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The Reliability Estimation of Pipeline Using FORM, SORM and Monte Carlo Simulation with FAD

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In this paper, the reliability estimation of pipelines is performed by employing the probabilistic method, which accounts for the uncertainties in the load and resistance parameters of the limit state function. The FORM (first order reliability method) and the SORM (second order reliability method) are carried out to estimate the failure probability of pipeline utilizing the FAD (failure assessment diagram). And the reliability of pipeline is assessed by using this failure probability and analyzed in accordance with a target safety level. Furthermore, the MCS (Monte Carlo Simulation) is used to verify the results of the FORM and the SORM. It is noted that the failure probability increases with the increase of dent depth, gouge depth, operating pressure, outside radius, and the decrease of wall thickness. It is found that the FORM utilizing the FAD is a useful and is an efficient method to estimate the failure probability in the reliability assessment of a pipeline. Furthermore, the pipeline safety assessment technique with the deterministic procedure utilizing the FAD only is turned out more conservative than those obtained by using the probability theory together with the FAD. The probabilistic method such as the FORM, the SORM and the MCS can be used by most plant designers regarding the operating condition and design parameters.

Key Words : Reliability, Failure Probability, FAD, FORM, SORM, Monte Carlo Simulation, Pipeline

1. Introduction

The energy supply/delivery industry is advancing to cope with the rapid growth of the economy. And the structures such as gas and oil delivery pipelines and storage structures of oil and gas have been installed in greater numbers at a vast domestic area. Defects in pipeline arisen during manufacturing and usage can reduce the reliability of pipeline. These defects are produced during welding, machining and designing process in manufacturing and produced by the variations of load and temperature, various corrosion circumferences and ground subsidence in usage.

Pipelines, like other structures in industries, are usually deteriorated according to varying boundary conditions. This natural deterioration in a metallic pipeline mainly occurs as a result of the damage caused by the surrounding environment. These pipeline, however, are difficult to replace because of economic and environmental factors. Therefore, it is necessary to evaluate the reliability of pipeline, and thus many researches on this subject have been progressed accordingly (Seo et al., 1999 ; Lin et al., 2004 ; Kwak et al.,

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2004 ; Kim et al., 2004 ; Lee and Kim, 2004)

The reliability of pipeline is evaluated by a universal method that uses failure pressure model, such as B31G and MB31G models, which are based on the internal pressure of the pipeline. But these models cannot consider any other loads except internal pressure. One of varying methods for evaluating the level of reliability of structures with defects like crack is the failure assessment diagram (FAD) and crack driving force. In this paper, the FAD is applied to evaluate the reliability of pipeline because of its convenience in application and simplicity in extension to another field of engineering practices (Seo et al., 1999 ; Lin et al., 2004 ; Kwak et al., 2004 ; Lee and Kim, 2005).

At present, design and reliability evaluation of a pipeline are usually performed by using a determination evaluation method. But this method has a limitation ; it cannot account for the uncertainty of variables such as the shape factor of a pipeline, load, and material property. Therefore, the probability theory must be applied in the reliability evaluation of a pipeline with regarding all parameters as random variables to consider the characteristic of variable distribution (Kim et al., 2004 ; Lee and Kim, 2004).

In this paper, a limit state for assessing the reliability of the pipeline considered has been formulated by using the FAD, and the failure probability of the pipeline is estimated by using the FORM (first order reliability method) and the SORM (second order reliability method). The reliability of the pipeline is assessed by using this failure probability. And the application of these methods to reliability estimation is investigated for a case study. Furthermore, the results obtained from the FAD are compared with the failure probability obtained by using the failure pressure models, and the effects of various boundary conditions on the reliability of the pipeline are systematically investigated. And the results obtained from the FORM and the SORM are compared with those estimated by the MCS (Monte Carlo simulation) and systematically analyzed to assess the accuracy of the reliability of pipelines.

2. FAD (Failure Assessment Diagram)

The FAD is probably the most widely used methodology for elastic plastic fracture mechanics analysis of structural components. Because the damage of structure is characterized as the combination of brittle fracture and plastic collapse, the FAD is composed of the x axis, which represents the effect of plastic collapse, and the y axis, which represents the effect of brittle fracture, as shown in Fig. 1. The line between the safe region and failure region in Fig. 1 represents the failure assessment line (FAL) derived from the theory of fracture mechanic. The state of structure with a defect is expressed by a specific value of (S_r, K_r) on the FAD. If this point is located inside region of the FAL, it can be assessed that the defect is an allowable defect. However, if this point is located outside region the FAL, it can be assessed that the defect is an unallowable defect (Kim et al., 2004 ; Anderson, 2005 ; Limited, 2001).

2.1 Resistance for the plastic collapse

In the Fig. 1, the x axis expressed as S_r is the resistance for the plastic collapse and defined as the Eq. (1). In the Eq. (1), σ_c is the flow stress of the material and σ_{ref} is the stress acted on the pipeline with a defect. If σ_{ref} increases, S_r increases and the pipeline experiences plastic col lapse, if σ_{ref} has the same value as σ_c (Kim et al.,

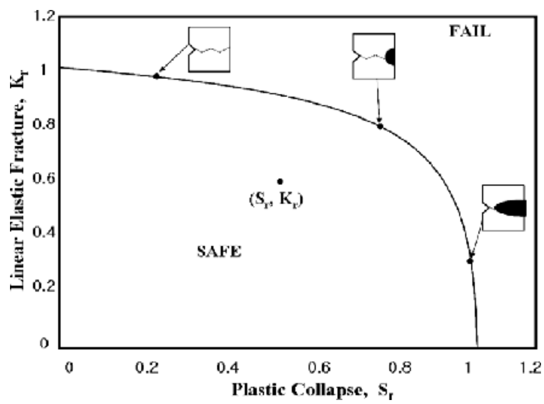


Fig. 1 Typical failure assessment diagram

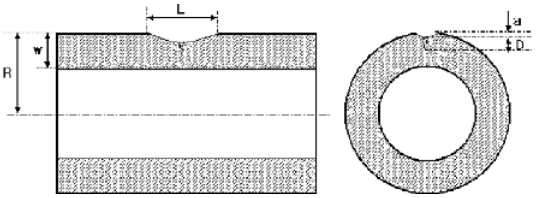


Fig. 2 Schematic of defects of buried pipeline with circumference crack

2004 ; Anderson, 2005 ; Limited, 2001).

$$S_r = \frac{\sigma_{ref}}{\sigma_c} \tag{1}$$

2.2 Resistance for the brittle fracture

In the Fig. 1, the y axis expressed as K_r is the resistance for the brittle fracture and defined as the Eq. (2). In the Eq. (2), K_{mat} is the fracture toughness of the pipeline material and K_I is the stress intensity factor, when the stress is acted on the pipeline with a defect. If K_I increases, K_r increases and the pipeline experiences the brittle fracture, if K_I has the same value with K_{mat} (Kim et al., 2004 ; Anderson, 2005 ; Limited, 2001).

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

2.3 FAD

For the pipeline with a defect such as that shown in Fig. 2, to utilize the FAD, the resistances for the plastic collapse, S_r, and the brittle fracture, S_r, must be calculated, respectively, to evaluate the state of the pipeline with a defect. These calculated values are compared with the values determined by using Eq. (3) derived from the Dugdale model.

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \left\{ \sin \left(\frac{\pi}{2} S_r \right) \right\} \right]^{-1/2} \tag{3}$$

In this paper, the equations to calculate the FAD for the defect such as that shown in Fig. 2 are provided in Table 1. In Table 1, P is the operating pressure of the pipeline, R is the outside radius of the pipeline, w is the wall thickness of the pipeline, D is the dent depth, a is the gouge depth, L is the gouge length, E is the elastic modulus of the pipeline material, c_{v0} is the reference Charpy energy, A is the cross section area of the Charpy test specimen, C_v is the Charpy energy, b is the Charpy energy correlation parameter, α is the flow stress parameter, σ_y is the yield strength of pipeline material, and σ_u is the ultimate strength of the pipeline material.

Table 1 Equations for organizing the failure assessment diagram

$K_r = \frac{[\sigma_m Y_m + \sigma_b Y_b]\sqrt{\pi a}}{K_{IC}}$, $S_r = \frac{\sigma_m \left(1 - \frac{a}{Mw}\right)}{\sigma_f \left(1 - \frac{a}{w}\right)}$
$Y_b = 1.12 - 1.39\left(\frac{a}{w}\right) + 7.3\left(\frac{a}{w}\right)^2 - 13.0\left(\frac{a}{w}\right)^3 + 14.0\left(\frac{a}{w}\right)^4$ $Y_m = 1.12 - 0.23\left(\frac{a}{w}\right) + 10.6\left(\frac{a}{w}\right)^2 - 21.7\left(\frac{a}{w}\right)^3 + 30.4\left(\frac{a}{w}\right)^4$ $\sigma_b = 10.2\frac{PRD}{2w^2}$ and $\sigma_m = \frac{PR}{w}\left(1 - 1.8\frac{D}{2R}\right)$, $K_{IC} = \left(\frac{EC_{v0}}{A}\right)^{1/2}\left(\frac{C_v}{C_{v0}}\right)^{1/2b}$ and $\sigma_f = \alpha(\sigma_y + \sigma_u)$ $M = \left[1 + 0.26\frac{L^2}{Rw}\right]^{1/2}$

3. Failure Pressure Model

The major factors for the failure of pipelines transporting high-pressure gas are mechanical damage and corrosion. Generally, the defect such as corrosion reduces the strength of the pipeline material. Therefore, the remaining strength of pipelines with defects such as corrosion must be evaluated to determine the safety margin in the design of a pipeline. The ASME B31G code, among others, is the most widely accepted method for the assessment of corroded pipelines. A failure equation for the corroded pipelines uses the data from the bursting experiment and is expressed with consideration of the two conditions below. First, the maximum hoop stress cannot exceed the yield strength of the material. Second, relatively short corrosion is projected with the shape of parabola and long corrosion is projected with the shape of rectangular (Lee and Kim, 2004 ; Anderson, 2005 ; Limited, 2001).

However, the results of analysis using ASME B31G code seem to be rather conservative. So Kiefner and Vieth proposed a more precise assessment of the remaining strength of corroded

Table 2 Equations of failure pressure models used to compute the failure probability of buried pipeline

	Equation of failure pressure
ASME B31G code	$P_f=1.1\frac{2\sigma_{yield}t}{D}[1-(d/t)]$, $M=\infty$ for $\sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}>4$ $P_f=1.1\frac{2\sigma_{yield}t}{D}\left[\frac{1-(2/3)(d/t)}{1-(2/3)(d/t)/M}\right]$ $M=\sqrt{1+0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}$ for $\sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}\leq 4$
MB31G code	$P_f=\frac{2(\sigma_{yield}+69)t}{D}\left[\frac{1-0.85(d/t)}{1-0.85(d/t)/M}\right]$ $M=\sqrt{1+0.6275\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.003375\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2}$ for $\sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}\leq 50$ $M=3.3+0.032\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)$ for $\sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}>50$

pipelines by modifying the ASME B31G model. Kiefner and Vieth pointed out some problems on the definitions of flow stress ($\bar{\sigma}=1.1\sigma_{yield}$) and bulging factor, and proposed a new flow stress such as $\bar{\sigma}=1.1_{yield}+69$(MPa) and a new bulging factor. The failure pressure equation for the corroded pipeline is shown in Table 2. In Table 2, P_f is the failure pressure, D is the outer diameter, M is the bulging factor, t is the thickness of the pipelines, d is the maximum depth of the corrosion region, L is the defect length of the corrosion region and σ_{yield} is the yield strength of pipeline material.

4. FORM (First Order Reliability Method)

To utilize the FORM initially, every variable is assumed have normal distribution, and the probability distribution is determined by variable's mean and standard deviation. The failure probability is calculated by using the FORM, which is one of the methods that use the reliability index. The FORM method is based on the first-order Taylor series approximation of a limit state function (LSF), which is defined as below (Lee and Kim, 2004; 2005; Ahammed, 1998; Mahadevan and Haldar, 2000a; 2000b).

$$Z=R-L \tag{4}$$

where R is the resistance normal variable, and L is the load normal variable. Assuming that R and L are statistically independent, normally distributed random variables, the variable Z is also normally distributed. The event of the failure occurs when $R<L$, that is $Z<0$. The probability of failure (PF) is given as below.

$$PF=P[Z<0]=\int_{-\infty}^{0}\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{Z-\mu_z}{\sigma_z}\right)^2\right\}dZ =\int_{-\infty}^{-\beta}\frac{1}{\sqrt{2\pi}}\exp\left\{-\frac{u^2}{2}\right\}du=\Phi(-\beta) \tag{5}$$

where μ_Z and σ_Z are the mean and standard deviation of the variable Z, respectively, and the new variable U is $U=(Z-\mu_Z)/\sigma_Z$, Φ is the cumulative distribution function for a standard normal variable, and β is the safety index or reliability index and the coefficient of variation (C.O.V) denoted as below.

$$\beta=\frac{\mu_Z}{\sigma_Z}=\frac{\mu_R-\mu_L}{\sqrt{\sigma_R^2+\sigma_L^2}} \tag{6}$$

$$C.O.V=\frac{\sigma_Z}{\mu_Z} \tag{7}$$

Equation (6) can be used when the system has a linear LSF. Actually, most real systems and cases do not have linear LSF but rather a nonlinear LSF. So, for a system that has a nonlinear LSF, Eq. (6) cannot be used to calculate the reliability index. Rackwitz and Fiessler proposed a method to estimate the reliability index that uses the procedure shown in Fig. 3 for a system having a nonlinear LSF. In this paper, we iterate the loop, as shown in Fig. 3, to determine a reliable reliability index until the reliability index converges to a desired value ($\Delta\beta\leq 0.001$) (Lee and Kim, 2004; 2005; Mahadevan and Haldar, 2000a; 2000b).

The LSF must be defined to formulate the FORM and evaluate the reliability. In this paper, the LSF

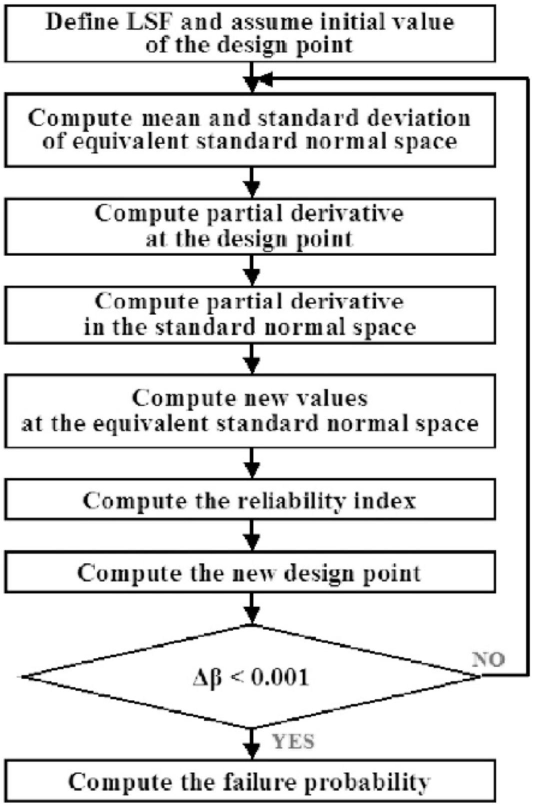


Fig. 3 Computation process of the reliability index

can be defined by using the formula for calculating the resistances against plastic collapse and brittle fracture to construct the FAD. And the reliability of the pipeline with a defect can be evaluated using this LSF.

$$Z=S_r\left[\frac{8}{\pi^2}\ln\left\{\sec\left(\frac{\pi}{2}S_r\right)\right\}\right]^{-1/2}-K_r \quad (8)$$

5. SORM (Second Order Reliability Method)

The computations required for reliability analysis of systems with linear LSF are relatively simple. However, the LSF could be nonlinear either due to a nonlinear relationship the random variables in the LSF or due to some variables being non-normal. Also, a linear limit state in the original space becomes nonlinear when this space is transformed to the standard normal space if any of the variables is non-normal.

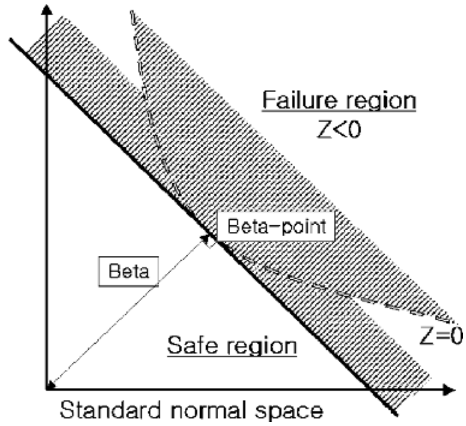


Fig. 4 Linear and nonlinear limit states

If the two limit states shown in Fig. 4, i.e. one linear and another nonlinear, are considered, the FORM approach will give the same reliability index for both cases. But it is apparent that the failure probability of the nonlinear limit state would be less than that of the linear limit state, due to the difference in the failure domains, shown by the shaded regions. The curvature of the limit state around the minimum distance point determines the accuracy of the first order approximation in the FORM. The curvature of any equation is related to the second order derivatives with respect to the basic variables. Thus, the SORM improves the FORM result by including additional information about the curvature of the limit state.

The SORM approach was first explored by Fiessler using various quadratic approximations. A simple closed form solution for probability computation using a second order approximation and adopting the theory of asymptotic approximation was given by Breitung (Mahadevan and Haldar, 2000a ; 2000b).

$$PF_{SORM}=\Phi(-\beta)\prod_{i=1}^{n-1}(1-\beta\kappa_i)^{-1/2} \quad (9)$$

where κ_i denotes the principal curvatures of the limit state at the minimum distance point and β is the reliability index calculated by using the FORM. The principal curvatures is computed by using steps shown Fig. 5 (Mahadevan and Haldar, 2000a ; 2000b).

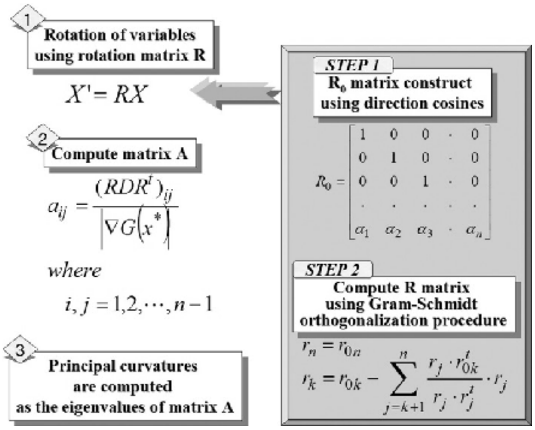


Fig. 5 Process of computing the principal curvatures

6. MCS (Monte Carlo Simulation)

Unlike many engineering analytical results, the ones obtained by probabilistic methods are difficult to verify experimentally. We use the MCS technique to verify the accuracy of the results obtained from FORM. Most engineering MCSs are usually performed by the steps shown in Fig. 6 (Mahadevan and Haldar, 2000; Mahadevan and Haldar, 2000).

In the MCS, many simulations are preformed. In each simulation, the values of the variables are randomly generated according to their probability density functions. And then the limit state function is used to evaluate the performance function in each simulation. Finally, the probability $P[Z<0]$ is estimated as;

$$P[Z<0]=\frac{N_f}{N} \tag{10}$$

where N_f is the number of simulations with $Z<0$, which is number of failures, and N is the total number of simulations. To obtain a reliable simulation results, the total number of simulation, N, is selected as:

$$N\geq\frac{100}{PF} \tag{11}$$

In this paper, N is chosen as 10^8 because we set the maximum target safety level of the buried pipeline corresponding to $PF=10^{-6}$ to ensure the perfect integrity of the buried pipeline.

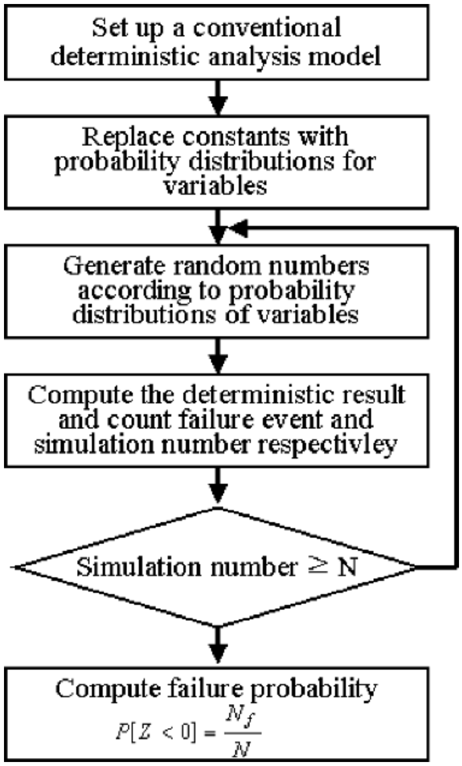


Fig. 6 Computation process of the failure probability obtained by the Monte Carlo simulation

7. Target Reliability

In the development of new design criteria, the appropriate target safety levels must be determined to apply reliability methods. A target safety level is defined as the maximum acceptable failure probability level for a particular limit state design to be accepted. The target safety level of the pipeline with a defect such as corrosion is the same level as that of the intact pipeline. The target failure probability from the DNV Rules is reproduced in Table 3. In this paper, the target failure probability for satisfying the target safety level is adopted as $PF^T=10^{-4}$ (Lee and Kim, 2004; 2005; Limited, 2001).

8. A Case Study

The random variables listed in Table 4 have been utilized to calculate the failure probability using the FORM, SORM and MCS with FAD.

Table 3 Various target failure probabilities with respect to different LS for buried pipelines

Limit State (LS)	Safety Classes		
	Low	Normal	High
SLS (Serviceability Limit State)	$PF^T=10^{-2}$	$PF^T=10^{-3}$	$PF^T=10^{-3}$
ULS (Ultimate Limit State)	$PF^T=10^{-3}$	$PF^T=10^{-4}$	$PF^T=10^{-5}$
FLS (Fatigue Limit State)	$PF^T=10^{-3}$	$PF^T=10^{-4}$	$PF^T=10^{-5}$
ALS (Accidental Limit State)	$PF^T=10^{-4}$	$PF^T=10^{-5}$	$PF^T=10^{-5}$

* PF^T : target failure probability

And the results have been used to assess the reliability of the pipeline (Kim et al., 2004 ; Lee and Kim, 2004 ; Limited, 2001).

9. Results and Discussion

A pipeline containing the defect in axial direction is analyzed with the MCS and the FORM by using the equation listed in Tables 1 and 2, and the data described in Table 4. The relationship between the failure probability and the variation of random variables is shown in Fig. 7 according to the FORM and the SORM. It is found from Fig. 7 that the failure probability increases with increase of dent depth, gouge depth, operating pressure and pipe outside radius, and decrease of pipe wall thickness. Moreover, the failure probability increases with increase of gouge length. The difference between the results of the FORM and the SORM is fairly large for the variation of dent depth. However, the results obtained by using the FORM and the SORM are much similar for the variations of gouge depth, operating pressure, pipe outside radius and pipe wall thickness. Table 5 quantitatively shows the mean percentile differences among the results of the FORM, the SORM and the MCS. Table 5 shows that the differences between the results obtained by the FORM and the SORM are large. However, the differences are not plotted as distinguished as shown in Fig. 7, because the absolute values of the failure probability estimated by the FORM and the SORM is very small.

Table 4 Random variables and their parameters used in a case study

Variable	Mean	C.O.V
P	7 MPa	0.01
E	207 GPa	0.04
C_{v0}	112,300 mJ	0.02
A	53.55 mm^2	0.03
C_v	55,200 mJ	0.025
σ_y	445.9 MPa	0.029
σ_u	593.4 MPa	0.024
R	457.2 mm	0.016
w	12.8 mm	0.023
D	2 mm	0.015
a	2 mm	0.015
L	120 mm	0.01
b	0.495	–
α	0.5	–

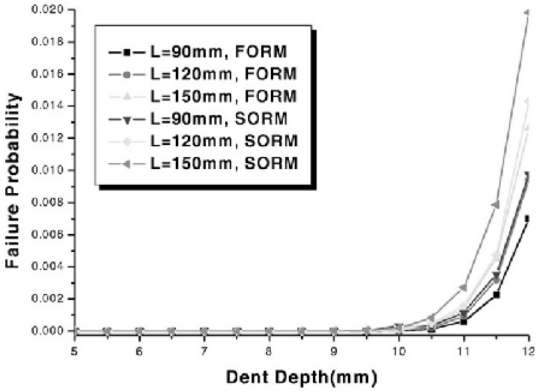
Table 5 Comparison of the mean percentile differences among results obtained by the FORM, the SORM and the MCS

	FORM vs. MCS [%][1]	SORM vs. MCS [%][1]	FORM vs. SORM [%][2]
Dent Depth	7.99	81.79	105.52
Gouge Depth	9.83	22.96	49.63
Operating Pressure	8.82	19.56	28.27
Outside Radius	7.01	10.45	23.16
Wall Thickness	4.52	8.63	18.57

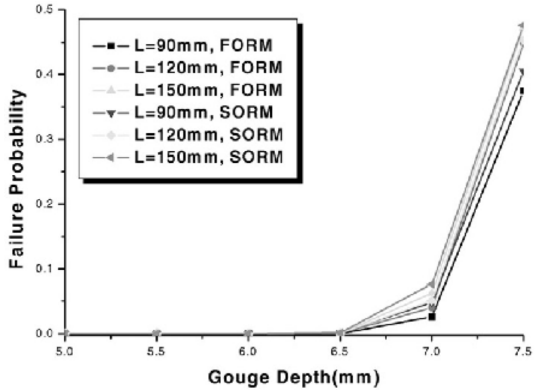
1 percentile difference=ABS{(result of MCS) −(result of FORM or SORM)}/(result of MCS) ×100

2 percentile difference=ABS{(result of FORM) −(result of SORM)}/(result of FORM) ×100

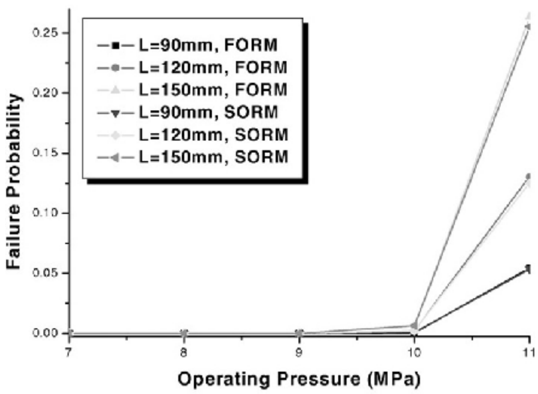
It is shown in Fig. 8 that the relationship among the results obtained by the FORM, the SORM, the MCS incorporated with the B31G model, and the MB31G model at gouge length of 120 mm. The failure probability increases with the increases of dent depth, gouge depth, operating pressure and pipe outside radius and decrease of pipe wall thickness. And it is noted from Fig. 8 that the failure probabilities obtained by the FORM, the SORM and the MCS are very similar for the variations of gouge depth and pipe wall thickness, but slightly different for the variations of dent depth, operating pressure and pipe outside radius. Table 5 shows the mean percentile differ-



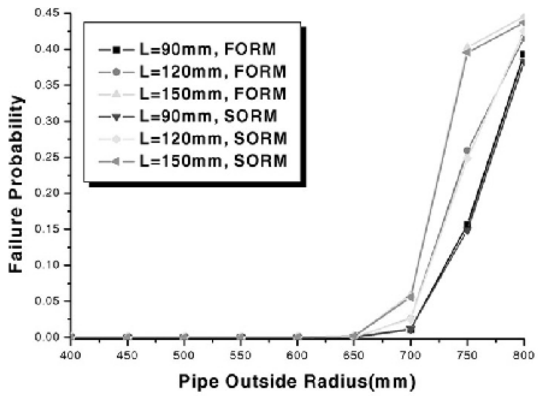
(a) dent depth



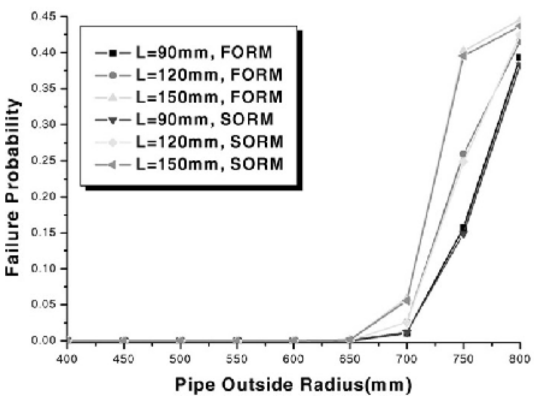
(b) gouge depth



(c) operating pressure



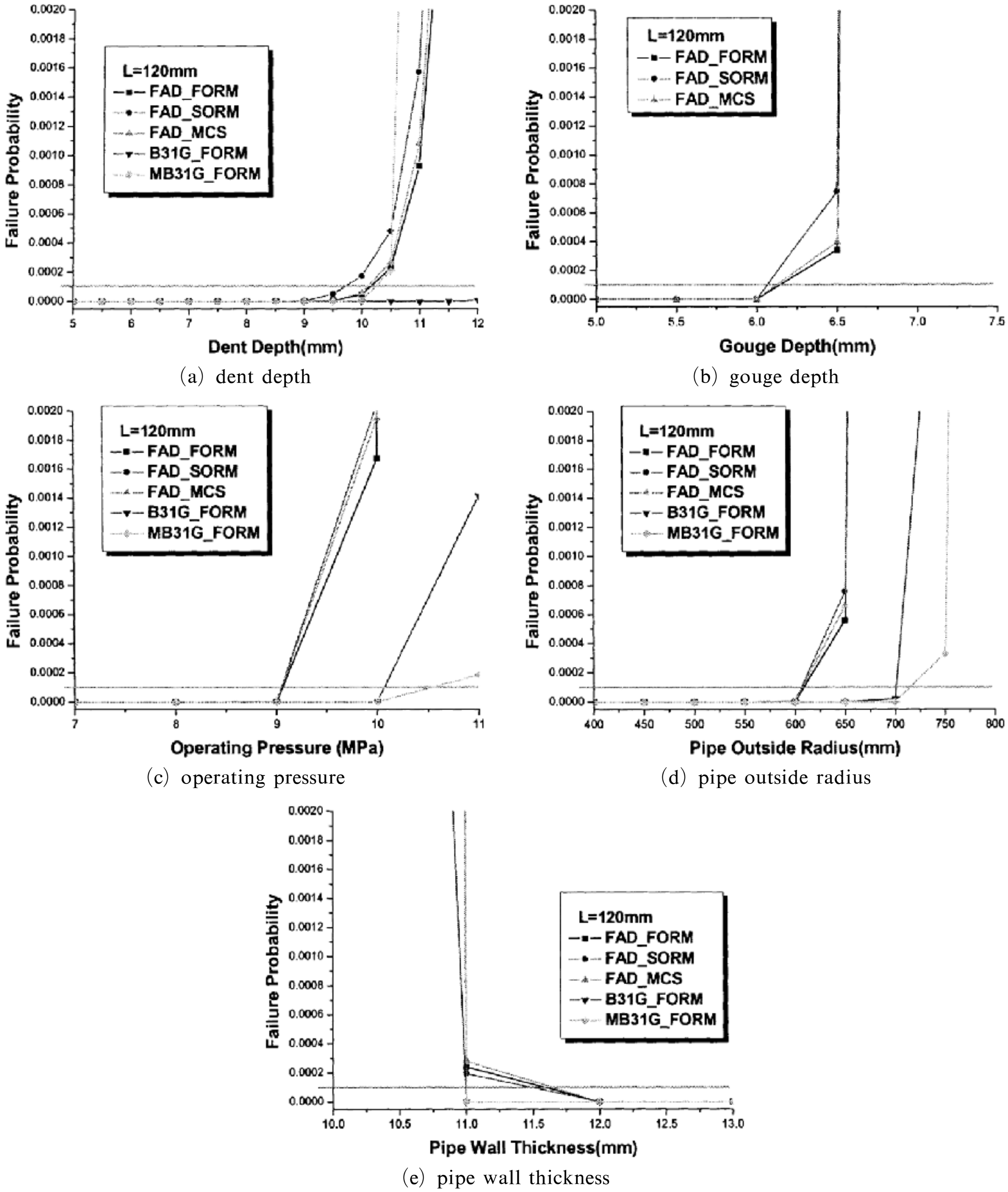
(d) pipe outside radius



(e) pipe wall thickness

Fig. 7 Relationship between failure probability and various random variables according to the FORM and the SORM ences among the results obtained by using the FORM and the SORM, and the MCS, respectively. It is recognized from Table 5 that the mean percentile difference between results of the FORM and the MCS is smaller than those between results of the SORM and the MCS. However, this difference is not shown clearly in Fig. 8.

In this paper, the Breitung's method is applied to calculate the failure probability using SORM. The Breitung's method uses the theory of asymp-



(a) dent depth

(b) gouge depth

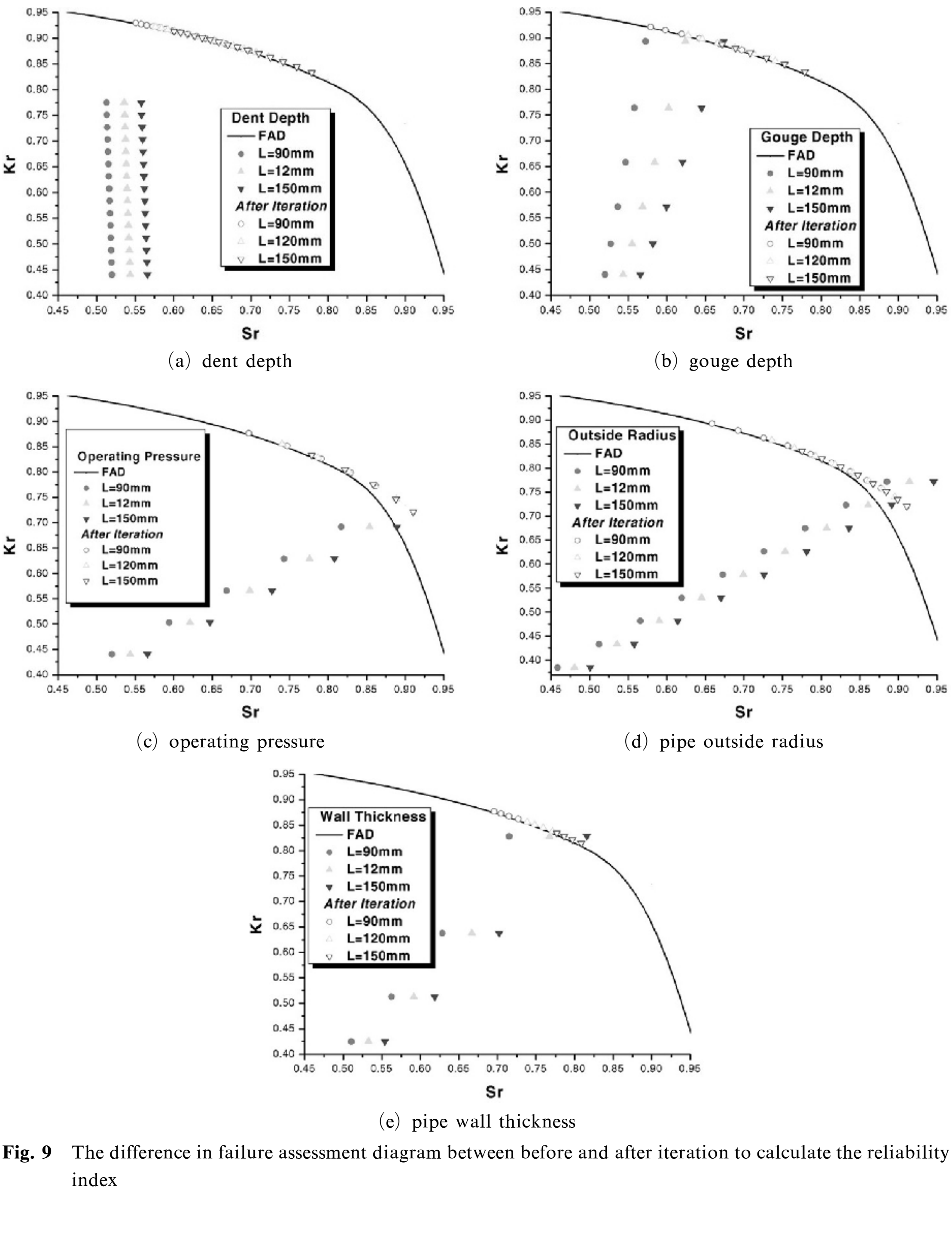
(c) operating pressure

(d) pipe outside radius

(e) pipe wall thickness

Fig. 8 Relationship between failure probability and the results obtained by using the FORM, SORM, MCS and failure pressure model such as B31G and MB31G models totic approximation and it is known that the asymptotic approximation shows accurate results for the larger values of reliability index.

Although the difference between the results of SORM and those of MCS is larger because of small reliability index, it is concluded that the FORM which has simple procedure is useful method to estimate the reliability of pipeline, because the failure probability obtained using SORM has same order with obtained failure probability from FORM



(a) dent depth (b) gouge depth (c) operating pressure (d) pipe outside radius (e) pipe wall thickness

Fig. 9 The difference in failure assessment diagram between before and after iteration to calculate the reliability index and MCS and the difference between FORM and MCS is very small. Because the failure probability is very small as the order of magnitude below 10^{-6}, the percentile differences between SORM and MCS are shown larger than those between FORM and MCS.

Since the MCS is performed with a total of 10^8 simulations, the failure probability computed by the MCS can be assumed to be a theoretical value. Therefore, the failure probability estimated by the FORM can be regarded as accurate for the case using the FAD.

The failure probability calculated by using the B31G and MB31G models is plotted together in Fig. 8, and the results are compared with the results obtained by using the FAD. To calculate the failure probability by utilizing the B31G and MB31G models, we assumed that the defect depth was the same with dent depth and that the gouge depth was zero. It is noted that the failure probability calculated by using the FAD is larger than those obtained by using the B31G and MB31G models, because the B31G and MB31G models can not consider various loads except the pressure inside the pipeline.

The horizontal line that is located along to 10^{-4} of failure probability indicates the target safety level. If the failure probability estimated for the pipeline is smaller than the target safety level, the pipeline may be considered safe. On the other hand, the pipeline is unsafe if the failure probability is larger than the target safety level. When the target safety level of $PF^T=10^{-4}$ is considered, the range of random variables for safety of pipelines is shown in Table 6. Using the data in Table 6 with consideration of the target safety level, the buried pipeline can be designed and the operating condition can be selected to satisfy the target safety level.

The deterministic method may not be accurate enough because of the lack of knowledge about the uncertainty of variables, when the engineer designs the pipeline or assesses the reliability. Thus, the probabilistic approach considering the statistical distribution of variables must be applied. It is highly suggested that when the pipeline is designed, appropriate limit state must be selected and the target safety level should be applied. The value satisfying the target safety level may be used to select the operating conditions and/or design parameters such as wall thickness, outside radius, and internal pressure and so on.

Table 6 Dimension ranges to satisfy the target safety level of $PF^T=10^{-4}$

	Dent Depth [mm] (under)	Gouge Depth [mm] (under)	Operating Pressure [MPa] (under)	Outside Radius [mm] (under)	Wall thickness [mm] (over)
FAD_FORM	10.2	6.3	9.0	610	11.6
FAD_SORM	9.7	6.1	9.0	610	11.6
FAD_MCS	10.2	6.3	9.0	610	11.6
B31G_FORM	–	–	10.1	700	11.0
MB31G_FORM	10.2	–	10.5	720	11.0

Figure 9 shows the FAD, which is displayed all assessment points for the variation of random variables before and after the iteration performed in order to estimate the reliability index. It is found from Fig. 9 that most of the assessment points are located in the safety region of the FAD before the iteration. However, most of assessment points move onto the FAL, because the value of the limit state function converges to zero with iterations. This phenomenon represents that the application of FAD in the FORM theory and thus the estimation of the failure probability accordingly seem appropriate.

Normally, pipelines are safe, if the failure probability calculated by the probability theory is smaller than about 10^{-4} level. Based on these criteria, it is found from Fig. 8 that more than half of the assessment points are not safe. On the other hand, most of the assessment points are safe from the results of Fig. 9. Therefore, it is found that the reliability assessment of the pipeline using the FAD is more conservative than those using a probability theory such as the FORM.

10. Conclusions

In this paper, the FORM (first order reliability method) and the SORM (second order reliability method) are used to estimate the failure probability and to evaluate the reliability of a pipeline with defect in axial direction. The MCS (Monte Carlo Simulation) is used to evaluate the applicability of the FORM and the SORM to the pipeline by comparing the failure probability. Using the FAD (failure assessment diagram), the effects of various random variables on the failure probability estimated by the MCS, the FORM and the SORM are systematically studied and the following results are obtained :

(1) The FORM is a useful and efficient method for estimating the failure probability in the evaluation of the reliability of the pipeline using FAD.

(2) The failure probability obtained by using the FORM, the SORM and the MCS increases with the increases of the dent depth, gouge depth, operating pressure and outside radius, and the decrease of the wall thickness.

(3) It is noted that the plant designer must select an appropriate limit state before the start of the design procedure about the pipeline. The values satisfying the target safety level according to the FAD can be used to select the operating condition and/or design parameters such as wall thickness, outside radius, internal pressure and varying boundary condition.

(4) The safety assessment of a pipeline using the FAD is more conservative than that obtained by using a probability theory.

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