL DE MODELAGEM COMPUTACIONAL
IX ECTM
ENCONTRO DE CIÊNCIA E TECNOLOGIA DE MATERIAIS

08 a 11 de Outubro de 2018
Instituto Federal Fluminense
Búzios - RJ

A SENSIBILITY ANALYSIS IN THE STRUCTURAL RELIABILITY OF STEAM GENERATOR TUBES

Alexandre Francisco[1] - afrancisco@metal.eeimvr.uff.br
Thais Ouverney[2] - thaismacedow@hotmail.com
[1]Universidade Federal Fluminense, EEIMVR - Volta Redonda, RJ, Brazil
[2]Universidade Federal Fluminense, EEIMVR - Volta Redonda, RJ, Brazil

Abstract. *The present work performs a sensibility analysis of basic variables involved in the functional relation that describes the structural integrity of steam generator tubes. These basic variables are associated with geometrics, loading, and material properties, and are subjected to fluctuation of random nature. In a complex structural system, it is important to determine the impact of each basic variable on the failure probability, because this information may reduce significantly the statistical effort for asssessing the structural reliability. In this work, the structural reliability of steam generator tubes is assessed in terms of the failure probability by applying the FORM method. This method allows to easily perform a sensibility analysis concerning the importance factor. This sensibility measure is determined considering two failure acceptance criteria: the limit load and the FAD, and distinct tube materials: stainless steel 316, inconel 600, inconel 690 and incoloy 800. The results show that the yield stress is statisticaly more sensible in the FAD criterion than in the limit load. The fracture toughness has high importance factor for the stainless steel 316 in the FAD criterion.*

Keywords: *Sensibility factors, Structural reliability, Steam generator tubes*

1. INTRODUCTION

Steam generator (SG) is a critical equipment in which their tubes are subjected to internal pressure, moderate temperature, and aggressive environment. Stress corrosion cracking may affect the structural integrity of the SG tubes. While a crack does not reach its tolerable limit size, the cracked tube is maintained in service, without compromising the regular operation of the SG. In this context, the structural reliabilty assessment is an adequate approach to derive crack acceptance criteria for SG tubes. It allows the maximum tolerable crack size to be assessed on a fitness-for-service basis (Cheaitani, 2007).

One of crack acceptance criteria is the limit load (LL), which assumes that the plastic collapse is the prevailing failure mode due to the very high ductility of SG tube materials. Although the LL criterion 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). Another crack acceptance criterion 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 cracked tubes when the failure mode is driven by two forces: elastic fracture and plastic collapse (BEGL, 2006).

Crack acceptance criteria are employed as a base for assessing the structural reliability of SG tubes. Such criteria provide the functional relations between the basic variables that describe the structural reliability problem. The failure probability of SG tubes may be calculated by applying the First Order Reliability Method (FORM). The FORM is considered a efficient computational method for assessing the structural reliability. The computational and statistical effort to solve the structural reliability problems is major related to the number of basic variables and the reliability method. The computational efficiency increases as the number of basic variables increases. The precision is generally dependent on parameters such as the number of basic variables.

Beyond the failure probability, the FORM method can provide sensibility measures. These sensibility measures may be obtained directly from values already calculated along the FORM method. Generally in the structural reliability problems, just some basic variables have influence on the failure probability. So it is interesting to reduce their number, without losing significantly the quality of the results. The sensibility analysis is an important procedure for assessing efficiently the structural reliability, since it is used to indicate which basic variables provide more influence on the failure probability. There are sensibility measures that express the influence of the basic variables for the structural reliablility method. One of the most common sensibility measure is the importance factor. As the procedure for calculating the importance factor uses current information from the FORM method, it does not provide any addicional effort to solve the problem (Enevoldsen, 1994). Mapa (2016) has implemented the FORM and SORM methods in a computational tool for performing a reliability sensitivity analilysis in two-dimensional steel frames. Nunes et al. (2017) has proved the effectiveness of a software for providing the ideal decision under uncertainty based on sensitivity analysis.

In structural reliability problems, sensitivity analysis may identify the relationship between the change in reliability and the change in the parameters of basic variables, such as means and standard deviations. Sensitivity analysis is also used to identify the most significant basic variables that have the highest contribution to reliability (Guo & Do, 2009). A number of methods and applications of such sensitivity analysis exists in literature. Among them, the reader is refered to Zhang & Zhang (2017) and Xiao et al. (2011).

In this work, the assessment of structural reliability of SG tubes is performed by applying the FORM method under LL and FAD criteria. In order to investigate the influence of basic variables on the results of failure probability, it is also performed a sensibility analysis concerning the importance factor. The results of importance factor show that the basic variable yield stress is statisticaly more sensible in the limit load criteria than in the FAD one. Other important basic variable is the relative relative crack depth. The importance factor value for the fracture toughness is considerable for the stainless steel 316 under the FAD criteria.

2. CRACK ACCEPTANCE CRITERIA

The main loading that leads SG tubes 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 inner 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. If the coordinate of an assessment point is below the LL assessment curve, the tube is suitable for continued operation. A schematic illustrating the safety margin for a crack using this diagram is shown in Fig. 1.

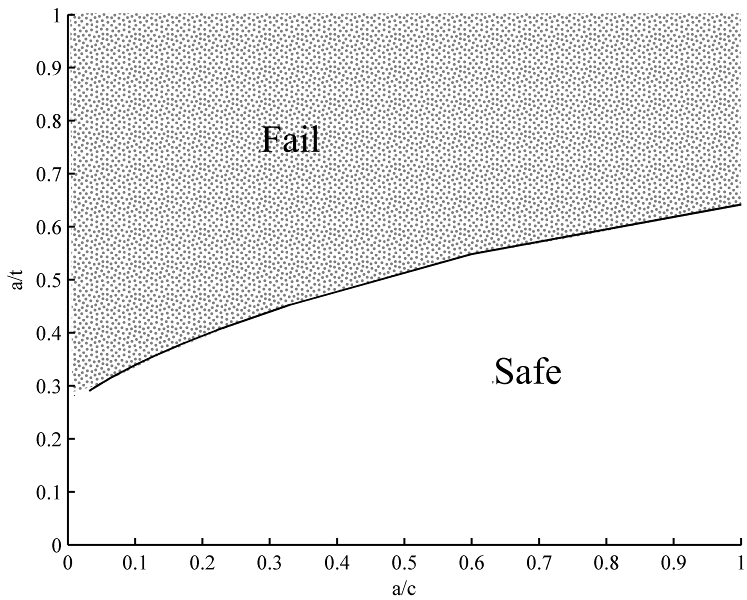

Figure 1- Safety margin using the limit load analysis

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 mode is driven by two forces: linear elastic fracture and plastic collapse. These driven forces are represented respectively by the parameters: toughness ratio, Kr, and load ratio, Lr, which 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.

A FAD assessment curve represents the failure locus, and if the assessment point is below this 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 579-1/ASME FFS-1 (2007) has proposed the following FAD assessment curve:

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

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

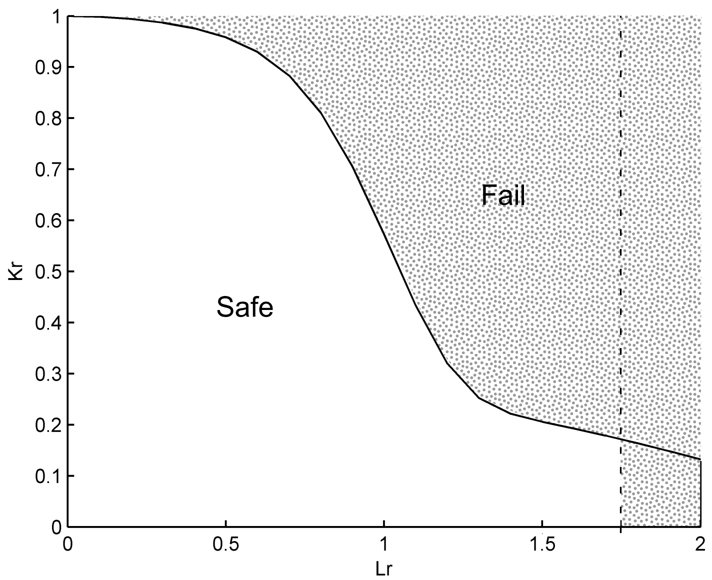

Figure 2- Safety margin using the FAD analysis

3. *FORM* METHOD

Structural 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 probabilistic approach, the governing parameters of the problem are modeled as random variables that represent all the relevant uncertainties influencing the failure of the SG tubes. These basic random variables are the components of the called random vector **X**.

For reliability assessments, the space **D** of basic random variables may be divided into failure and 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 so it is called failure surface. The failure probability is determined by the following integral (Melchers, 1999):

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

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.

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

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

The $FORM$ method makes use of the first and second moments of the basic random variables for calculating the failure probability, and requires a linearized form of the failure limit-state function $g(\mathbf{x})$ at the mean values of the random variables. The failure probability is calculated by

$$P_f = \Phi(-\beta), \tag{8}$$

where $\Phi(.)$ is a standardized normal cumulative distribution function, and β is the reliability index. Through the algorithm developed by Hasofer & Lind (1974), the reliability index is calculated by

$$\beta = min(\mathbf{u}.\mathbf{u})^{1/2}, subject\, to\, G(\mathbf{u}) = 0 \tag{9}$$

where **u** is the reduced random vector, in which their components are standardized normal variables transformed from the basic random variables **x**. That means that the reliability index is the smallest distance between the origin of the space of standardized normal variables and the failure surface $G(\mathbf{u}) = 0$, at the design point.

An iterative scheme for determining the design point is described in the following algorithm:

- Given $g(\mathbf{x})$ and $\mathbf{u}^0$:
- compute $G(\mathbf{u}^0)$ and $\nabla G(\mathbf{u}^0)$;
- for $k = 1$ until convergence do
  - $\mathbf{u}^k = \frac{\nabla G(\mathbf{u}^{k-1})}{\nabla G(\mathbf{u}^{k-1}).\nabla G(\mathbf{u}^{k-1})}[\nabla G(\mathbf{u}^{k-1}).\mathbf{u}^{k-1} - G(\mathbf{u}^{k-1})]$;
  - compute $G(\mathbf{u}^k)$ and $\nabla G(\mathbf{u}^k)$;
  - update $\mathbf{u}^{k-1}$;
- end for

4. SENSIBILITY ANALYSIS

Besides the $FORM$ method calculates the reliability index, it allows to easily perform a sensibility analysis concerning the importance factor. The importance factor is a measure that is used to study the effects of hypotesis and data errors on proposed failure limit-state functions.

The importance factor indicates which basic random variables are the most important in the failure probability calculation. According to Sagrilo (2004), the importance factor of each basic random variable x_i is defined by

$$I_i = \alpha_i^2, \tag{10}$$

where α_i is the direction cosino related to the variable u_i of the normal vetor to the failure surface $G(\mathbf{u}) = 0$ at the design point. Each α_i can be considered a measure of the relative importance of the uncertainty in the corresponding basic variable on the reliability index (Sorensen, 2004), defined by

$$\alpha_i = \frac{\nabla G(\mathbf{u})_i}{[\nabla G(\mathbf{u}).\nabla G(\mathbf{u})]^{1/2}}. \tag{11}$$

Beck (2014) has described that, when $I_i \approx 0$, the corresponding basic variable has a few contribution in the failure probability, and such basic variable can eventually be eliminated or substituted by a deterministic value. That is, the basic variable with low importance factor can be considered as deterministic one in the structural reliability assessment. On the other side, the variable with high importance factor is the one that mostly contribute in the failure probability. However, the interpretation of I_i must be more cautious when the basic variables are mutually dependent (Ditlevsen & Madsen, 2007).

5. RESULTS AND DISCUSSIONS

A partial through-wall axial crack with the aspect ratio $a/c = 0.25$ is assumed to be present outside the SG tube, between two support plates or between the first support plate and the tube sheet. The tube wall tickness is 1.0923 mm, the inner tube radius is 8.4327 mm, and the applied pressure is 28.26 MPa. The stainless steel 316, inconel 600, inconel 690 and incoloy 800 are considered as the materials.

The mechanical properties of the materials such as yield stress and fracture toughness are given in a range of values, in Table 1. The mean value is the average of the range and the standard deviation corresponds to the confidence interval of 95%. The normal distribution is considered for the yield stress, and the lognormal distribution for the fracture toughness.

Table 1- Range of values for mechanical properties.

$Material$	σ_y (MPa)	K_{mat} (MPa$m^{1/2}$)
316	$170 - 310$	$112 - 278$
600	$221 - 262$	$349 - 386$
800	$205 - 415$	$412 - 456$
690	$280 - 480$	$314 - 347$

Other basic random variables are the correlation coefficient and the relative crack depth ($h = a/t$). Their statistical data are provided in Table 2. The normal distribution is considered for both the random variables.

Table 2- Statistics for basic random variables.

$Variable$	$Mean$	$Standard\,deviation$
ϕ	1.104	0.0705
h	80.0 $\%TW$	11.0 $\%TW$

5.1 Two random variables

The first sensibility analysis is performed considering two basic random variables under LL and FAD criteria. In this analysis, the random vector under the LL criterion is $\mathbf{x} = (\sigma_y, \phi)$, and under the FAD criterion is $\mathbf{x} = (\sigma_y, K_{mat})$.

After applying the $FORM$ method, the failure probabilities calculated under the LL and FAD criteria are shown in Table 3. The failure probabilites under the FAD criterion are lower than ones under the LL criterion. This evidence comes out the fact that the failure region under the FAD criterion is more extensive.

Regarding the materials, as the mean value of yield stress is increased the failure probability is decreased; except for the inconel 600. The inconel 690 is the material that presents the lowest failure probability under both the crack acceptance criteria.

Table 3- Failure probability using two variables.

	P_f	
$Material$	LL	FAD
316	0.4057	0.0621
600	0.3892	0.0000
800	0.1255	0.0163
690	0.0169	0.0002

The Fig. 3 shows the importance factor values that allow to see the contribution of each basic random variable on the failure probability. As it can be observed in this figure, the yield stress is the variable that presents the least influence on the failure probability under the LL criterion. By the other side, the yield stress is the most important variable under the FAD criterion using two variables.

The stainless steel 316 has a small mean value and a large variability of the fracture toughness. Therefore, the importance factor for fracture toughness is significative on the failure probability under the FAD criterion. Once the variablity of the yield stress in the inconel 600 is rather short, the importance factor under the LL criterion is quite negligible.

5.2 Three random variables

The next sensibility analysis is performed considering three basic random variables under LL and FAD criteria. In this analysis, the random vector under the LL criterion is $\mathbf{x} = (\sigma_y, \phi, h)$, and under the FAD criterion is $\mathbf{x} = (\sigma_y, K_{mat}, h)$.

Figure 3- Importance factor using two variables: (a) 316, (b) 600, (c) 800, and (d) 690.

Table 4- Failure probability using three variables.

	P_f	
$Material$	LL	FAD
316	0.4670	0.0923
600	0.4602	0.0000
800	0.2630	0.0185
690	0.1200	0.0003

The behavior of the failure probability using three variables is similar to the one using two variables, as it can be seen in Table 4. Since more uncertainties is introduced into the structural problem with relation to the last case, the value of the failure probability is increased just a few;

except for the inconel 690, which presents a greater increase under the LL criterion.

The Fig. 4 shows that the relative crack depth is the variable which presents the most contribuition to the failure probability under the LL criterion. However, the yield stress remains the most important variable under the FAD criterion; except for the inconel 600, for which the relative crack depth is the prominent variable. The variability of the relative crack depth overcomes greatly the variability of the yield stress for the inconel 600, so that the former variable is more statisticaly sensible.

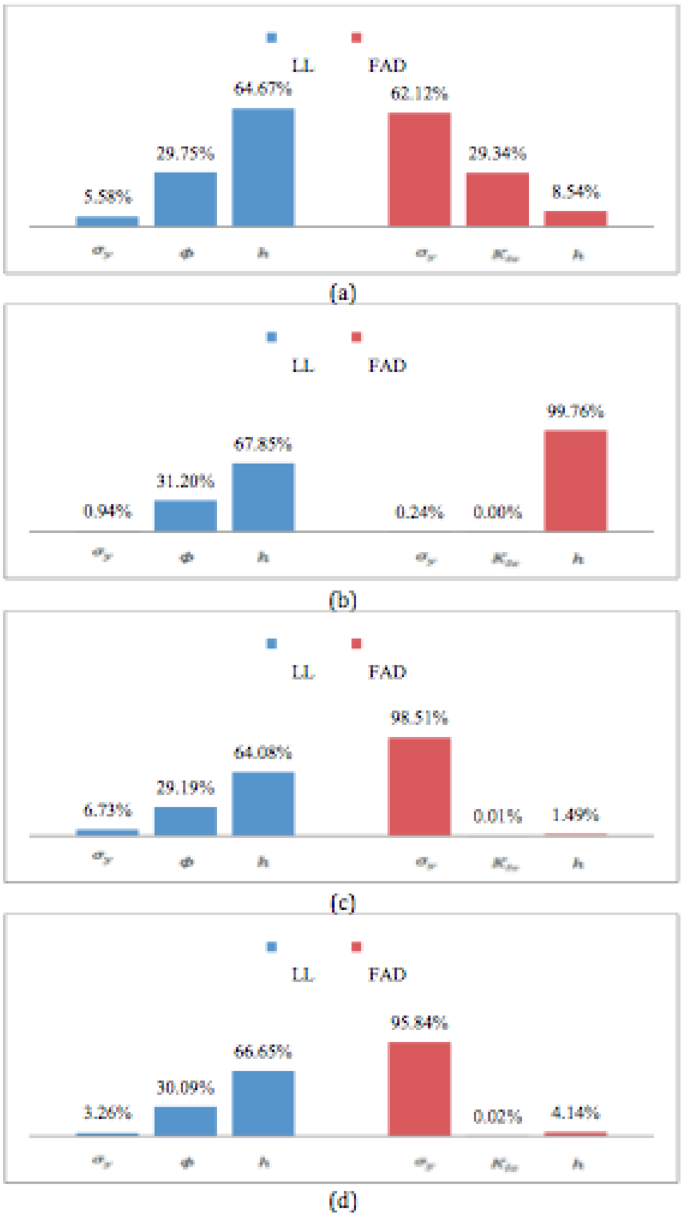

Figure 4- Importance factor using three variables: (a) 316, (b) 600, (c) 800, and (d) 690.

6. CONCLUSIONS

The structural reliability assessment is performed on SG tubes with partial through-wall axial cracks. Applying the $FORM$ method, the inconel 690 is the material that presents the lowest failure probability under both LL and FAD criteria.

The yield stress is the variable that presents less contribution to the failure probability under the LL criterion, but the greater contribution under the FAD criterion. The fracture toughness has considerable importance factor for the stainless steel 316, however it could be considered deterministic for the other materials.

The importance factor depends on the mean value and the variability of the basic random variables. This dependence can explain the singularity for the inconel 600 observed in the importance factor using three variables and the failure probability under the FAD criterion.

Acknowledgements

The authors acknowledge the Eletronuclear and CAPES by the support given for the accomplishment of this work.

REFERENCES

Anderson, T. (2005),*"Fracture Mechanics, Fundamentals and Applications"*, CRC Press.

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

BEGL, (2006), *Assessment of the integrity of structures containing defects*, R6 Revision 4 and amendments, British Energy Generation Ltd.

Beck, A. T., (2014), *Curso de Confiabilidade Estrutural*, Escola de Engenharia de São Carlos – EESC/USP.

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, 295, 457-467.

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

Ditlevsen, O.; Madsen, H.O. (2007),*"Structural reliability methods"*, 2º ed., John Wiley and Sons Ltd, Chichester.

Enevoldsen, I. (1994), Sensitivity Analysis of Reliability - Based Optimal Solution. Journal of Engineering Mechanics, 120, 198-205.

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

Guo, J.; Do, X. (2009), Reliability sensitivity analysis with random and interval variables. International Journal of Numerical Methods in Engineering, 78(13), 1585–1617.

Hasofer, A.M.; Lind, N.C. (1974), An exact and invariant first-order reliability format. Journal of Engineering Mechanics, 100, 111-121.

Mapa, D.L.S. (2016),*"Confiabilidade estrutural de pórticos metálicos planos"*, Dissertacao de Mestrado, Universidade Federal de Ouro Preto, Ouro Preto.

Melchers, R.E. (1999),*"Structural reliability analysis and prediction"*, 2º ed., John Wiley and Sons.

Nunes, C.Y; Neto, N.M.A.; Prazeres, P.G.C.; Junior, S.J.R.; Sampaio, R.A.C. (2017), "Software development on the Matlab for structural reliability and sensitivity analysis", *XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering*, Florianopolis, sc, Brasil.

Sagrilo, L.V.S. (1999), *Confiabilidade estrutural – métodos analíticos para análise de confiabilidade*, Notas de aula – COPPE/UFRJ, Rio de Janeiro.

Sorensen, J.D. (2004),*"Notes in Structural Reliability Theory and Risk Analysisn"*, Institute of Building Technology and Structural Engineering: Aalborg University.

Xiao, N.-C., Huang; H.-Z.; Wang, Z.; Pang, Y.; He, L. (2011), Reliability sensitivity analysis for structural systems in interval probability form. Struct. Multidisc. Optim., 44, 691-705.

Zhang, T.; Zhang, Y. (2017), A new model for reliability design and reliability sensitivity analysis of a hydraulic piston pump. Journal of Risk and Reliability, 213 (1), 11-24.