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# Application of first and second order reliability methods in the safety assessment of cracked steam generator tubing

L. Cizelj [a], B. Mavko [a], H. Riesch-Oppermann [b]

[a] *Reactor Engineering Division, "Jožef Stefan" Institute, Ljubljana, Slovenia*
[b] *Institut für Materialforschung II, Kernforschungszentrum Karlsruhe, Karlsruhe, Germany*

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**Abstract**

The First- and Second Order Reliability Methods (FORM and SORM) have been applied in the safety assessment of steam generator tubes with through-wall axial stress corrosion cracks. The underlying probabilistic fracture mechanics model takes into account the scatter in tube geometry, material properties and stable crack propagation. Also, the effect of the maintenance strategy has been considered. A realistic numerical example has been given to compare the failure probabilities calculated by FORM and SORM to those obtained by different versions of Monte Carlo simulations. The relative errors of the numerical methods employed have been analysed, which has shown that FORM performs in an acceptable and SORM in an excellent manner. Some changes in failure surface properties, caused by different maintenance strategies, are indicated and a sensitivity analysis of influencing parameters is made. The results obtained demonstrate the applicability of FORM and SORM in the safety assessment of stress corrosion cracked steam generator tubing.

## 1. Introduction

The steam generator tubing constitutes a substantial part of the second fission-product barrier in a pressurised water reactor nuclear power plant. The tubing made of Inconel-600 is subjected to various ageing processes which might significantly decrease its structural reliability. One of the most frequently observed ageing processes is stress corrosion cracking, which is observed mainly in the areas exposed to high residual stresses such as the expansion transition zone at the top of the tube sheet. Stress corrosion results in deep, often through-wall axial cracks. The number of affected tubes has been reported to exceed 1/3 of the tubing in a steam generator [Hernalsteen, 1991].

To control the level of the structural reliability of the steam generators, maintenance strategies are usually applied which consist mainly in non-destructive in-service inspections and plugging of excessively degraded tubes. One of the recently developed maintenance strategies [Vyve and Hernalsteen, 1991] allows the steam generators to be operated with axial cracks up to a certain crack length. The impact of such a maintenance strategy on the steam generator failure probability was investigated by Mavko and Cizelj [1992]. They proposed a suitable probabilistic fracture mechanics model and obtained the numerical solutions using a direct Monte Carlo simulation. Relatively low failure probabilities have been expected and calculated. Therefore, direct Monte Carlo simulation proved to be costly and lengthy,


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especially in performing parametric and sensitivity studies.

As a variety of numerical methods of solving structural reliability problems have already been proposed (for the review see for example [Brueckner, 1987], [Schuëller and Stix, 1987] and [Bjerager, 1991]), an attempt has been made to improve the calculation times while retaining the acceptably accurate results. Special attention has been paid to the First- and Second-Order Reliability Methods (FORM and SORM, respectively). In probabilistic fracture mechanics, FORM and SORM have been introduced by Riesch-Oppermann and Brueckner-Foit [1988] who demonstrated their applicability in cases of fatigue and creep crack growth [Riesch-Oppermann, 1989; Riesch-Oppermann and Brueckner-Foit, 1991]. Their work resulted in the development of the zerberus computer code [Cizelj and Riesch-Oppermann, 1992], which has been upgraded to accommodate the present analysis.

The objective pursued here is to demonstrate the applicability of FORM and SORM also to stress-corrosion crack growth, in particular in steam generator safety assessment studies. Therefore, a brief description of the probabilistic fracture mechanics (PFM) model [Mavko, 1992] used will be followed by an outline of the FORM and SORM methods as implemented in the Zerberus code [Cizelj and Riesch-Oppermann, 1992]. The applicability of FORM and SORM will be demonstrated by analysing a realistic numerical example which is representative of severely stress corrosion cracked steam generator tubes under hypothetical accident conditions.

## 2. PFM model

### 2.1. Failure probability calculations

The statistical reliability theory in structural mechanics (with probabilistic fracture mechanics as the special case) deals with the determination of failure probabilities $P_f$ of structural components from the scatter of the applied loads and structural resistance properties. The failure behaviour of the structure is described by a failure function $g(x)$, depending on *basic random variables* $x = (x_1, \ldots, x_n)$ which denote applied loads and structural resistance parameters such as dimensions and material properties. By definition, $g(x) < 0$ implies failure, whereas no failure occurs with $g(x) > 0$. $g(x) = 0$ defines the so-called *failure surface*, a hypersurface in the $n$-dimensional space of the basic variables. The failure surface separates the *failure domain F* (*with* $g(x) > 0$) and the *safe domain* ($g(x) > 0$). The failure probability $P_f$ can be calculated as the probability content of the failure domain $F$:

$$P_f = \int_F f_1(x_1) \ldots f_n(x_n)\, \mathrm{d}x_1 \ldots \mathrm{d}x_n, \qquad (1)$$

where $f_i(x_i)$ represents the probability densities of the respective basic variables $x_i$, which for the sake of simplicity are assumed to be stochastically independent.

### 2.2. Failure function

The failure of the tube containing a through-wall axial crack is defined by the plastic limit load model (for details see [Mavko and Cizelj, 1992] and references therein):

$$g(a_1, R, t, K, \delta, \sigma_Y + \sigma_M) = \sigma_f - m\sigma_\phi, \qquad (2)$$

where $\sigma_f$ is the flow stress, $\sigma_\phi$ is the pressure induced hoop stress and the bulging factor $m$ is given by [11] Erdogan, 76

$$m = 0.614 + 0.386\, e^{(-2.273 a_1/\sqrt{Rt})} + 0.874(a_1/\sqrt{Rt}), \qquad (3)$$

$a_1$, $R$ and $t$ being the crack half-length at the end of inspection cycle, the tube mean radius and the tube wall thickness, respectively. The flow stress $\sigma_f$ is defined by yield stress $\sigma_Y$ and ultimate tensile strength $\sigma_M$ and adjusted to the operating temperature conditions by application of the temperature correction coefficient $\delta$, where appropriate:

$$\sigma_f = K(\sigma_Y + \sigma_M)\delta. \qquad (4)$$

$K$ represents the experimentally determined constant which actually describes the degree of strain hardening behaviour of the tube material. The membrane stress perpendicular to the crack direction $\sigma_\phi$ is the pressure ($p$) induced tube hoop stress:

$$\sigma_\phi = p\left(\frac{R}{t} - \frac{1}{2}\right). \tag{5}$$

The tubes are fixed into a tube sheet which provides additional circumferential rigidity and obstructs bulging. The *Tube Sheet Reinforcing Factor* (RF) has been proposed to account for this effect [Frederick et al., 1989]. It is defined as correction coefficient to the flow stress factor $K$ (see Eq. (4)) given the critical crack half-length in the free span tube $a_c$:

$$\mathrm{RF}(a_c) = 1 + 10\,\mathrm{e}^{-1.8\,a_c/\sqrt{Rt}}. \tag{6}$$

The critical crack length in a free span tube can be obtained by setting $\sigma_f - m\sigma_\phi = 0$ and inverting Eq. (3). Unfortunately, its use is restricted to the cracks, tangent to the tube sheet, which may not be true for the numerous cracks propagating from the tube sheet [Frederick et al., 1989].

*2.2.1. Crack length distribution*

When the in-service inspection of the steam generator is completed, the probability density of the measured crack lengths can be estimated. Tubes with crack lengths equal to or exceeding the plugging limit PL are taken out of service. Thus, the crack half-length after in-service inspection is defined by the random variable $a_0$:

$$a_0 = \begin{cases} a_m, & a_m < \frac{1}{2}\mathrm{PL} \\ 0, & a_m \ge \frac{1}{2}\mathrm{PL} \end{cases}, \tag{7}$$

$a_m$ being the random variable representing the measured crack half-length. Plugging the tubes with cracks exceeding PL will be the only maintenance action considered in this paper. The changes in maintenance strategy are expressed as changes in the value of PL applied.

*2.2.2. Crack propagation*

A fraction of cracks is propagating in a stable manner during the period between two consecutive inspections. The crack propagation is basically governed by the residual and operational stresses in the tubes, operating temperature and the chemical composition of the reactor coolant. At the moment, this process is not very well understood which results in rare and scattered crack tip velocity data [McIlree et al., 1990].

A reasonable solution has been proposed by Hernalsteen [1991], who performed a very profound statistical analysis of non-destructive inspection results and proposed to predict the crack propagation using Gamma distributed random variables. Assuming that the non-destructive examination results give reasonable crack propagation prediction, a simple stochastic combination of the propagation law proposed in [Hernalsteen, 1991] with the measured crack length is presently applied to yield the end-of-inspection cycle crack half-length $a_1$:

$$2a_1 = 2a_0 + 2a_g. \tag{8}$$

Such an approach is considered to yield an accurate prediction provided constant tube loading conditions and the time between two consecutive inspections. Derivation of a propagation law suitable for ~~other~~ other plants with different loading and inspection history would therefore require explicit load and time dependence of the crack propagation. Some attempts to use linear-elastic fracture mechanics [Scott, 1991] gave promising results, but still need some more accurate estimates of residual stress field.

The way to implement another crack propagation model in Eq. (8) is straightforward. One should only calculate variable $a_g$ in Eq. (8) using a suitable stress-corrosion crack growth law, which also accounts for the scatter in the residual and operational stresses.

## 3. FORM and SORM

A brief description of FORM and SORM algorithms as implemented in the Zerberus code will be given below. Further details can be found in [Cizelj and Riesch-Oppermann, 1992].

*3.1. First Order Reliability Method (FORM)*

The analytical solutions of the failure integral (Eq. (1)) are limited to a few of very special cases. However, for *standard normally* distributed basic variables and the linear failure function the analytical solution of the failure integral (Eq. (1)) is given by:

$$P_f = \Phi(-\beta), \tag{9}$$

$\Phi(\,)$ being the cumulative standard normal distribution and $\beta$ the so called *reliability index*, which represents the distance between the origin of the space of basic variables and the *design point* $x^*$ on the failure surface. The design point ($x^*$) is a point on the failure surface having the minimum distance to the origin of the space of basic variables, thus contributing most to the failure probability.

In the case of the non-linear failure function, a linearisation at the design point provides an approximate value of the failure probability:

$$P_f \approx \Phi(-\beta). \tag{10}$$

For non-normal basic variables, a transformation from the physical ($\boldsymbol{x}$) space to the standard normal ($\boldsymbol{u}$) space is performed. If the basic variables are assumed to be stochastically independent, the transformation is defined by:

$$U_i = \Phi^{-1}(F_i(X_i)) \tag{11}$$

with standard normal variables $U_i$ and its inverse by:

$$X_i = F_i^{-1}(\Phi(U_i)). \tag{12}$$

Application of the inverse transformation (Eq. (12)) allows the failure function in the physical ($\boldsymbol{x}$) space to be evaluated.

Unfortunately, the accuracy of FORM depends mainly on the properties of the failure surface and the approximation error cannot be obtained analytically.

### 3.2. Sensitivity factors

The reliability index $\beta$ is defined by the minimum distance between the failure surface and the origin of the normal space. Therefore, the failure probability sensitivity to the scatter of each basic variable may be expressed as follows:

$$\frac{\partial\beta}{\partial u_i} = \frac{\partial}{\partial u_i}\sqrt{\sum_{j=1}^{n} u_j^2} = \frac{u_i^*}{|\boldsymbol{u}|} = \alpha_i^* \tag{13}$$

$\alpha_i^*$ being denoted as sensitivity factors. Consequently, the vector $\boldsymbol{\alpha}^* = (\alpha_1^*, \ldots, \alpha_n^*)$ is the unit directional vector of the design point $\boldsymbol{u}^*$ in the normal space.

### 3.3. Second Order Reliability Method (SORM)

Various methods have been suggested to improve the accuracy of FORM calculations and to give a rough estimate of the quality of approximation [Madsen et al., 1986; Fiessler et al., 1979]. The general idea is to approximate the failure surface by a quadratic hyper-surface rather than by a hyper-plane. The main curvatures $\kappa_j$ of the quadratic hyper-surface at the design point are equal to those of the failure surface. Using all $n-1$ main curvatures, the SORM approximation of the failure probability is obtained from [Madsen et al., 1986]:

$$P_f \approx S_1 + S_2 + S_3, \tag{14}$$

with

$$S_1 = \Phi(-\beta)\prod_{j=1}^{n-1}(1-\beta\kappa_j)^{-0.5}, \tag{15}$$

$$S_2 = [\beta\Phi(-\beta) - \varphi(\beta)]\left\{\prod_{j=1}^{n-1}(1-\beta\kappa_j)^{-0.5} - \prod_{j=1}^{n-1}\left(1-(\beta+1)\kappa_j\right)^{-0.5}\right\}, \tag{16}$$

$$S_3 = (\beta+1)[\beta\Phi(-\beta) - \varphi(\beta)] \times\left\{\prod_{j=1}^{n-1}(1-\beta\kappa_j)^{-0.5} - \mathrm{Re}\left[\prod_{j=1}^{n-1}\left(1-(\beta+i)\kappa_j\right)^{-0.5}\right]\right\}. \tag{17}$$

Re[ ] represents the real part of the complex argument and $i$ the imaginary unit. $S_1$ is an asymptotic approximation of $P_f$ which is exact for $\beta \to \infty$. $S_2$ and $S_3$ are correction terms. $\Phi$ and $\varphi$ are the cumulative distribution function and probability density function, respectively, of the standard normal distribution.

Table 1
Steam generator data summary

| Variable | Distribution | | Unit | Comment |
|---|---|---|---|---|
| | Type | Parameters | | |
| $R_{out}$ | Normal | $\mu = 9.525, \sigma = 0.0254$ | mm | $R = R_{out} - 0.5t$ |
| $t$ | Normal | $\mu = 1.055, \sigma = 0.0464$ | mm | – |
| $a_m$ | Gamma | $\alpha = 10.3, \beta = 1.0$ | mm | assumed |
| $a_g$ | Gamma | $\alpha = 1.25, \beta = 0.8$ | mm | [Hernalsteen, 1991] |
| $K$ | Normal | $\mu = 0.545, \sigma = 0.03$ | – | [Vyve and Hernalsteen, 1991] |
| $\delta$ | Normal | $\mu = 0.928, \sigma = 0.003$ | – | assumed |
| $(\sigma_Y + \sigma_M)$ | Normal | $\mu = 1080.0, \sigma = 54.3$ | MPa | at room temperature (20°C) |

Distributions not truncated;
*Normal distribution:* $\mu$ = mean, $\sigma$ = standard deviation.
*Gamma distribution:* $\alpha$ = shape, $\beta$ = scale parameter.

Table 2
Comparison of failure probabilities (in %); case with RF

| Plugging limit | FORM | SORM | DMC | ISM | ASM | ESM |
|---|---|---|---|---|---|---|
| ∞ | 1.520 | 1.944 | 1.908 | 1.881 | 1.862 | 1.896 |
| 20.0 | 1.270 | 1.472 | 1.428 | 1.405 | 1.410 | 1.413 |
| 18.0 | 0.9450 | 0.9443 | 0.936 | 0.9274 | 0.9287 | 0.9342 |
| 16.0 | 0.5497 | 0.4631 | 0.468 | 0.4686 | 0.4666 | 0.4660 |
| 14.0 | 0.2526 | 0.1923 | 0.198 | 0.1984 | 0.1973 | 0.2022 |
| 12.0 | 0.0959 | 0.0710 | 0.0729 | 0.0736 | 0.0735 | 0.0659 |
| 10.0 | 0.0314 | 0.0236 | 0.0253 | 0.0243 | 0.0243 | 0.0274 |
| 8.0 | 0.0092 | 0.0071 | 0.0079 | 0.0072 | 0.0072 | 0.0078 |

DMC direct Monte Carlo method;
ASM adaptive sampling MC method;
ISM importance sampling MC method;
ESM efficient sampling MC method.

Table 3
Comparison of failure probabilities (in %); case without RF

| Plugging limit | FORM | SORM | DMC | ISM | ASM | ESM |
|---|---|---|---|---|---|---|
| ∞ | 2.374 | 3.135 | 3.084 | 3.038 | 3.030 | 3.093 |
| 20.0 | 2.126 | 2.667 | 2.592 | 2.557 | 2.536 | 2.497 |
| 18.0 | 1.743 | 2.012 | 1.967 | 1.945 | 1.949 | 1.900 |
| 16.0 | 1.147 | 1.171 | 1.187 | 1.174 | 1.186 | 1.139 |
| 14.0 | 0.5819 | 0.5357 | 0.5602 | 0.5566 | 0.5548 | 0.5351 |
| 12.0 | 0.2351 | 0.2066 | 0.2157 | 0.2136 | 0.2127 | 0.2084 |
| 10.0 | 0.0799 | 0.0702 | 0.0733 | 0.0725 | 0.0717 | 0.0754 |
| 8.0 | 0.0239 | 0.0215 | 0.0221 | 0.0219 | 0.0219 | 0.0234 |

DMC direct Monte Carlo method;
ASM adaptive sampling MC method;
ISM importance sampling MC method;
ESM efficient sampling MC method.

## 4. Numerical example

### 4.1. Data summary

A typical steam generator as installed in the Slovenian Krško nuclear power plant subjected to hypothetical accidental operating conditions is taken as a numerical example [Mavko and Cizelj, 1992]. The accident condition considered is a feed-line break, the differential pressure being 196 bar (for procedures employed see [Mavko et al., 1993]) A summary of geometrical and material data is given in Table 1 together with the assumed "as measured" crack length distribution. The effectiveness of the implemented maintenance strategy (e.g., applied plugging limit PL) is shown by the means of a parametric analysis. Also, the safety contribution of the tube sheet reinforcing effect RF is shown by considering two cases: with and without RF.

The following Monte Carlo simulations have been used in the analysis: direct Monte Carlo (DMC), Importance Sampling MC (ISM) [Brückner, 1987], Adaptive Sampling MC (ASM) [Bucker, 1988], and Efficient Sampling MC (ESM) [Harbitz, 1986].

### 4.2. Failure probability calculations

The absolute values of the failure probabilities as calculated by various numerical methods are listed in Table 2 and Table 3, for the cases with and without RF, respectively. All numerical methods employed, with the exception of FORM, show very good agreement. Additionally, the safety effect of the maintenance strategy employed is clearly visible. Referring to DMC results in Table 2 and considering the beneficial influence of the RF, the change in the PL applied may change the failure probability by up to two orders of magnitude. This remains true also if the benefits of RF are neglected (Table 3).

The RF contribution increases with decreasing PL by up to one order of magnitude at low PL values, as can be seen by comparing Table 2 with Table 3.

### 4.3. Relative errors

The relative errors inherent in the numerical methods employed are presented in the following way. The results of direct Monte Carlo simulation are assumed to be *exact*; however, the magnitude of their statistical error is also illustrated by the

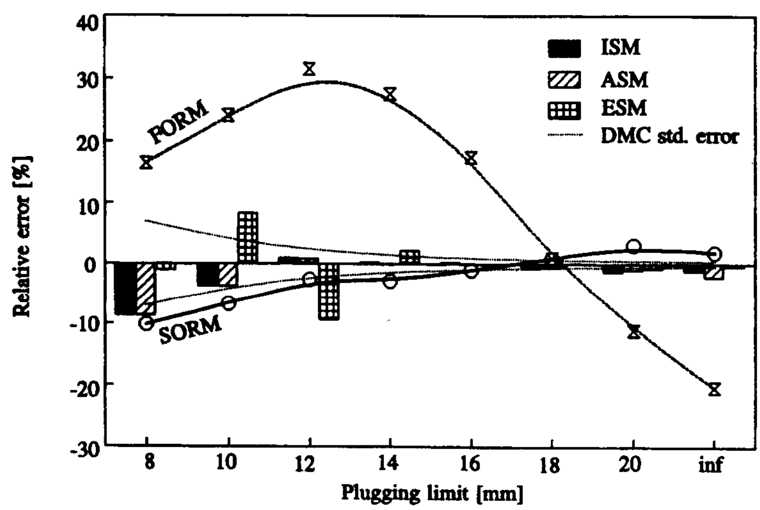


Fig. 1. Relative errors for the case with RF.

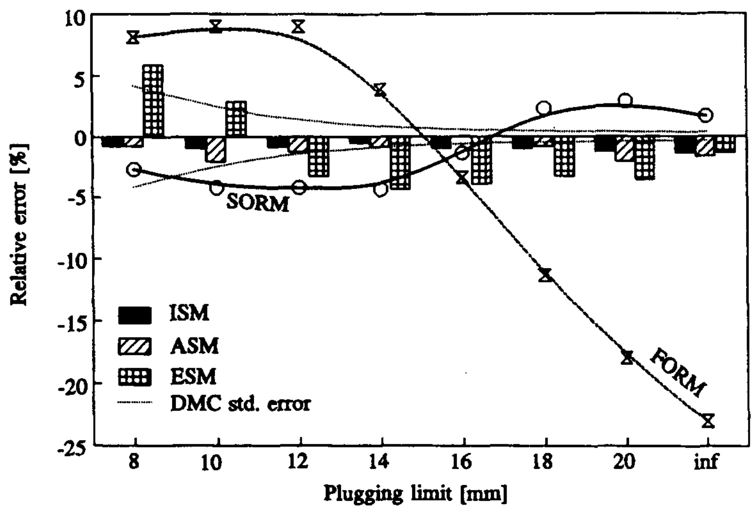

Fig. 2. Relative errors for the case without RF.

standard error. Then, the results of other methods employed are given through their relative errors with respect to the DMC simulation. Again, the results of the two different failure functions (with and without RF) are shown in Fig. 1 and Fig. 2, respectively.

As expected, FORM results are subjected to the most severe scatter. Although its relative error may reach up to 30% (at PL = 12 mm in Fig. 1), FORM reported the correct order of magnitude over the entire range considered. Further, FORM tends to underestimate the failure probability at higher values of PL (Fig. 1). Decreasing the PL value below 18 mm, on the other hand, consistently shows overestimates. The same can be observed in Fig. 2, the changing point now being slightly below PL = 15 mm. In both cases, in the practically interesting region of the plugging limit (say, 8 to 14 mm), FORM consistently overestimates the failure probability and therefore provides conservative estimates.

SORM, on the other hand, has always performed with the relative error below 10%. It should be noted that its performance is quite comparable to those achieved by Monte Carlo simulations. As FORM and SORM are usually executed sequentially (as within the Zerberus code [Cizelj and Riesch-Oppermann, 1992]), it may be of particular importance that, within the practically interesting region of PL, both methods always bounded the *exact* result.

### 4.4. *Sensitivity analysis*

As shown by Eq. (13), the sensitivity analysis represents a natural extension of the FORM calculations. As we already showed the qualitatively correct FORM results in our case, we may assume that sensitivity coefficients provided by eq. (13) constitute an acceptably accurate approximation.

The basic variables involved may be categorised by two cases. First, the variables shown in Table 4 have sensitivity factors that tend to be virtually constant with respect to PL. However, they exhibit a slight maximum at PL = 16 mm in both cases (with or without RF). Further, the scatter of variables $R_{out}$ and $\delta$ hardly contributes

Table 4
Sensitivity factors of basic variables (at PL = 16 mm)

| Variable | With RF | Without RF |
|---|---|---|
| R | $-0.524\times10^{-2}$ | $-0.967\times10^{-2}$ |
| $\delta$ | $0.126\times10^{-1}$ | $0.16\times10^{-1}$ |
| $\sigma_Y+\sigma_M$ | 0.2011 | 0.2707 |
| $K$ | 0.2214 | 0.2978 |
| $t$ | 0.2961 | 0.3358 |

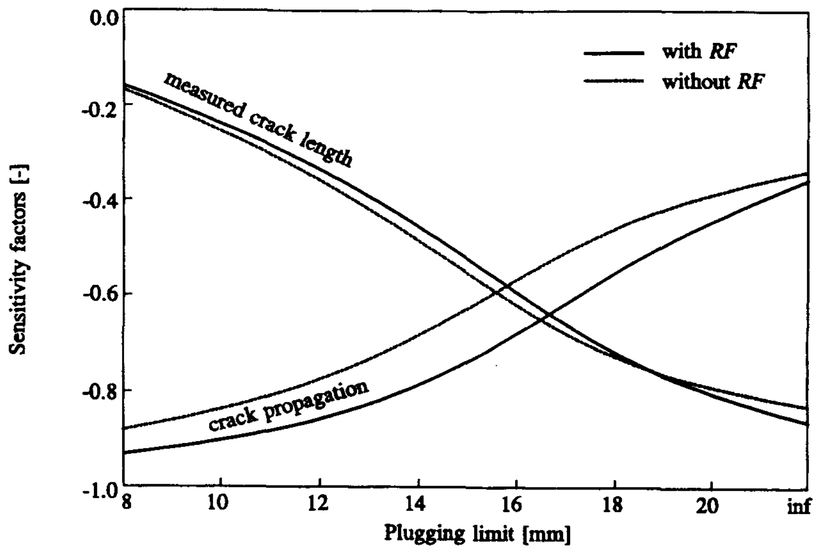


Fig. 3. Sensitivity factors of most sensitive basic variables.

to the failure probability as can be seen from the sensitivity factors and might be neglected in future analyses. Studying the sensitivity factors of basic variables $K$ and $\delta$ (Table 4) and recalling Eq. (4) lead to the following conclusion. Although both basic variables are influencing the failure function in the same way, their contributions to the failure probability vary by about one order of magnitude. The reason for such behaviour is the quite different amount of scatter of both basic variables, as can be seen from Table 1.

Second, the measured crack length and crack propagation (Fig. 3) exhibit very pronounced changes while PL is changed. At lower PL values, crack propagation is shown to be the most important basic variable influencing the steam generator tube failure probability. It should be noted again that the PL region between 8 and 14 mm

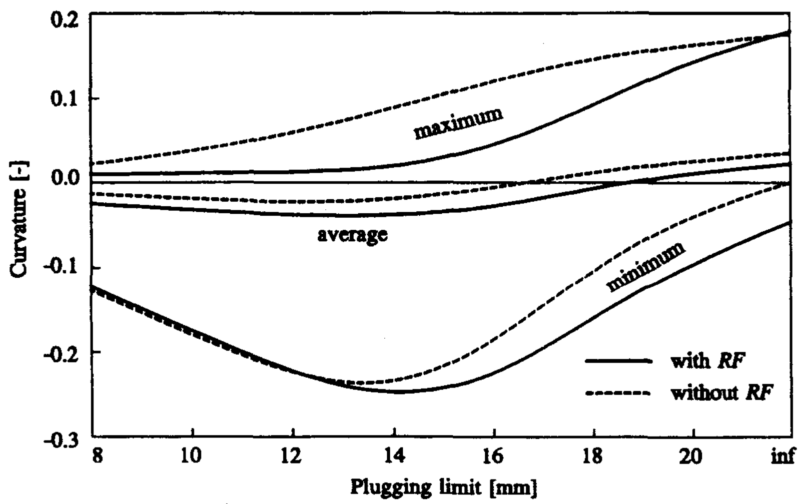


Fig. 4. Failure surface curvatures.

represents the PL values of practical interest, thus urging for more accurate and reliable crack growth modelling.

### 4.5. Failure surface curvatures

As the quality of both FORM and SORM approximations is basically governed by the curvatures of the failure surface, let us examine the changes of curvatures caused by changes in PL. In Fig. 4, the maximum (most positive), the minimum (most negative) and the average value of all curvatures as calculated by SORM are shown.

The overestimates of the failure probability obtained by FORM are obviously caused by the mainly negative curvatures of the respective failure surfaces. The RF influence is basically expressed by bending the failure surface to gain more negative curvatures, especially in the middle range of PL values. The sign of FORM and SORM errors may be explained regarding the average value.

## 5. Conclusions

The First and Second Order Reliability Methods have been applied in the reliability analysis of axial stress corrosion cracks in steam generator tubes. Their performance has been compared to various Monte Carlo simulation methods and an acceptable accuracy of FORM and excellent results from SORM have been obtained.

Furthermore, varying the maintenance strategy parameter (the plugging limit PL) in the range of practical interest (8 mm < PL < 14 mm) showed a consistent overestimation of FORM and an underestimation of SORM. Therefore, applying FORM only yielded conservative results and applying both FORM and SORM bounded the *exact* results.

The sensitivity analysis of basic variables outlined the importance of the reliable crack growth prediction. A simple random variable has been used to describe the crack propagation. Therefore, development of physically crack propagation model is considered as the most urgent topic for future research.

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