博士論文

Development of Reliability Based Assessment Method for Piping Containing Local Metal Loss Existing at Structure Discontinuity

(不連続部に局部減肉を有する配管の信頼性基準評価手法の開発)

曲　強

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Chapter 1. Introduction

1.1 Background

In chemical plants, inner pressed pipes, vessels and storage tanks are the most important structures. The safety of the pipe must be ensured in all processes of design [1-4], construction, maintenance [5-8]. In Japan, most of equipment and structures in chemical plant have been severing for over 40 year. The aging of structures becomes serious maintenance issue, the awareness of importance of accident prevention [9,10] increases fast recently. The explosion of aged high-pressure structures might causes miserable accident, so the evaluation of pressed structures becomes more and more important.

The most typical aging problem of the pressed pipe is metal loss which caused by corrosion or abrasion [11], especially the corrosion under insulations (CUI). CUI is a form of localized corrosion leads to metal loss at the outside surface of pipes, reduces the pipe's resistance to internal pressure [12]. Because it happen under the insulation, it is hard to be inspected in time. If it is placed for long time, the leak of internal liquid or blast would happen and lead to huge disasters. One the other hand, if the pipe containing metal loss is repaired or replaced too frequently, there will be a huge unnecessary maintenance cost. In order to ensue both safety and economics, a proper Fitness-For-Service assessment is necessary for the maintenance of aged structures.

1.2 Fitness-For-Service assessment

1.2.1 Recent maintenance method in Japan and oversea standard

In Japan, the recent methods of maintenance [5] of inner pressed structures doesn't allow the defected structures to continue operating. Once the flaw is inspected, the structure must be replaced or repaired regardless the size of the flaws. This is a too conservative method which maintains a too much high safety level of the pipe. This method also underestimates the reasonable service life of the structures, and leads to high maintenance cost for the frequently repair or replacement.

In US and European countries, the maintenance method of inner pressed structures is developed basing on a recognition that the small damages or flaws might have negligible influence on the structure's safety level. As a product, a maintenance method, Fitness-For-Service (FFS) assessment is developed, and it is widely applied in US and Europeans countries. The FFS assessment is integrity evaluation of structures containing damages or flaws. The evaluation determines an acceptable size of flaw or acceptable working pressure for those defected structures. By FFS assessment, the defected structures qualified in the evaluation can continue to work.

Recently in Japan, however, the method to evaluate the defected structures hasn't been developed, so the application of overseas FFS assessment standards has been considered to be a rational solution for the maintenance issues of the chemical plants in Japan.

In the overseas standard, the API579-1/ASME FFS-1 [18] is most noticeable. In this API579 standard, the standardized procedures are provided to evaluate structures containing different kinds of flaws or damages, such as crack-like flaws, metal loss, pitting corrosions, weld misalignment, shell distortions and others. However, there are different standards of industry standard such as material standards and design standards, therefore the applicability of API standard in Japan is not clear. Furthermore, for the structures which has complicated geometries, the evaluation method with treatment of risk hasn't been developed yet. Instead, a conservative method (API method) based on deterministic approaches is given in API579 for insurance.

In chemical plants, the maintenance of pipe with CUI is most directly related to the evaluations of local metal loss. In API579, the FFS assessment process of local metal loss has been provided.

1.2.2 Recent development of FFS guidance for metal loss in Japan

Although recently there is no FFS assessment applied in Japan, the experts and engineers are doing efforts to improve this situation. High Pressure Institute of Japan (HPI) developed a guidance of metal loss, "Metal loss assessment for pressure equipment based on reliability" which is going to be published. In this guidance, for maintenance issue of CUI, the FFS assessment method for local metal loss at straight pipe has been provided. A probabilistic reliability based assessment method and the limit state function of critical burst pressure (P_{bc}) to geometries of metal loss are given in this guidance. The API579 methods for local metal loss at straight pipe are referred, and serval improvements are made by the results of research of Y.Mogami [15] and T.Kaida [16] to develop applicable FFS assessment method for Japan. However, for the cases of local metal loss located at structure discontinuity, the assessment method is not provide in this guidance.

The metal loss is actually more likely to happen at the discontinuity of the pipe because of easier invading and storage of the rain water at the discontinuity of insulation. Therefore it is important to develop the FFS assessment method for the pipe containing local metal loss at discontinuity.

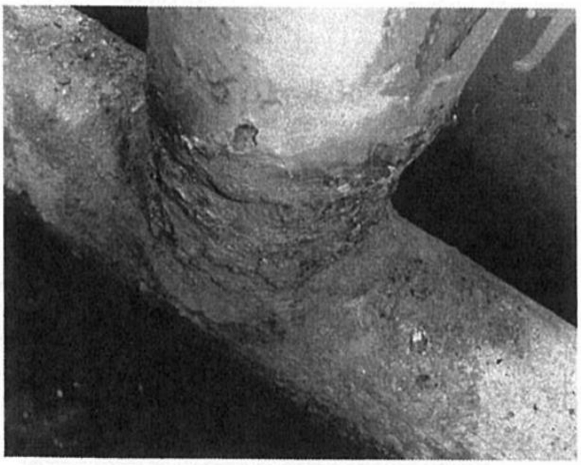


Figure 1.1. CUI located at tee pipe discontinuity [17]

1.3 Problem statement of API579 method

In API579, for the cases of local metal loss located at structure discontinuity, only a deterministic assessment method is provided, and the limit state function of P_{bc} to geometries of metal loss hasn't been developed.

The process of API579 assessment of local metal loss at discontinuity is shown in Fig 1.3. In this process, the thickness average method and reinforcement area method are included. The maximum allowable working pressure (MAWP) calculated from reinforcement area method is compared to the working pressure. If the MAWP is greater than the working pressure, this metal loss is acceptable, the pipe is able to continue operating. While if MAWP is less than working pressure, the pipe should be replaced or repaired.

1.3.1 Thickness average method

This is an approach to treat the local metal loss to a general metal loss. For the case of tee pipe containing circumferential metal loss, the average value of remain thickness can be calculated by Eq.(1-1).

$$t_{am} = t - 2s\left(t - t_m\right)/d \qquad \text{Eq.(1-1)}$$

where the t_{am} is averaged value of remain thickness, t is the total thickness of main pipe, t_{mm} is minimum of remain thickness s is width of metal loss, d is the inner diameter of branch pipe. There is no reference or evidence, which proves the reasonableness of the thickness average method.

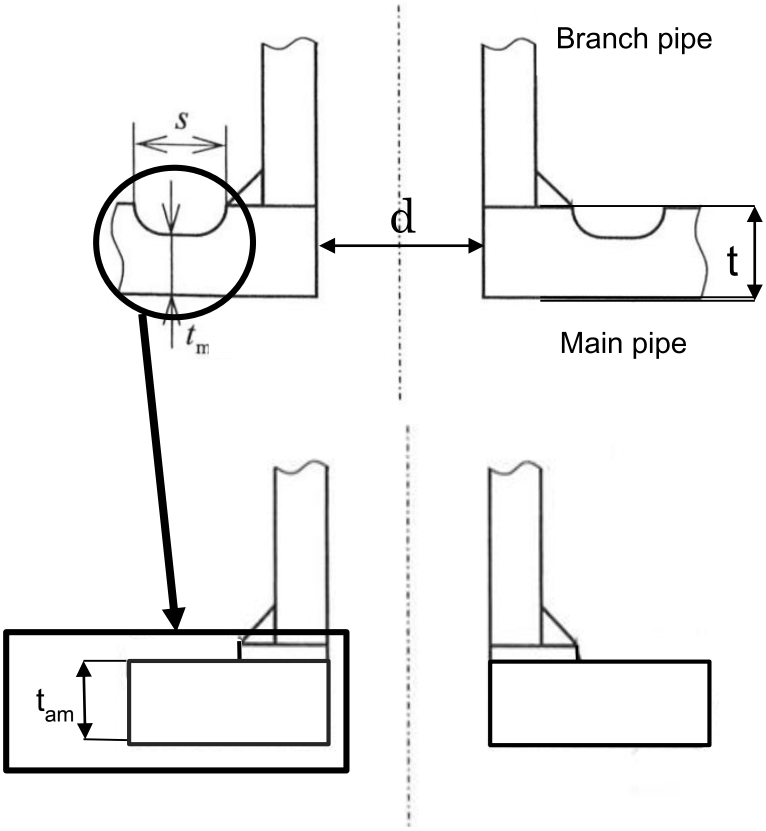


Figure 1.2 Thickness Average Method

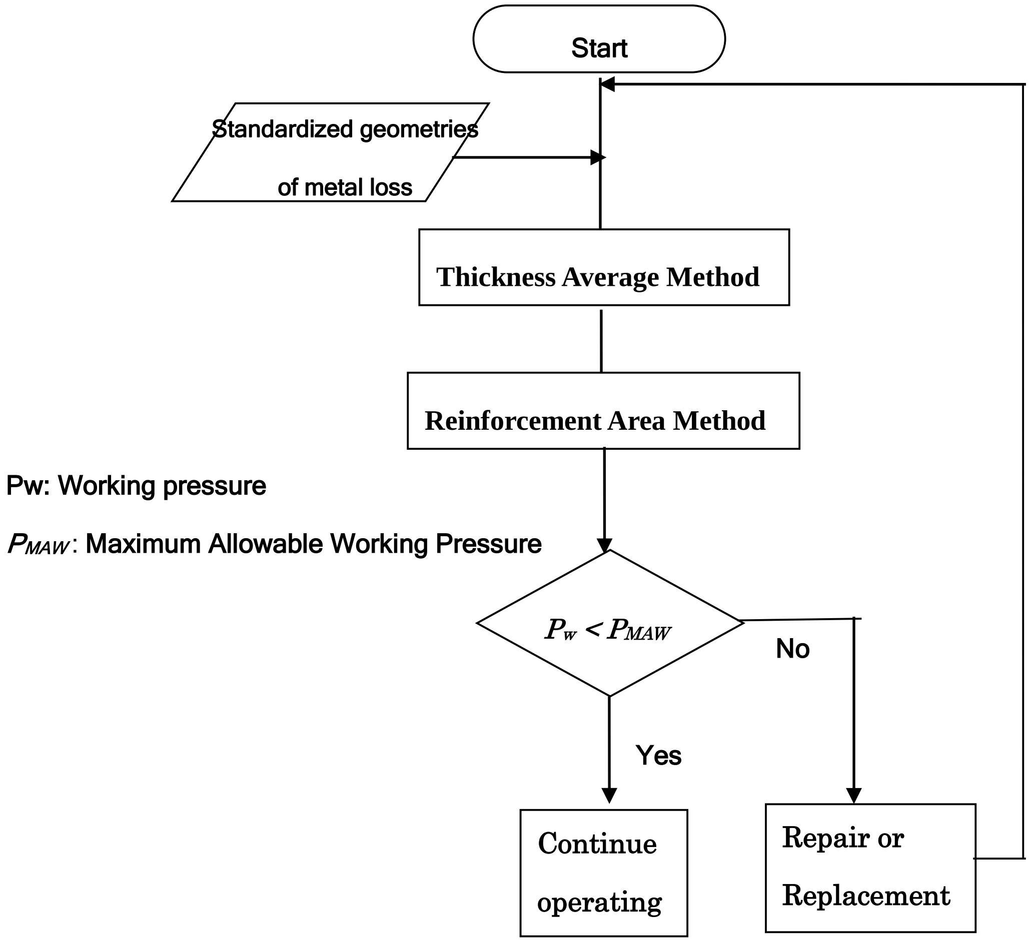


Figure 1.3 Deterministic approaches of assessment of metal loss in API579

1.3.2 Reinforcement area method [18]

The reinforcement area method is a traditional method used in the piping design. The region of the nozzle reinforcement zone is defined by the length of l_v, l_{no} and l_{ni} shown in Fig.1.3 which can be determined by Eq.(1) to Eq.(3).

$$l_v = \max\left[d, \frac{d}{2} + t + t_n\right] \qquad \text{Eq.(1-3)}$$

$$l_{no} = \min\left[2.5t, 2.5t_n\right] \qquad \text{Eq.(1-4)}$$

$$l_{ni} = \min\left[2.5t, 2.5t_n\right] \qquad \text{Eq.(1-5)}$$

Where d is the inside radius of branch pipe, t is the wall thickness of main pipe and t_n is the wall thickness of branch pipe.

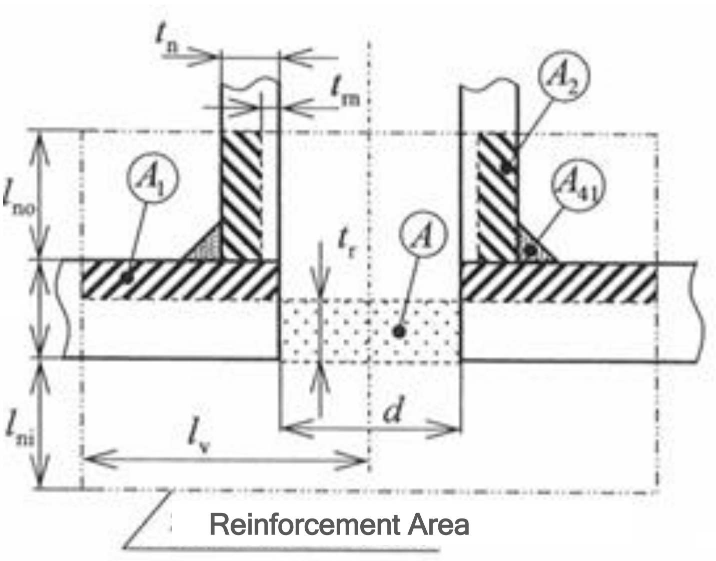


Figure 1.4 Reinforcement Area Method

If the local metal loss having geometries of width s_m and depth t_m exists inside of the reinforcement zone ($s_m < l_v - \frac{d}{2} - t_n$), the average thickness t_{am} can be obtained from the thickness average method in 1.3.1.

The *MAWP* can be computed by Area Replacement Method (ARM). Each area shown in Fig.1.3 inside the nozzle reinforcement zone should satisfy the following expression.

$$A_1 + A_2 + A_{41} > A \qquad \text{Eq.(1-7)}$$

$$A_1 = 2\left(t - t_r\right)\left(l_v - \frac{d}{2}\right) \qquad \text{Eq.(1-8)}$$

$$A_2 = 2l_{no}\left(t_n - t_{rn}\right) \qquad \text{Eq.(1-9)}$$

$$A = t_r d \qquad \text{Eq.(1-10)}$$

A_{41} is the area of reinforcing pad. t_{rn} and t_r are functions of the internal pressure shown as Eq.(1-11) and Eq.(1-12) , and t equals to average t_{am} .

$$t_r = \frac{d_o P}{2\sigma_a \eta + 0.8P} \qquad \text{Eq.(1-11)}$$

$$t_{rn} = \frac{d_{on} P}{2\sigma_a \eta + 0.8P} \qquad \text{Eq.(1-12)}$$

where P is the internal pressure, d_o is the outside radius of main pipe, d_{on} is the outside radius of branch pipe, σ_a is yield stress and η is the welding efficiency ($\eta = 1$). The *MAWP* is the maximum internal pressure which satisfies Eq.(1-7), and it can be conducted to Eq.(1-13). The calculated *MAWP* should be equal to or exceed the design *MAWP* to ensure the safety of continued operation.

$$P_{MAW} = \frac{2\sigma_a \eta t_B}{D_B - 0.8t_B} \qquad \text{Eq.(1-13)}$$

$$t_B = \left(1 - \frac{d}{2l_v}\right)\eta t + \frac{l_{no}}{l_v} t_n + \frac{A_{41}}{2l_v} \qquad \text{Eq.(1-14)}$$

$$D_B = d_0 + \frac{l_{no}}{l_v} d_{on} \qquad \text{Eq.(1-15)}$$

In the reinforcement area method, the allowable stress is used to calculate the standard value MAWP. The burst of pipe happens when the cross sectional reached the value of tensile strength, therefore, it is too conservative to use allowable stress to evaluate the burst internal pressures.

To summarize the problems of the API579 assessment process, firstly the MAWP evaluated by allowable stress is much lower than the P_{bc}, so API579 produces too much conservative result. Secondly, the reasonableness of thickness average method is not clarified, the safety margin of API579 is unknown.

1.4 Objectives

In order to develop the guidance of metal loss evaluation for Japan, the API579 is considered to be a good reference. However, due to the thickness average method (TAM) and reinforcement area method (RAM), API579's evaluation process of local metal loss at pipe discontinuity provides an unclear safety margin and possibly huge conservative results. Also because of the difference of industry standards such as material standards or design standards, the applicability of API standard in Japan is not clear. As a result, as a piolet research, it is important to investigate the safety margin of API579 process. Therefore, the first objective of this research is to investigate the applicability of API579 assessment to piping containing local metal loss at discontinuity in Japan.

Since the requirement of awareness of risk increases fast, a quantitative assessment of risk caused by uncertainties in structure geometries or material is necessary for recent maintenance process of equipment in chemical plants. Therefore, a reliability based assessment method should be developed for pipe containing metal loss. Because the piping structure containing local metal loss at discontinuity is very complicated case in structural analysis, the limit state function for this case hasn't been developed yet. To provide the solution, this research aims to develop a reliability based assessment method for piping containing local metal loss at discontinuity. The method includes advanced analysis technique to simulate the criteria of burst, response surface method to reduce the computational cost for reliability calculation, and probabilistic analysis to reduce the complexity of limit state function in evaluation process.

This reliability based assessment method developed in this research solves the current existing unreasonableness in Japan's maintenance methods of internal pressed structures. It also replenishes deficiencies of evaluation method provided in API579, and contributes to the development of maintenance standard of pressed piping. It will be proposed to guidance making of metal loss assessment in future.

Chapter 2. Proposals and Methodology

2.1 Proposal of reliability based assessment process for local metal loss

For the cases of metal loss located at structure discontinuity, the limit state function of critical loads to geometries of metal loss is not existing. To perform analysis assessment for these case, an assessment method including sample points collection by FEM analysis and limit state function exploration by response surface method is proposed in this chapter firstly. The flowchart is shown in Fig.2.1.

2.2 Methodology

2.2.1 Nonlinear FEM analysis with criteria of burst by dashpot elements

In FEM analysis, after the stress reaches the yield stress or tensile strength (for different stress-stain curve), the defamation increases fast, and the FEM model becomes unstable. The calculation cannot continue in implicit analysis method, and it becomes impossible to calculate the ultimate pressure for pressed pipe without any solution.

In order to complete the calculation under the unstable condition, in this research, dashpot element in the ANSYS is used. Dashpot element is a damper element which prevents the model from a huge deformation by damping effects. This damping force is proportional to the relative velocity of the two nodes that define the element. For a piping subject to an internal pressure, if the internal pressure reaches the value near the critical internal pressure, the force applied on the dashpot element increases extremely fast and the energy which equals to multiple of force and displacement is changes along with the force. According to this property, the timing when the energy of dashpot elements changes extremely is defined as the moment of maximum of plasticity instability.

For different stress-strain curves the maximum of plasticity instability show different criteria of pipe. In design process, for insurance of safety, a conservative stress-strain curve of elastic-perfectly plastic solid is generally used. In this stress-strain curve, after stress reaches the yield stress, the stress has no longer increased even the strain increases. For this case, when the structures reached maximum of plasticity instability, it means at least one sectional cross reached the yield stress, this timing is defined as plasticity collapse.

In this research, the stress-strain curve which considered the working harden after the elasticity with a vertex of tensile strength is used. Therefore, the maximum of plasticity instability means sectional cross reached the tensile strength, so it is defined as the burst of pipe. This definition of burst is also used in M.KAMAYA's research [24], he defined the burst criteria as the maximum of plasticity instability in ABAQUS. The reasonableness of this definition has been proved by previous researches. In A.OHNO's research [25], straight pipe burst experiments and FEM analysis have been conducted. He concluded that, comparing the burst pressure from FEM analysis and burst experiment, the relative error is smaller than ±20%. In H.TAYA's research [26], he applied dashpot to FEM analysis to calculate the burst pressure of a straight pipe, and compared to the experiment result. The relative error is smaller than the concluded value of acceptable error

20% in his calculation. He concluded the dashpot is an accurate method to calculate the burst pressure.

2.2.2 Response surface method

The reliability method containing optimization design approaches can be conducted to calculate the reliability index directly for those structures with limit state function. However, for those complicated structure without existing limit state function, Monte Carlo (MC) simulation of FEM analysis is generally used. It requires amount of times of FEM analysis, and leads to huge computational time consuming and cost. If the limit state function is developed for these cases, it will be very convenient to apply reliability method.

In this research, a regression analysis is performed to develop the limit state function for the case of piping containing metal loss at discontinuity, so that reliability method can be conducted. In statistics, response surface method (RSM) explores the relationships between several explanatory variables and one or more response variables [19]. It uses a sequence of designed experiments to obtain an optimal response. There are several different surrogate models for the regression analysis. With a proper surrogate model, it is able to develop the function of relation by a small number of sample points. In this research, the sample points are obtained from FEM analysis. In R.Jin's research, he compared 4 different surrogate models which are polynomial regressions (PR), Kriging model, Multivariate adaptive regression splines and radial basis function. He concluded that PR is the most efficient method both in terms of model construction and prediction [20]. In this research, 2nd order PR method is proposed to explorer the relationship between P_{bc} and geometries of metal loss and tensile strength.

2.2.3 Reliability method

Reliability method quantifies the safety margin by an index of β. The simplest limit state function includes 2 terms of *R* and *L* where the *R* is résistance term and *L* is load term as Eq.(2-1)

$$g = R - L \qquad \text{Eq.(2-1)}$$

The *R* and *L* are independent random variables with distributions. Mean values of them are μ_R and μ_L, variations are σ_R andσ_L, the reliability level β can be calculated by Eq.(2-2)

$$\beta = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R + \sigma_L}} \qquad \text{Eq.(2-3)}$$

The probability of failure is defined as Eq.(2-3)

$$P_f \approx \Phi(-\beta) \qquad \text{Eq.(2-3)}$$

where the $\Phi(\ )$ is the Standard normal cumulative distribution function.

2.3 Metal loss assessment by partial safety factors

2.3.1 Partial Safety Factor (PSF)

In a deterministic deign, the safety factor is applied to the resistance in the safety check expression to ensure the capacity of system exceeds the loads. The expression is shown as follow.

$$\frac{R}{\gamma} \geq \sum_{i=1}^{n} L_i \qquad \text{Eq.(2-4)}$$

where R is nominal resistance, L_i are various loads, and γ is the safety factor. Thus, this method doesn't provide a treatment of the uncertainties existing in strength and loads, and it is also unable to evaluate the actual safety margin by this method.

On the other hand, partial safety factors are individual safety factors that are applied to the independent variables in the safety expression.

$$\frac{R}{\varphi} \geq \sum_{i=1}^{n} \gamma_i \cdot L_i \qquad \text{Eq.(2-4)}$$

where γ_i, φ are partial safety factors. These partial safety factors are developed using probabilistic analysis in which the resistance and loads are defined as random variables with distributions. The calculation of PSF is based on reliability method considering a limit state model, distributions of the main independent variables of the model, and a target reliability or probability of failure. Hence, the uncertainties of loads and resistance can be treated by separately combining the nominal value of each variable with its own partial safety factor, and also the safety margin is introduced by the target reliability or probability of failure

A general calculating method of partial safety factors is reliability method including first order reliability method (FORM). In reliability method, for nonlinear limit state, the computation of the minimum value of reliability index becomes an optimization problem:

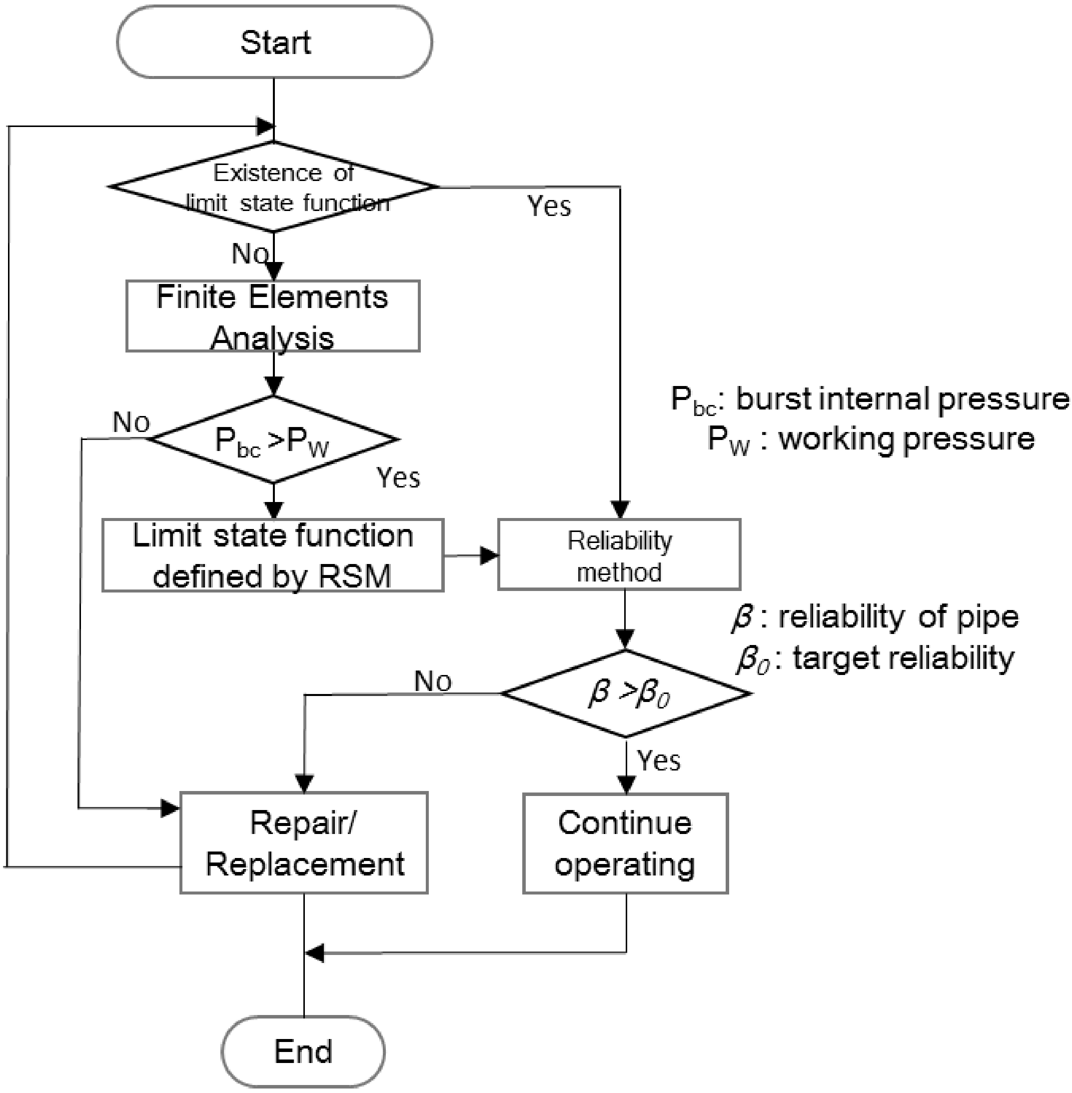


Figure 2.1 Flowchart of reliability analysis proposed in this paper

$$\text{Minimize } \beta = \sqrt{u^T u}$$
$$\text{Subject to } g(u) \leq 0 \qquad \text{Eq.(2-5)}$$

where $\boldsymbol{u}$ is a vector of standardized variables. It is able to search the shortest distance from the origin to the g()=0. The searches points is the design points (R^*, L^*), and partial safety factors can be calculated by

$$\gamma_L = \frac{L^*}{\mu_L}, \quad \varphi_R = \frac{\mu_R}{R^*} \qquad \text{Eq.(2-6)}$$

2.3.2 Probabilistic sensitivity analysis

In reliability analysis, variables' distribution properties have the most directly influence on the result of probability of failure. Therefore, in order to promote the accuracy of reliability analysis, the correctness of the random distribution of variables are demanded. Though promoting data collecting method, distribution approximating approaches and increasing the numbers of sample data, the accuracy of distribution can be ensured. However, collecting large numbers of sample data by experiment or during operating takes long time and the cost is very high.

Because all random variables do not have equal influence on the reliability analysis result, a measure of sensitivity can be used to quantify the influence of each basic random variable [13]. Higher sensitivity means higher influence to Pf.

M.SHINOZUKA [14] defined an index called rate sensitivity as Eq(2-7).

$$\alpha_i = \frac{\partial Pf}{\partial X_i} \frac{\overline{X_i}}{\overline{Pf}} \qquad \text{Rate Sensitivity} \qquad \text{Eq(2-7)}$$

However, this sensitivity only investigates the influence of mean value of variable. In order to evaluate the influence of variation of variable on Pf, in T.KAIDA's research [16], he defined an index called probabilistic sensitivity as Eq(2-8).

$$\frac{\partial Pf}{\partial X_i} \frac{\sigma_{X_i}}{\sigma_{Pf}} = \eta_i \frac{\sigma_{X_i}}{\sigma_{Pf}} \qquad \text{Probabilistic Sensitivity} \qquad \text{Eq(2-8)}$$

where $\eta_i = \partial Pf / \partial X_i$ is the physical sensitivity. Physical sensitivity is the slope for each of the random variables of the probability of failure Pf. It shows the influence of each random variable on Pf directly, however the probabilistic characteristics of variable is not considered by physical sensitivity.

Both rate sensitivity defined in M.SHINOZUKA's research [14] and probabilistic sensitivity defined in KAIDA's research [16] considers the probabilistic properties of variables. Rate sensitivity is the physical sensitivity normalized by mean value of Pf and Xi; while probabilistic sensitivity is the physical sensitivity normalized by deviation of Pf and Xi. In this definition, the deviation of Pf is only a mathematical index for the normalization. The probabilistic sensitivity is a normalized sensitivity to show the relation between the variation of variable and changes of Pf.

In statistics, the mean value can be predicted accurately even by small numbers of data; however, to generate a random distribution requests amount of data. Therefore, comparing to center sensitivity, the probabilistic sensitivity is much more important index which contributes to reduction of data collecting cost. This index provides evidence to rank the variables to different priority levels. For the variables having higher sensitivity, the accuracy of distribution must be ensured by collecting enough sample data and using advanced statistics techniques. One the other hand, for the variables having lower sensitivity, it is not necessary to cost much for its data collecting. For those variables having extremely low sensitivity, it can be treated as constant, the nominal value.

In T.KAIDA's research [16], the probabilistic sensitivity is found to be directly related to the direction cosine α_i^* which is production of reliability method. He used direction cosine for the assessment of probabilistic sensitivities. Therefore, referring T.KAIDA's research [16], the direction cosine α_i^* is also used to measure probabilistic sensitivity in this research.

This analysis of probabilistic sensitivity helps to reduce the numbers of variables for data collecting, and promote the convenience of proposed safety check expressions and partial safety factors.

Chapter 3. Finite Element Analysis of Pipe Containing Local Metal Loss at Discontinuity

3.1 Introduction

Before doing a Fitness-For-Service assessment, it is important to understand the definition of critical state in FEM analysis. It is also necessary to clarify difference between the metal losses existing at the straight pipe and pipe with discontinuity.

To perform a reliability analysis, a limit state function that shows the relation of burst internal pressure and metal loss dimensions must be defined. For the case of straight pipe, the expression proposed Svensso's [22] can be applied as the limit state function; while for the case of pipe with discontinuity, the theoretical derivation is hardly possible, as a result, there is no existing theory expression can be utilized till now. A general method to solve this difficulty is to perform a regression analysis. In Chapter 4, the detail of definition of limit state function will be stated.

In order to obtain the sample points for regression analysis, FEM analysis is involved in this study. By inputting different combinations of metal loss geometries regarding width and depth and material tensile strength, the burst internal pressures are calculated.

These calculated critical in pressures are also used to compare with the *MWAP*s which are calculated in accordance with API579-1/ASME FFS-1 standard. The safety margin can be evaluated by the ratio of P_{bc} /*MAWP*.

3.2 Previous Research

3.2.1 Tee pipe burst experiment [21]

As a previous research, Yamaguchi has performed an experiment to investigate the safety margin of assessment by using the reinforcement area method, which is given in API579 procedures. In his experiment, a tee pipe was used as the test model. The parameter of test tee pipe are given in a)~c) as follows,

a) Design inner pressure P : 2.6MPa

b) Material allowable stress σ_a : 92N/mm^2

c) Wield efficiency η: 1

where the materials allowable stress refers to JIS B 8265 standard, and the wield efficiency is generally defined as value 1 in researches while the wield efficiency is generally defined as 0.9 in engineering practice.

The material of the main pipe and branch pipe are respectively STPG370 200A Sch30 and STPG370 100A Sch40. The nominal yield stress and nominal tensile strength are given in Table 3.1 [21].

Table 3.1 Material properties of main pipe and branch pipe of Yamaguchi's experiment [21]

	Main pipe	Branch pipe
Yield stress (MPa)	343	311
Tensile strength (MPa)	481	476
Elongation at break	40%	39%

In his experiment, a ring shape metal loss with geometries regarding width of 30mm and depth of 4.5mm was grinded around the nozzle area on the main pipe as shown in Fig.3.1 [21]. Water was injected to the test tee pipe to increase the internal pressure until the test pipe bursts. The internal pressure at the burst time is recorded, and this recorded internal pressure is the plastic collapsing internal pressure. The experimental result showed that the burst happened when the internal pressure reached the value of 19.7MPa, and breakage located at center part of metal loss bottom surface as shown in Fig.3.2 [21]

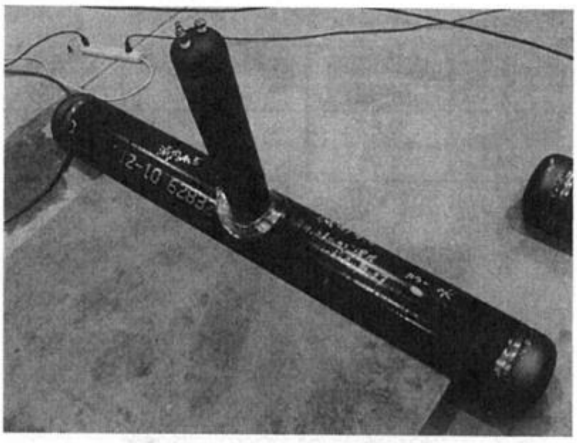


Figure 3.1 Test tee pipe of Yamaguchi' experiment [21]

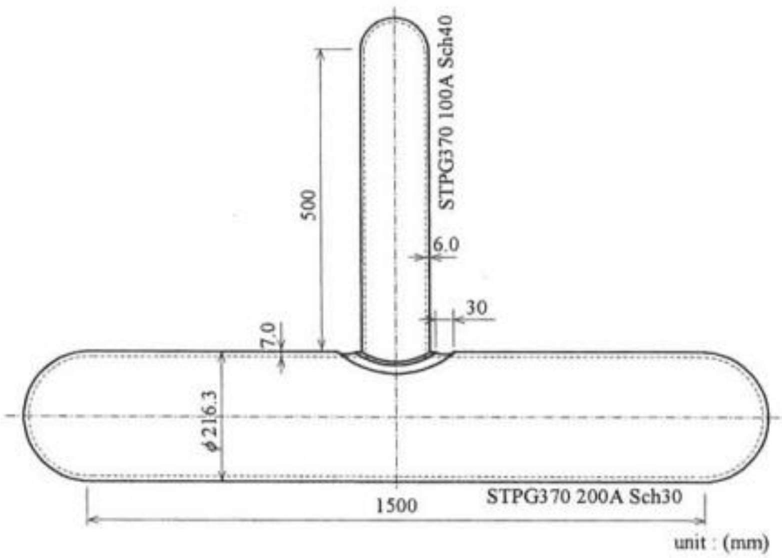


Figure 3.2 Geometries of test tee pipe and grinded metal loss [21]

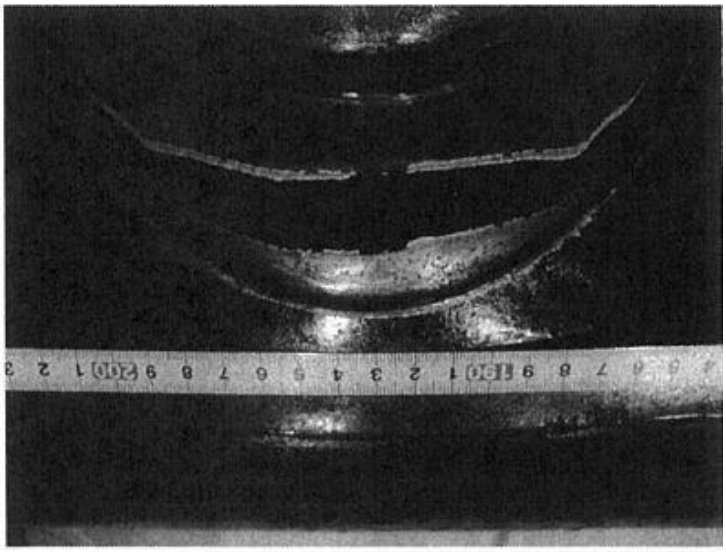


Figure 3.3 Results of Yamauguchi's experiments. Breakage located at the center of bottom surface of metal loss [21]

3.2.2 Conclusion from experimental result

In his experiment, the experimental result is compared to the *MAWP* evaluated by API standard. The *MAWP* of this test tee pipe is 2.6MPa which coincidently equals to design internal pressure. The safety margin of P_{bc} /*MAWP* of this test pipe is more than 7.5. All these suggest that the assessment process of API579 produced a conservational evaluation with an unreasonable high safety margin.

3.3 FEM analysis on test tee pipe model

In Yamaguchi's study, due to the high cost, only one case of local metal loss geometry was tested. In order to obtain more sample points about the relationship among P_{bc} and metal loss geometries, material properties, as well as to investigate the application of reinforcement area method on other cases, FEM analysis is considered as a convenience and proper solution.

In this research, a FEM analysis model consistent with test tee pipe in Yamaguchi' experiment was modeled. The reasonableness of this FEM analysis model can be verified by the experiment result.

3.3.1 FEM analysis model, material properties and boundary conditions

Solid works 2014, *Hypermesh 13.0* and *ANSYS 13.0* are used respectively for building solid model, meshing and FEM analysis. The completed FEM model of the same structure geometries with test tee pipe is element-plotted in ANSYS as shown in Fig.3.4. Half model is used to reduce the computational time. The geometries of model and material are shown in Table 3.2.

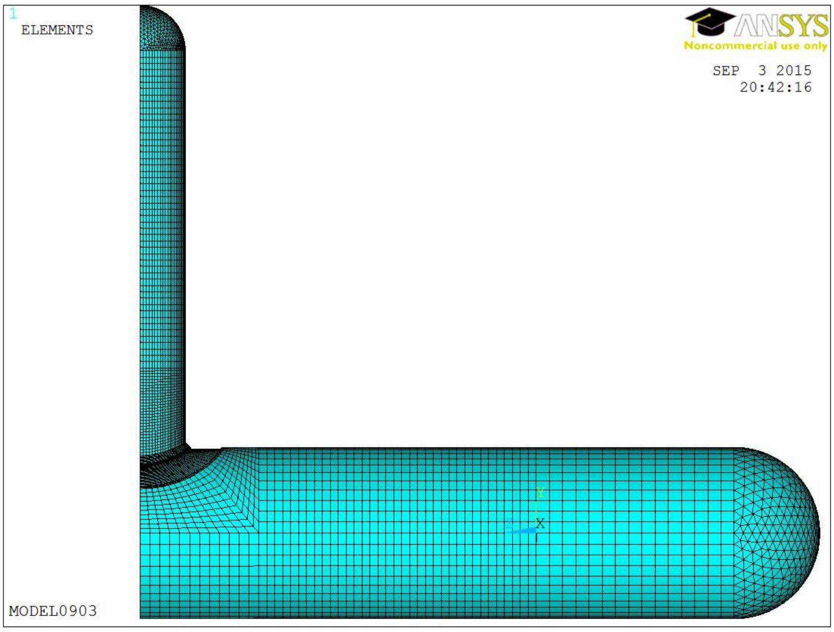


Figure 3.4a Overall view of half model element-plotted in ANSYS

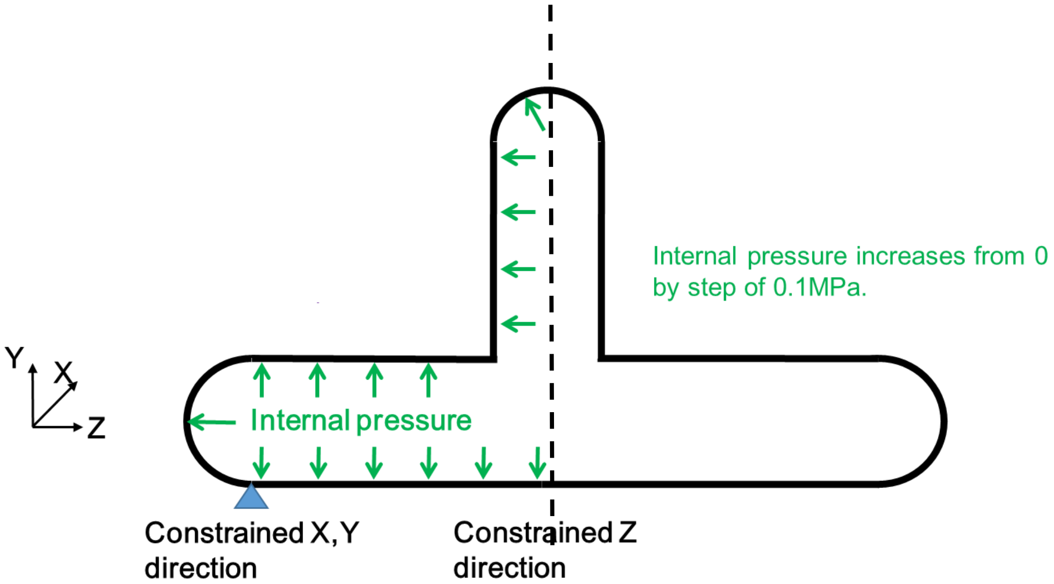


Figure 3.4b stress distributions before the definition of criteria of burst in FEM

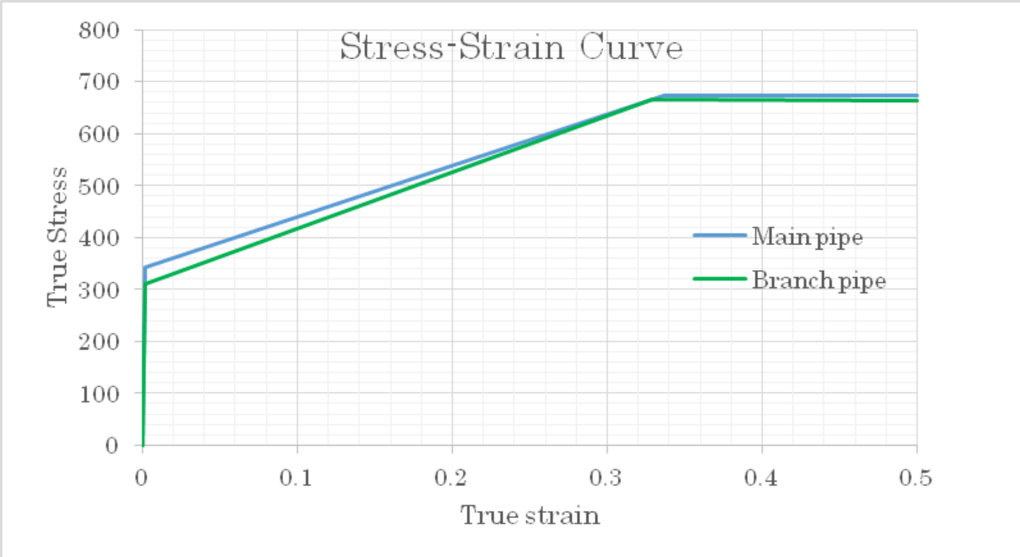


Figure 3.5 Stress-Strain curves used in FEM analysis

Table 3.2 Analytical geometries and material of FEA model

	Parameters
Material	STPG370
Geometries of Main pipe	200A Sch 30 Outer Diameter 216.3mm; Thickness 7.0mm; Length (half): 1500mm
Geometries of branch pipe	100A Sch40 Outer Diameter 114.3mm; Thickness 6.0mm; Length 500mm

The material properties are defined as: density is 7.9g/cm3; Young's modulus is 201GPa; Poisson's ratio is 0.3; yield stress of the main pipe is 343MPa, that of branch pipe is 311MPa; True tensile strength of the main pipe is 671.1MPa, that of branch pipe is 666.3MPa. The stress-strain curves of main pipe and branch pipe are defined as trilinear shown in Fig 3.5. After reaching the tensile strength, the material is assumed to entry on a rigid plasticity state and stress becomes a horizontal line.

Periodic boundary condition is given to this half model. Internal pressure is loaded on the inner surface of main pipe and branch pipe, and the pressure increases by steps (step length=0.1MPa).

3.3.2 Definition of critical state of burst in FEM analysis

Dashpot element is applied to the elements on the FEM model. The burst is defined as the maximum of plasticity instability, which is measured by the normalized energy of dashpot element. The Fig3.6 shows the stress distribution at the metal loss (width 30mm,depth 4.5mm) when a) a few nodes reach yield stress, b) all cross section reach yield stress, c) a few nodes reach tensile strength. d) all cross section reach tensile strength, and this is the timing that the FEM analysis model reaches the maximum of plasticity instability. At this moment, the normalized energy of dashpot element increased extremely fast. By this measurement, the burst pressure of FEM model can be recorded.

3.3.3 Verification of reasonableness of FEM analysis model by experimental results

The value of burst internal pressure from FEM analysis is 19.1 MPa, and it is nearly consistent with the experimental result 19.7 MPa. This proved the reasonableness of the FEM analysis model and the burst criteria.

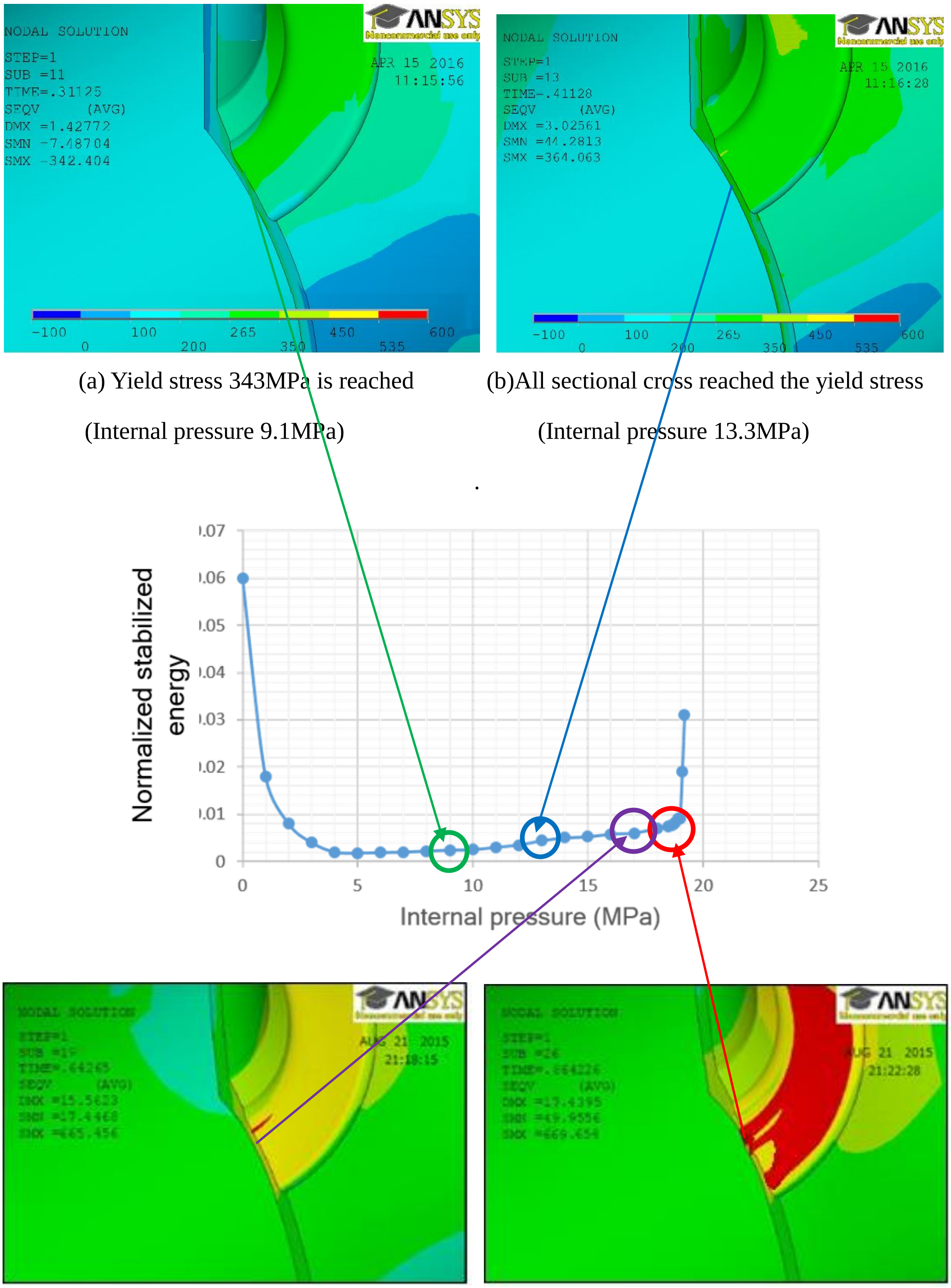
3.3.4 FEM analysis for varied geometries of metal loss

Since the reasonableness has been verified, it is accurate and efficient to apply FEM analysis to calculate the P_{bc} for the other cases with different input variables. The P_{bc} has dependence on several variables, however it is difficult to perform analysis for all variables. Therefore before performing analysis, it is important to identify the variables having high influence on P_{bc}.

In Mogami's research [15], he investigated the dependence of P_{bc} on geometry dimension regarding dimeter of straight pipe and the size of metal loss. He concluded that, the width and depth of metal loss have the greatest influence on the P_{bc}. Referencing his results, the metal loss's width and depth are regarded as input variables in this research. The values of input width and depth are shown in Table 3.3.

Table 3.3 Input metal loss geometries for calculation of P_{bc}

Variables	Values
Width (mm)	10, 20, 30, 40 (mm)
Depth (mm)	1, 1.5, 2.5, 3.5, 4.5 (mm)



(a) Yield stress 343MPa is reached (Internal pressure 9.1MPa)

(b)All sectional cross reached the yield stress (Internal pressure 13.3MPa)

(c)Tensile strength 664MPa is reached (Internal pressure 16.8MPa)

(d)All sectional cross reached the tensile stress (Internal pressure 19.1MPa)

Figure 3.6 stress distributions before the definition of criteria of burst in FEM

The P_{bc} calculated by FEM analysis for various cases of input metal loss geometries are shown in Table 3.4. In Fig 3.7, calculated values of P_{bc} are plotted against the metal loss depth, and curves in different colors show the values of P_{bc} for different cases of metal loss width. It can be observed that, the value of P_{bc} changes with both metal loss width and depth. The P_{bc} of tee pipe decreases when the metal loss is in larger geometries.

3.3.5 Comparison between MAWP evaluated by API579 standard and P_{bc} calculated by FEM analysis

In order to investigate the applicability of API579 standard, the MAWP evaluated by API579 for each case above is compared with the P_{bc} calculated by FEM analysis. The values of MAWP are shown in Table 3.5 and the comparison results are shown in Fig.3.8.

It can be observed that, in each figure, the P_{bc} calculated by FEM analysis is much greater than MAWP evaluated by API579. The least ratio of P_{bc} to MAWP is 6.2 units which is shown in Fig 3.8 (d) when the depth reaches 4.5mm. This indicates that, for the cases of metal loss investigated in this research, the MAWP by API579 is a over-conservative value to evaluate the safety margin. It is also observed that, the changes of P_{bc} occur noticeably when the depth of metal loss changes, while the MAWP evaluated by API579 barely changes with the metal loss changes. It indicates that the MAWP evaluated by API579 cannot guarantee a certain level of safety margin. If the metal loss progresses to an extremely huge size, the MAWP by API579 might become invalid and produce an opposite result.

Table 3.4 Burst internal pressure calculated by FEM analysis

for various metal loss width and depth (Tensile strength =671MPa)

Case No	Width of metal loss (mm)	Depth of metal loss (mm)	P_{bc} (MPa)
1	10	1	33.5
2	10	1.5	32.9
3	10	2.5	31.7
4	10	3.5	27.6
5	10	4.5	23
6	20	1	33.0
7	20	1.5	32.3
8	20	2.5	30.1
9	20	3.5	25.4
10	20	4.5	21.7
11	30	1	31.6
12	30	1.5	30.2
13	30	2.5	27.4
14	30	3.5	23.5
15	30	4.5	19.1
16	40	1	29.8
17	40	1.5	28.1
18	40	2.5	24.7
19	40	3.5	20.1
20	40	4.5	18.2

Table 3.5 Values of MAWP evaluated by API579 process for case 1~20

Case No.	MAWP by API579 (MPa)	Case No	MAWP by API579 (MPa)
1	6.8	11	6.4
2	6.7	12	6.1
3	6.5	13	5.5
4	6.3	14	4.9
5	6.1	15	4.4
6	6.6	16	6.2
7	6.4	17	5.8
8	6.0	18	5.0
9	5.6	19	4.3
10	5.2	20	3.5

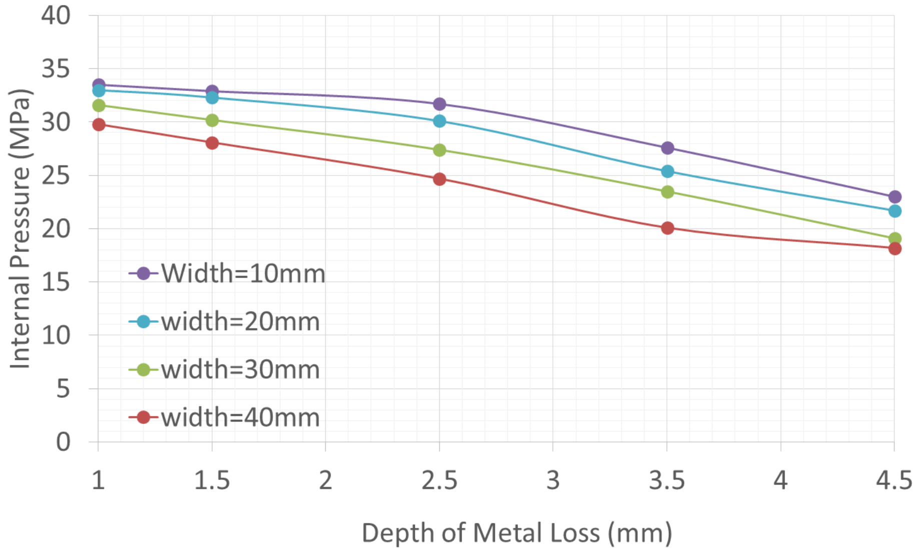
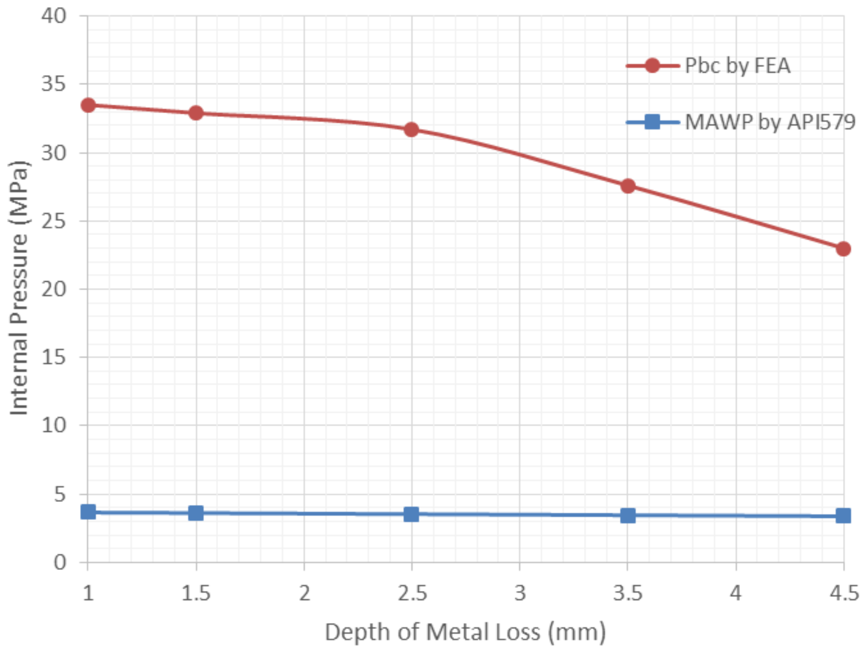
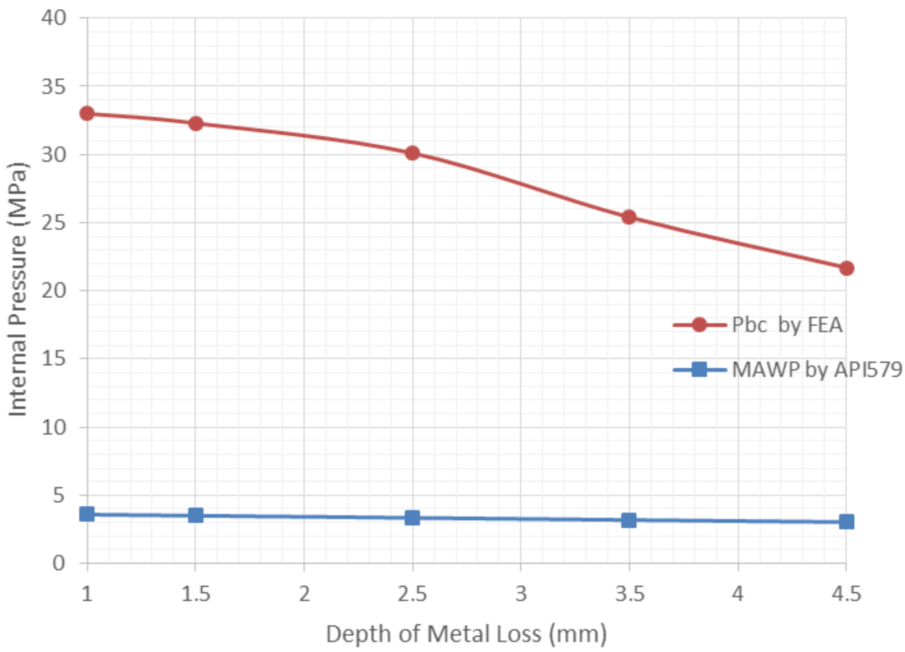


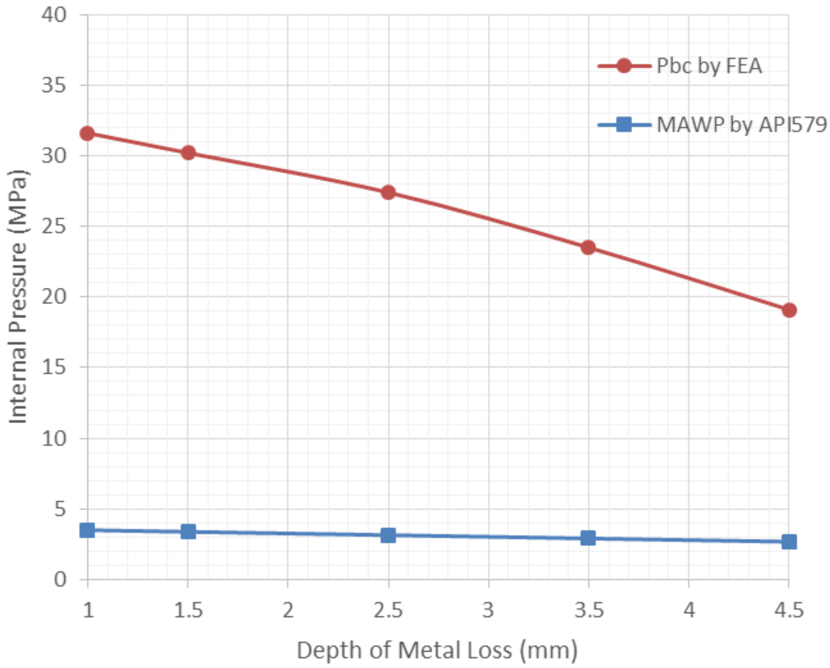
Figure 3.7 Relation between P_{bc} and depth of metal loss for deferent width of metal loss



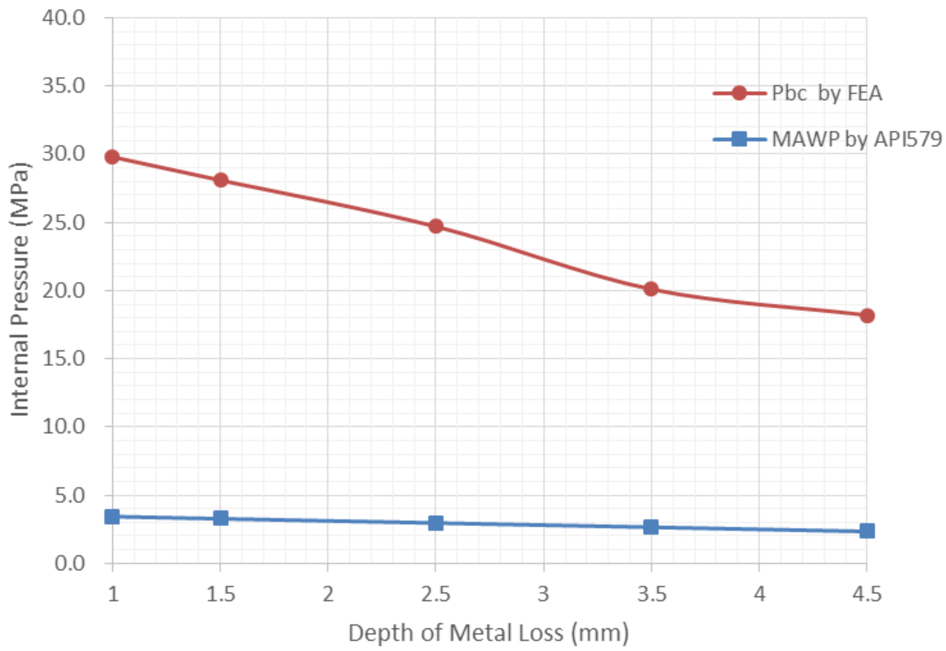
(a) Width of metal loss = 10 mm



(b) Width of metal loss = 20 mm



(c) Width of metal loss = 30 mm



(d) Width of metal loss = 40 mm

Fig 3.8 Comparison between P_{bc} and MAWP that calculated by FEA and API579 respectively.

3.3.6 FEM analysis for varied tensile strength

The tensile strength is also acknowledged as an important factor which has great influence on P_{bc}. Therefore, in this research, tensile strength is also regarded as an input variable. Since this research is focusing on a concrete model of tee pipe, thus the diversity of material is not considered. The varied values of tensile strength are used to investigate the influence of uncertainty of material property on P_{bc}. Therefore, two cases of tensile strength with a ±20MPa deviation from mean value were added to the FEM analysis. The results are shown in Table 3.6 and Table 3.7.

3.4 Summary and Conclusions

In chapter 3, nonlinear FEM analysis is performed to calculate the burst internal pressure of a tee pipe model, which contains local metal loss. The calculated P_{bc} are compared to the MAWP evaluated by API579. The conclusions are as follows.

1. The reasonableness of the FEM analysis model used in this research is verified by comparing with the experiment result of Yamaguchi's research.
2. The assessment process of pipe provided in API579 cannot quantify the remaining safety margin for the pipe containing local metal loss at discontinuity. It might produce over-conservative assessment result, which leads to unnecessary maintenance cost.

Table 3.6 Burst internal pressure calculated by FEM analysis

for various metal loss width and depth

(Tensile strength =690MPa)

Width (mm)	Depth (mm)	P_{bc} (MPa)		Width (mm)	Depth (mm)	P_{bc} (MPa)
10	1	34.5		30	1	32.5
10	2.5	32.6		30	2.5	28.1
10	3.5	28.4		30	3.5	24.1
10	4.5	23.5		30	4.5	19.5
20	1	34.0		40	1	30.7
20	2.5	31.0		40	2.5	25.3
20	3.5	26.1		40	3.5	20.5
20	4.5	22.2		40	4.5	18.5

Table 3.7 Burst internal pressure calculated by FEM analysis

for various metal loss width and depth

(Tensile strength =650MPa)

Width (mm)	Depth (mm)	P_{bc} (MPa)		Width (mm)	Depth (mm)	P_{bc} (MPa)
10	1	32.0		30	1	30.2
10	2.5	30.3		30	2.5	26.2
10	3.5	26.4		30	3.5	22.5
10	4.5	22.0		30	4.5	18.3
20	1	31.6		40	1	28.5
20	2.5	28.8		40	2.5	23.6
20	3.5	24.3		40	3.5	19.2
20	4.5	20.8		40	4.5	17.4

Chapter 4. Reliability Assessment

4.1 Introduction

In chapter 3, it is concluded that, the recent assessment process provided in API579 cannot produce an accurate evaluation of remaining safety margin for pipe containing local metal loss at discontinuity. In order to quantify the remaining safety margin, it is necessary to apply probabilistic reliability analysis in the metal loss assessment.

In chapter 4, through performing reliability analysis on a concrete physical model, an example reliability based on assessment process is proposed. The exampled model of tee pipe is very much typical pipe branch that widely used in chemical plant, so the limit state function, safety check expression and partial safety factors developed in this research are also proposed.

4.2 Definition of limit state function

4.2.1 Response surface of P_{bc}

In chapter 3, FEM analysis are performed on 52 cases for various input of metal loss width, depth and tensile strength. The calculated P_{bc} are shown in Table 3.4, Table 3.6, and Table 3.7. With these sample points, it is possible to explorer the relationships between P_{bc} and geometries of metal loss, tensile strength.

For a better applicability and convenient to compare with the standard, the depth of metal loss is substituted by remaining thickness in chapter 4 and chapter 5. The remaining thickness is calculated by total thickness subtracting metal loss depth.

In this research, 2nd order polynomial regression is used to fit the nonlinear relationship between the values of input variables in FEM analysis and values of the calculated P_{bc}. The explored function is shown in Eq. 4-1. R^2 of this regression is 0.9833, which is in a very high level, and indicates the successful of our model.

$$\begin{aligned} P_{bc} &= P\left(s_m, t_m, \sigma_{ts}\right) \\ &= -200.56 + a_1 s_m + a_2 t_m + a_3 \sigma_{ts} \\ &\quad + b_1 s_m t_m + b_2 s_m \sigma_{ts} + b_3 t_m \sigma_{ts} \\ &\quad + c_1 s_m^2 + c_2 t_m^2 + c_3 \sigma_{ts}^2 \end{aligned} \qquad \text{Eq.(4-1)}$$

$$\begin{array}{lll} a_1 = 0.128; & a_2 = 0.959; & a_3 = 0.609; \\ b_1 = 1.595\times10^{-2}; & b_2 = -4.247\times10^{-4}; & b_3 = 7.492\times10^{-3}; \\ c_1 = -2.075\times10^{-3}; & c_2 = -3.51\times10^{-1}; & c_3 = -4.354\times10^{-4}; \end{array}$$

where the s_m is the width of local metal loss, the t_m is the main pipe remain thickness, and the σ_{ts} is the tensile strength.

Figure 4.1 shows comparison between predicted value of P_{bc} by Eq.4-1 and the sample values of P_{bc}. The horizontal axis is the sample values calculated by FEM analysis that will explained with details in the last chapter, and the vertical axis are the fitted values by Eq.4-1. It is observed that the plots are located near the y=x line, which indicates the fitted values are nearly consistence with the calculated values. Without performing the FEM analysis, it is possible to predict an accurate values of P_{bc} by Eq.4-1.

4.2.2 Definition of limit state function

The failure model defined in this research is the burst of the pipe. It happens when the cross section of pipe thickness reach the tensile strength. In chapter 3, the internal pressure when plasticity burst happens is defined as a P_{bc}. So the limit state is the condition when working pressure reaches the value of P_{bc}. Therefore, the limit state function is defined as following in Eq.(4-2)

$$g = P_{bc} - P_{applied} \qquad \text{Eq.(4-2)}$$

Burst pressure P_{bc} represents the maximum of resistance to fracture, and P_w represents the load. The $P_{applied}$ can be the load of normal working pressure or a transient load during accident, then this limit state function can be used for different purposes of evaluations. In this research, to develop a maintenance method of piping evaluation for chemical industries, only the case of normal working condition ($P_{applied}$ = P_w) is investigated.

In 4.2.1, a function showing the relationship between P_{bc} and input variables is obtained by the polynomial regression. These input variables contain regarding metal loss width, main pipe remain thickness and tensile strength which can be directly measured. The limit state function is converted to Eq.4-3

$$g = P\left(s_m, t_m, \sigma_{ts}\right) - P_W \qquad \text{Eq.(4-3)}$$

where the expression of $P\left(s_m, t_m, \sigma_{ts}\right)$ is showed in Eq.(4-1).

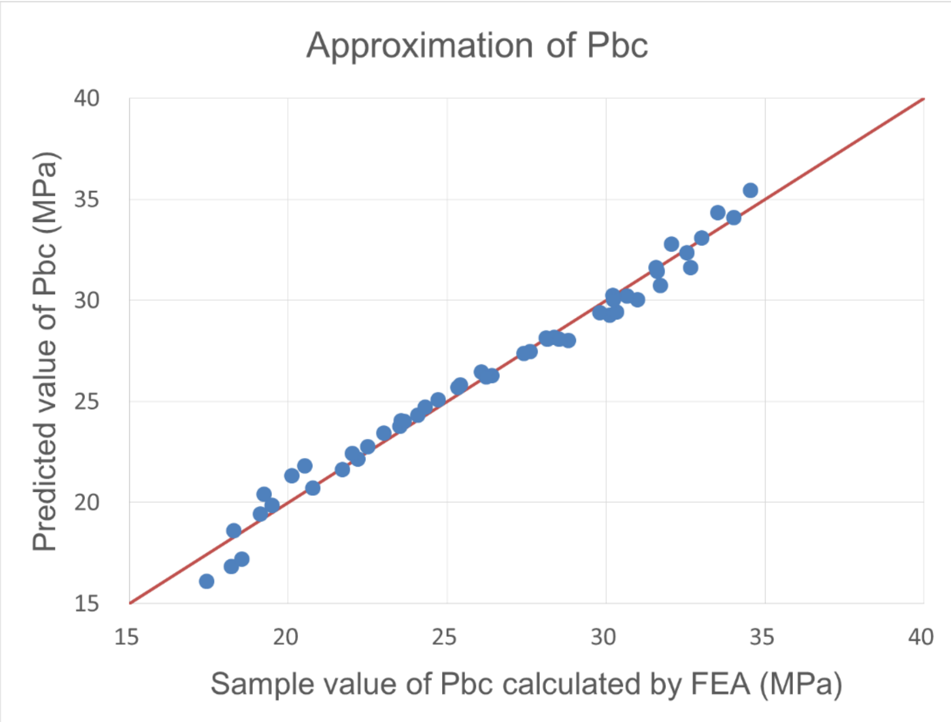


Figure 4.1 Accuracy of approximation of P_{bc}

4.3 Probabilistic distributions of variables

In this research, metal loss width, main pipe remain thickness, tensile strength and working pressure are treated as random variables. The probabilistic properties are shown in Table 4.1.

In D.N. VERITAS' research, the tensile strength of Japan's STP carbon steel material has been tested and recorded. It is found the, the STP carbon steel has small variation, and it is less than 5% of its nominal value. In this research, the COV of tensile strength referred from D.N.VERITAS' paper [23].

In different chemical plants and for different performances, the internal pressure of pipes or vessels is managed for different level. However, most of the cases, the internal pressure are managed very carefully and precisely during normal operating. According to investigation, the average deviation level of working pressure is 0.03. The internal pressure by operating-mistakes or during accident are not considered in this research.

4.4 Target reliability level adopted in API579

In this research, target reliability levels are referred from API579. Three levels of target reliability are adopted in API579 to satisfy the different requirements of safety. The values of β and corresponding values of Pf are given in Table 4.2. The highest level of reliability is 4.75, and the corresponding Pf is 10^{-6}.

In risk management, the risk is defined as the impact multiplies failure frequency. The failure frequency can be shown by the probability of failure calculated from reliability analysis. Therefore, from the aspect of risk management, the reliability level should be determined by its impact to surrounding when the structure failed. For piping in chemical plants, the reliability level is generally determined by dangerous level of the carrying fluid. In HPIS Z 109TR [28], a guidance to be published of metal loss assessment developed by High Pressure Institute of Japan (HPI), the reliability level of piping is divided into 2 levels showing in Table 4.3a. According to the explanation, the pipe carrying the toxic or flammable fluid should be maintained for higher safety level.

On the other hand, for those structures with huge impacts, the reliability level should be decided after open discussion by stakeholder related. It is a not only a structural safety issue of engineering, but also a social issue involving plenty of citizens.

Table 4.1 Probabilistic properties of variables in modeling of the limit state

Variable	Distribution	Mean value	COV
Main pipe remain thickness t_m (mm)	Normal	6, 4.5, 3.5, 2.5	0.1
Metal loss width s_m (mm)	Normal	10, 20, 30, 40	0.1
Material tensile strength (MPa)	Weibull	670	0.05
Working pressure (MPa)	Gumbel	Changeable value	0.03

Table 4.2 Target Reliability Levels adopted in API579

	Probability of failure	Reliability index
Low safety level	2.3×10^{-2}	2.00
Medium safety level	10^{-3}	3.09
High safety level	10^{-6}	4.75

Table 4.3a Target Reliability Levels adopted in HPIS Z 109TR [28]

Reliability class	Probability of failure	Reliability index
Low safety level	10^{-4}	3.72
High safety level	10^{-6}	4.75

Table 4.3b Reliability level explanations [28]

Reliability class	Explanations
Low safety level	Even the internal fluid was leaked with the breakage, there is no such toxicity or flammability, safety treatments are possible
High safety level	The internal fluid with high degree of influence was leaked with the breakage, and spreading around

4.5 Reliability level of MAWP by API579

In chapter 3, a comparison between MAWP evaluated by API579 and P_{bc} calculated by FEM analysis was performed. It showed that the safety margin ($P_{bc}/MAWP$) is too high.

In this chapter, the reliability level of the MAWP by API579 is investigated. The MAWP is applied as the working pressure, and the limit state function is defined as follows.

$$g_{API579} = P(s_m, t_m, \sigma_{ts}) - MAWP \qquad \text{Eq.(4-4)}$$

First order reliability is performed to evaluate the reliability index of the MAWP for different cases of input mean values of width and main pipe remain thickness. The results are shown in Table 4.3.

It is observed that the reliability index is much beyond the highest target reliability level for most of the cases. And at the same time, it shows the unreasonable high reliability level of MAWP, which is evaluated by API579.

4.6 Reliability contour curves

It is very convenience to use reliability contour curves on failure assessment diagram to evaluate the satisfaction of reliability level. Figure 4.2 shows a failure assessment diagram, which contains three target reliability contour curves. These reliability contour curves are calculated for the cases when metal loss width equals to 30mm. Though changing the mean value of working pressure in Eq.4-2, it is able to search the maximum value of working pressure, of which the corresponded reliability satisfies the target reliability. This maximum value of working pressure is recorded and plotted on the diagram. The flow chat of this approach is shown in Fig. 4.3.

In Fig.4.2a), the purple curve shows the limit state when Eq(4-2) equals 0. If a metal loss is inspected and the standardized width is 30mm and main pipe remain thickness is 3.5, the plotted working pressure shouldn’t exceed the purple curve (23.5MPa). If the plotted working pressure is between β=2.0 contour curve and β=3.09 contour curve, the reliability of this tee pipe is between 2.0 and 3.09.

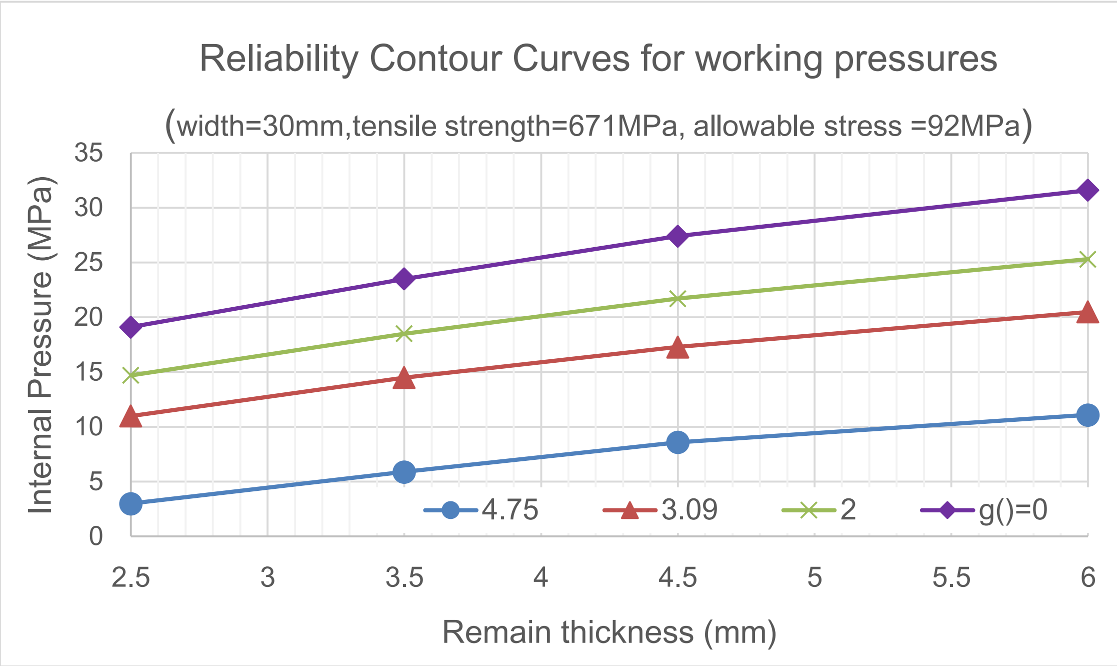


Figure 4.2 (a) Reliability contour curve on a failure assessment diagram. Purple curve is the limit state when g=0; gray curve is β=2.0 contour curve; orange curve is β=3.09 contour curve; blue curve is β=4.75 contour curve.

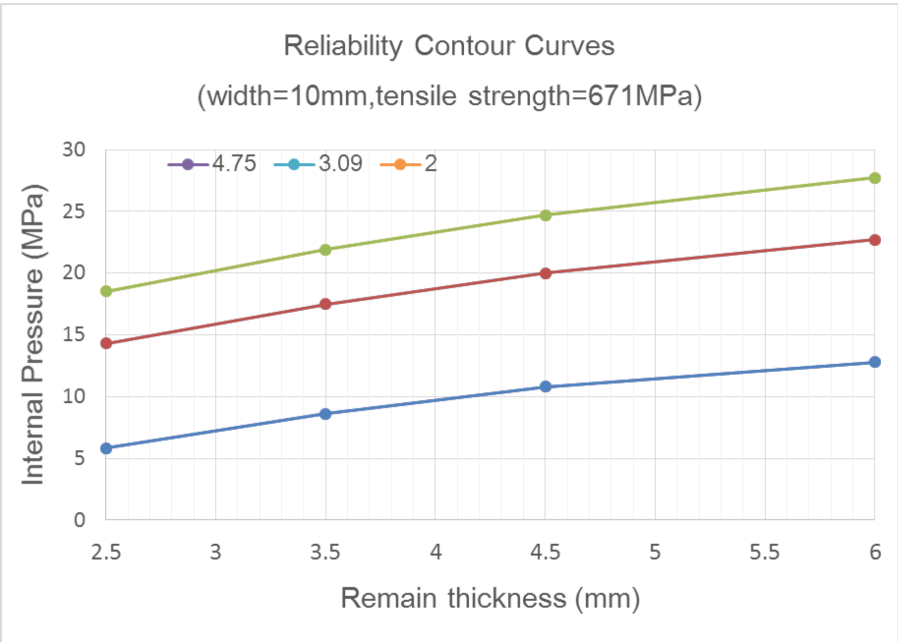


Figure 4.2 (b) Reliability contour curve for different remain thickness of main pipe (metal loss width =10mm)

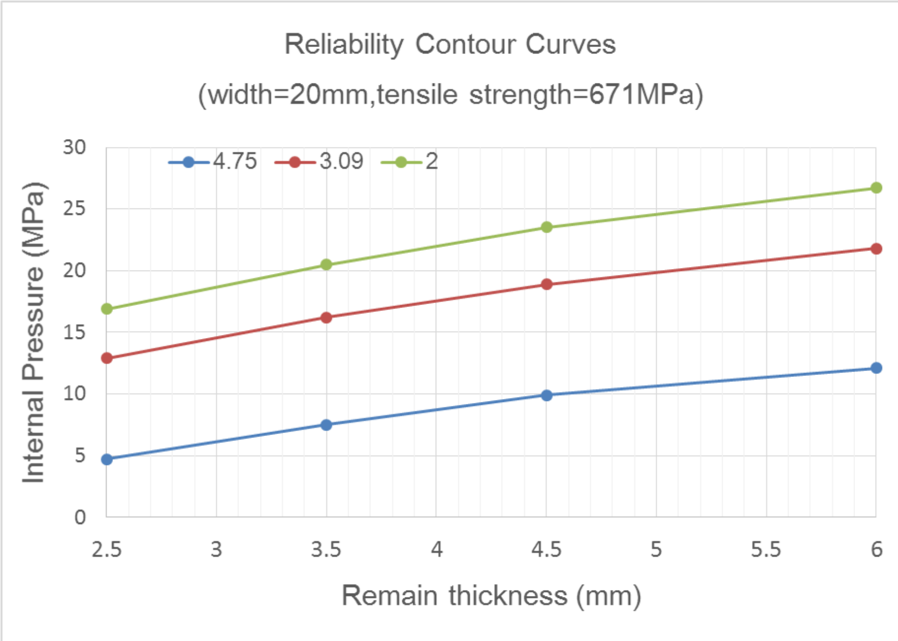


Figure 4.2 (c) Reliability contour curve for different remain thickness of main pipe (metal loss width =20mm)

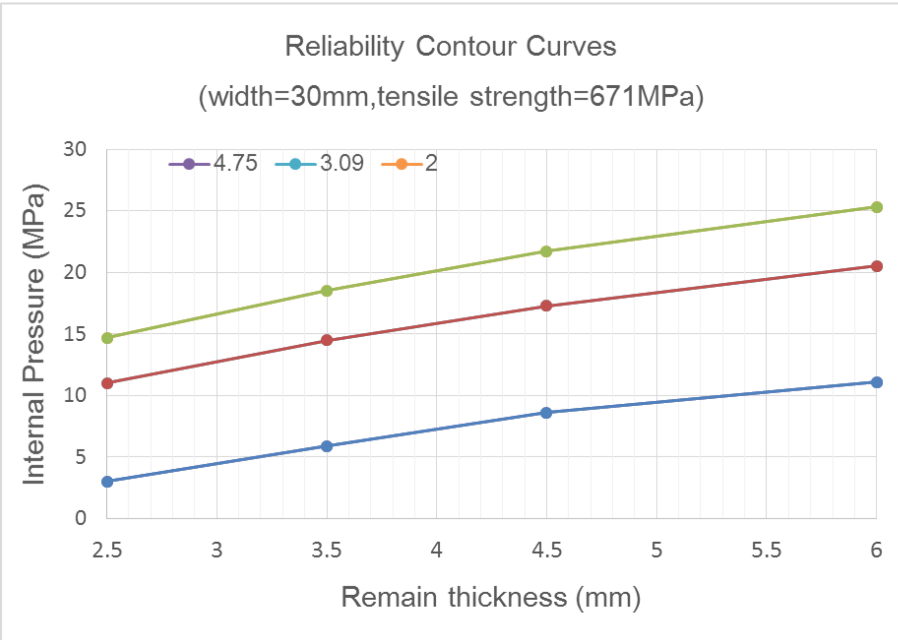


Figure 4.2 (d) Reliability contour curve for different remain thickness of main pipe (metal loss width =30mm)

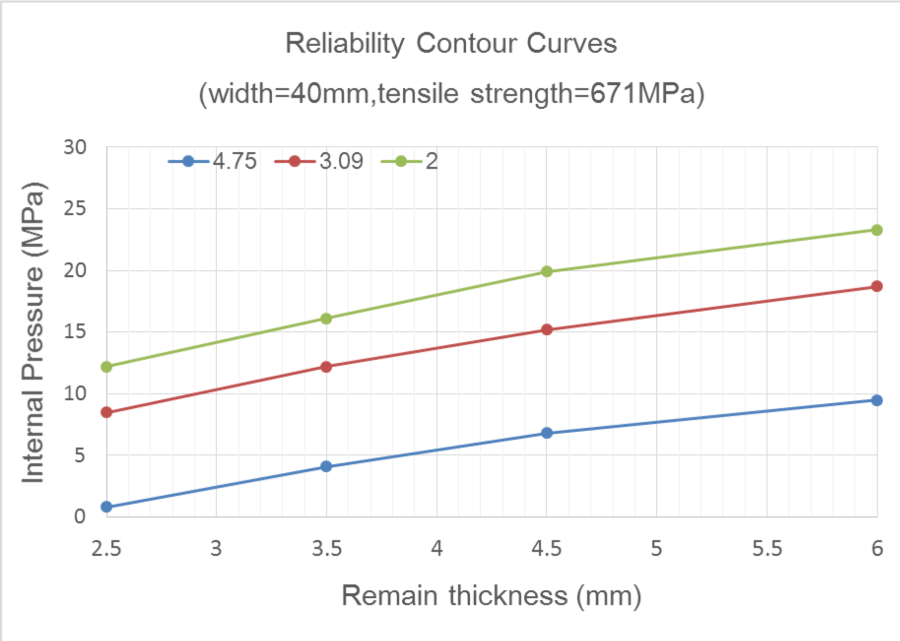


Figure 4.2 (e) Reliability contour curve for different remain thickness of main pipe (metal loss width =40mm)

4.7 Safety check expression and Partial Safety Factors of selected target reliability level

For different geometries of metal loss, the reliability contour curves are different. The various reliability contour curves can be represented by one expression, and this kind of expression is the safety check expression.

In this research, a safety check expression for the example tee pipe containing local metal loss is proposed and it is shown as Eq.4-5

$$P\left(s_{mm} \cdot PSF_s , \frac{t_{mm}}{PSF_t} , \frac{\sigma_{tsm}}{PSF_\sigma} \right) \geq P_{Wm} \cdot PSF_P \qquad \text{Eq.(4-5)}$$

Where the PSF_S, $PSF_{t,}$, PSF_σ, PSF_P are the partial safety factors (PSF) and the s_{mm}, t_{mm},σ_{mm} and P_{Wm} are the nominal values of metal loss width, main pipe remain thickness, tensile strength and working pressure. With this proposed safety check expression and calculated partial safety factors, the evaluation of reliability region of example tee pipe that contains metal loss becomes available.

The partial safety factors are also productions of approaches shown in Fig.4.3. The partial safety factors are calculated for each level of reliability in Table 4.2 and each case of metal loss geometries in Table 4.1. The results are shown in table 4.3.

Figure 4.3 shows the changes of PSF along with the width of metal loss. It is observed that the partial safety factor of tensile strength has a highest value, and isn't influenced by the changes of geometries of metal loss. The partial safety factor of main pipe remain thickness has second highest value, and it starts to decrease when main pipe remain thickness becomes higher than 4.5mm. By comparing (a) with (d), it is observed that the partial safety factor of metal loss width is proportional to its mean value. The partial safety factor of working pressure stays very low value and doesn't change along with the geometries of metal loss.

Figure 4.4 shows the changes of PSF along with the width of metal loss. It is observed that only the partial safety factor of metal loss width changes noticeably along with the changes of mean value of metal loss, and a further noticeable increase starts from the point when metal loss width reaches the value of 20mm in both cases.

Figure 4.5 shows the changes of PSF along with chosen target reliability level. It is observed in both (a) and (b) that only partial safety factor of tensile strength changes noticeably when the target reliability changes; while partial safety factor of others barely changes with the different target reliability levels.

From these relationships observed, it is reasonable to divide the values of calculated PSF shown in Table 4.3 into 4 parts in accordance with different sizes of metal loss. The boundary values of division are defined as metal loss= 20mm and main pipe remain thickness = 4.5mm respectively. The values of partial safety factors are regenerated and shown in Table 4.4 by taking the average value of PSF in each part. And the examination of this approximation is performed in Chapter 5.

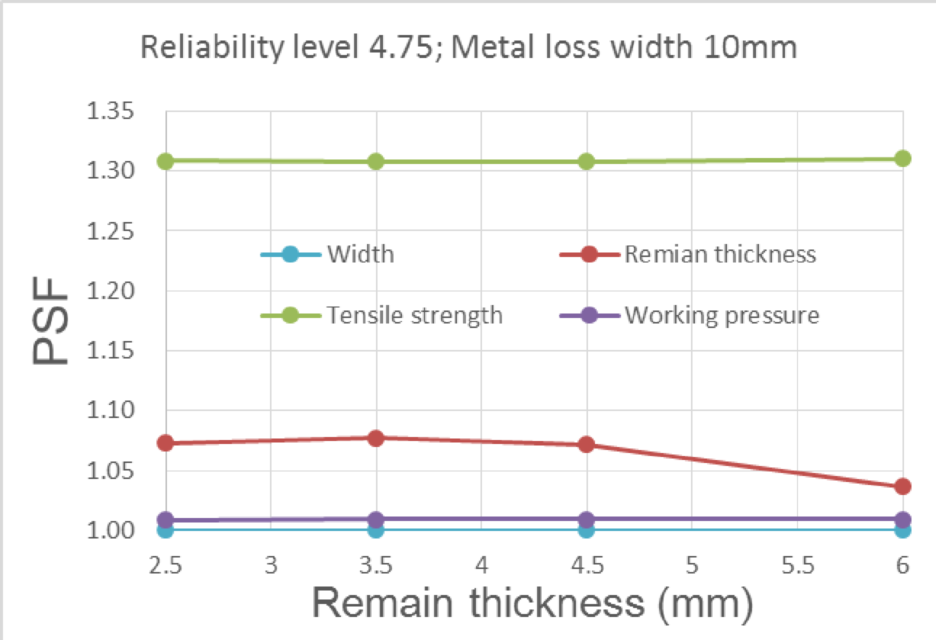
In Fig.4.3, it can be observed that the partial safety factor of remain thickness did not change even remain thickness decreased. This is because the partial safety factor is calculated for each designated reliability level, and it shows the relation between the load and the variable presented. In calculation of PSFs, when remain thickness ratio decreases, the maximum of applied pressure also decreases in order to satisfy the target reliability level. As shown in Fig.2(a), the relation between remain thickness and the maximum pressure which satisfies is near a linear relation. As a result, the safety factor of remain thickness stayed as a stable value even the remain thickness decreased.

4.8 Summary and Conclusions

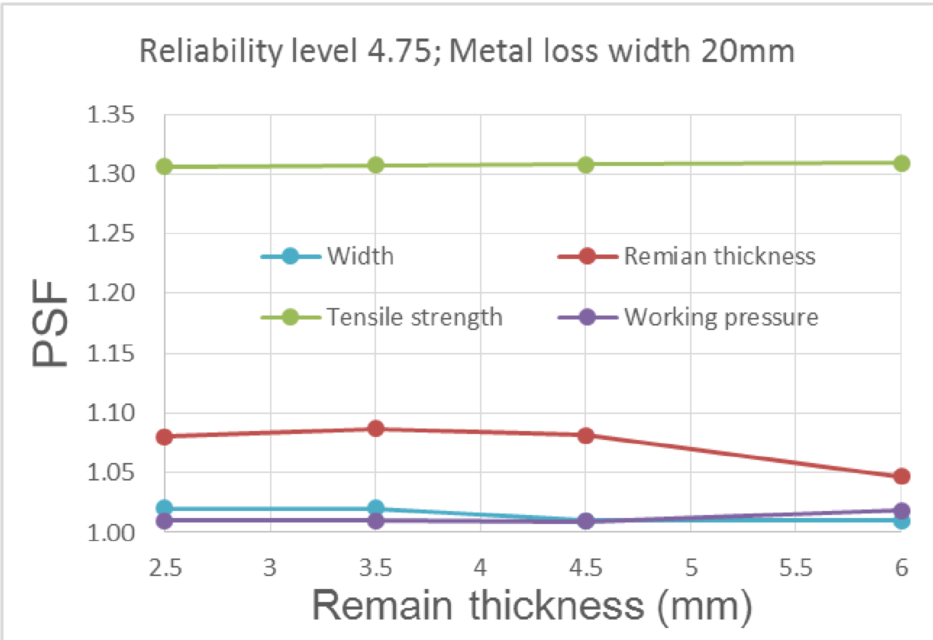
In chapter 4, it is the first time to perform a reliability analysis to develop the reliability based on safety check expression and partial safety factors for the example tee pipe model.

Due to the absence of limit state function, it was impossible to perform the reliability analysis on the pipe containing local metal loss at discontinuity. In chapter 4, the limit state function of the example tee pipe is developed by response surface method, which is performed from using the sampling points calculated in chapter 3. The function fitted by 2nd order polynomial regression is proved to be accurate enough in predicting the burst internal pressure.

In chapter 4, a safety check expression and a group of values of PSF are proposed. This proposal allows us to evaluate the reliability of example tee pipe, which contains different geometrical dimensions of metal loss located at branch.

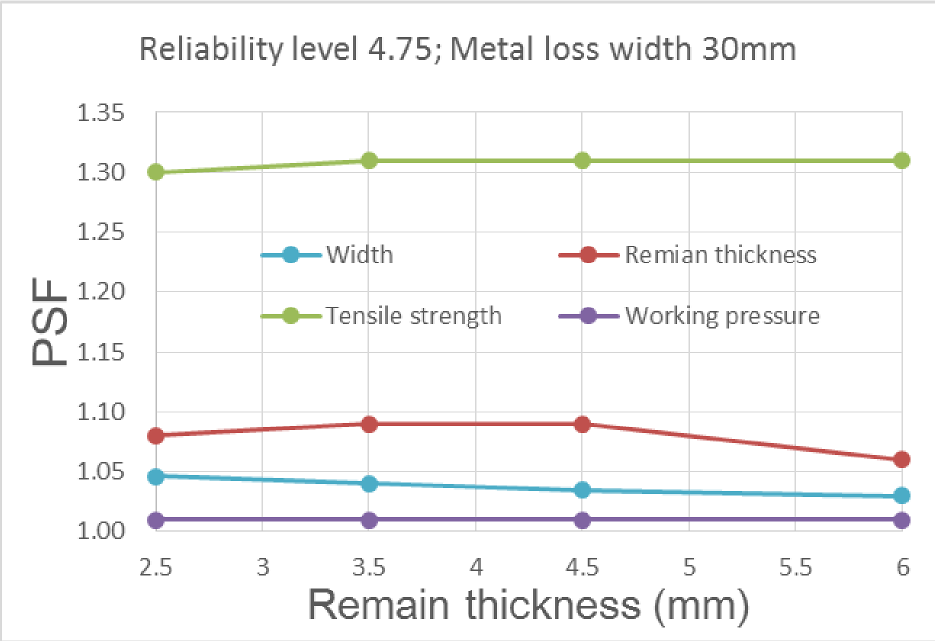


(a) Metal loss width =10mm

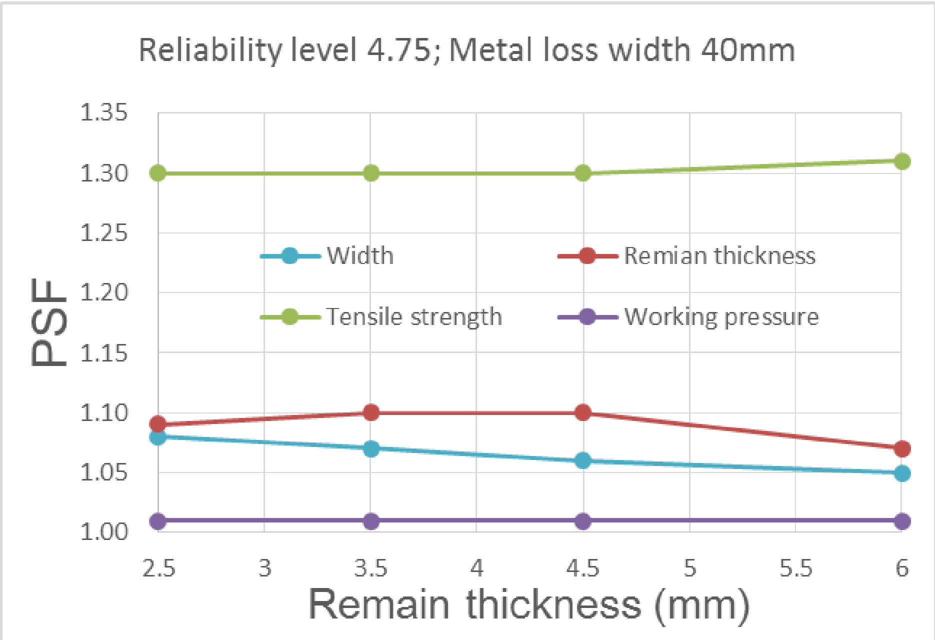


(b) Metal loss width =20mm

Figure 4.3 The relation between PSF and pipe main pipe remain thickness (β=4.75)

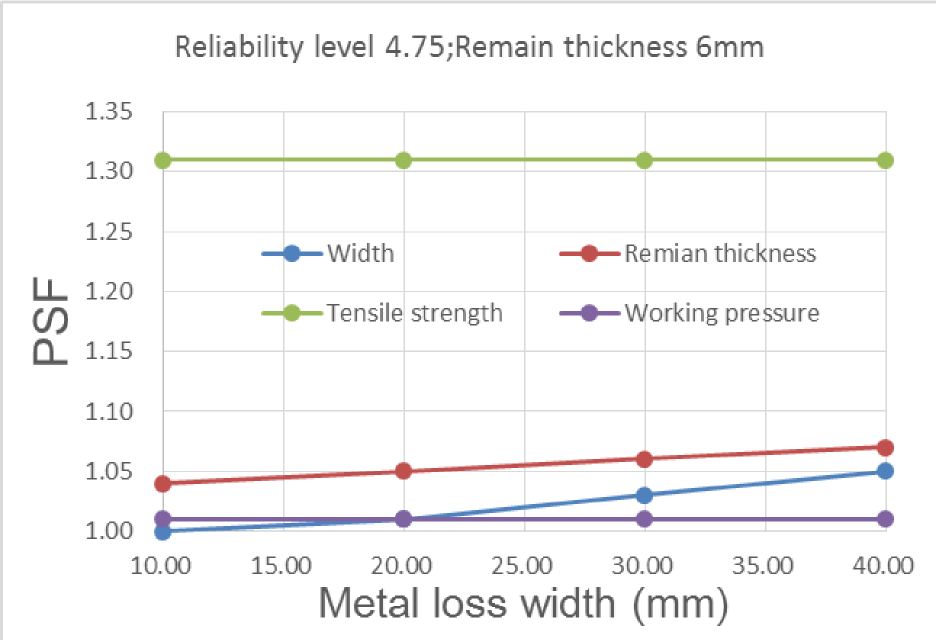


(c) Metal loss width =30mm

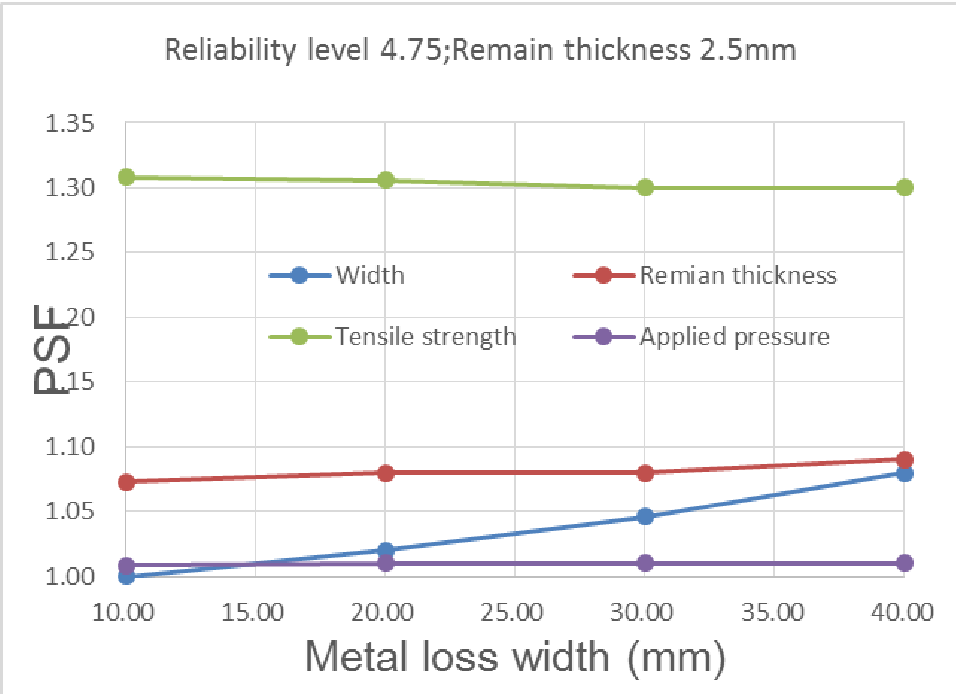


(d) Metal loss width =40mm

Figure 4.3 The relation between PSF and pipe main pipe remain thickness (β=4.75)

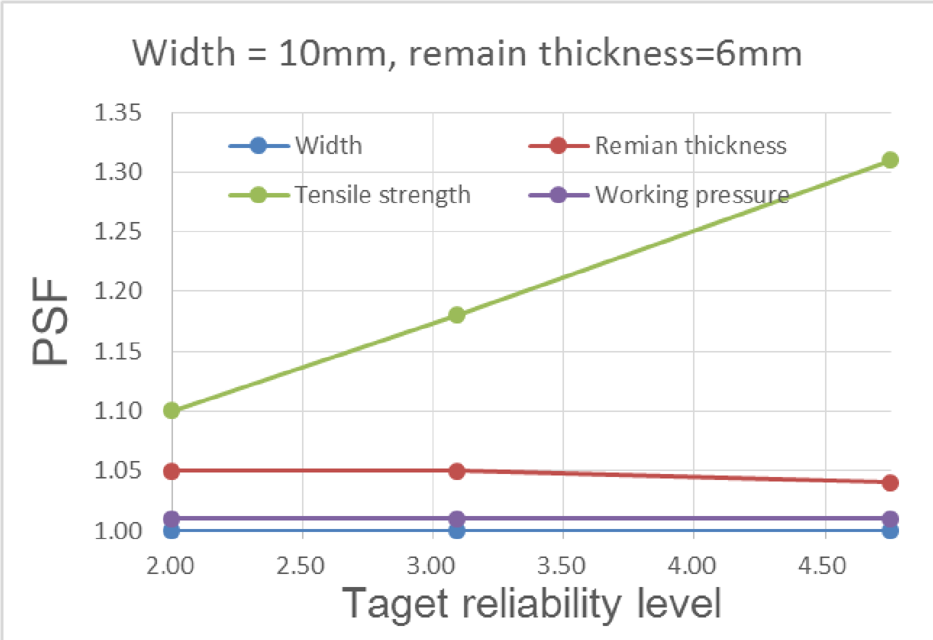


(a) Case of more main pipe remain thickness

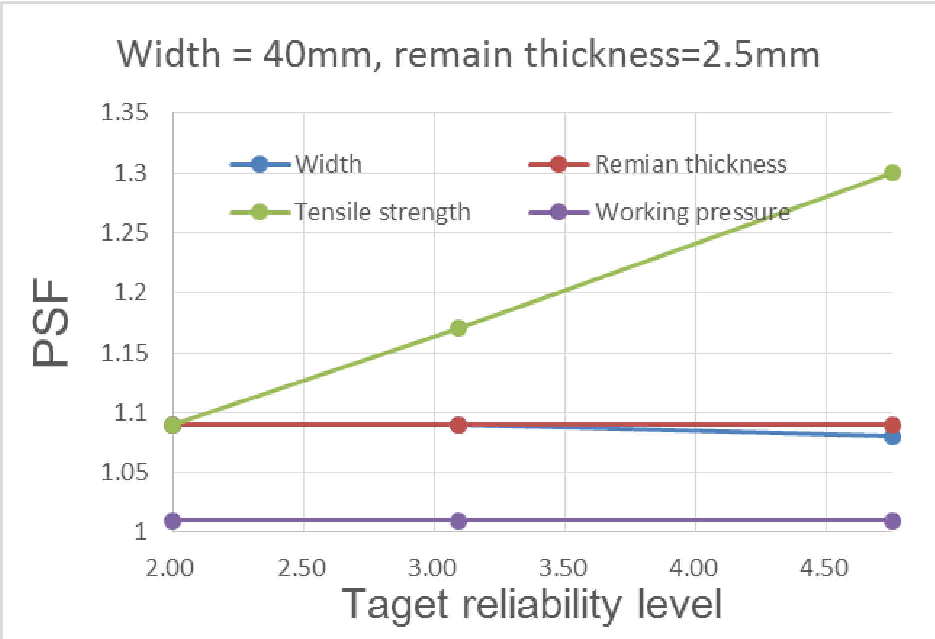


(b) Case of less main pipe remain thickness

Figure 4.4 The relation between PSF and width of metal loss (β=4.75)



(a) Small size of metal loss



(b) Large size of metal loss

Figure 4.5 Relation between PSF and target reliability level

Table 4.3 Calculated Partial Safety Factors for varied geometries of metal loss

s_m	t_m	Reliability level =4.75				Reliability level =3.09				Reliability level =2.0			
		PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P
10	6	1.00	1.04	1.31	1.01	1.00	1.05	1.18	1.01	1.04	1.05	1.11	1.01
10	4.5	1.00	1.07	1.31	1.01	1.00	1.07	1.18	1.01	1.01	1.07	1.11	1.01
10	3.5	1.00	1.08	1.31	1.01	1.00	1.08	1.18	1.02	1.01	1.07	1.10	1.02
10	2.5	1.00	1.07	1.31	1.01	1.00	1.07	1.18	1.01	1.00	1.07	1.11	1.01
20	6	1.01	1.05	1.31	1.02	1.01	1.06	1.18	1.01	1.01	1.06	1.11	1.01
20	4.5	1.01	1.08	1.31	1.01	1.02	1.08	1.18	1.01	1.02	1.08	1.10	1.01
20	3.5	1.02	1.09	1.31	1.01	1.02	1.08	1.18	1.01	1.02	1.08	1.10	1.01
20	2.5	1.02	1.08	1.31	1.01	1.02	1.08	1.18	1.01	1.02	1.07	1.10	1.01
30	6	1.03	1.06	1.31	1.01	1.03	1.07	1.18	1.01	1.02	1.07	1.10	1.01
30	4.5	1.04	1.09	1.31	1.01	1.04	1.09	1.17	1.01	1.03	1.08	1.10	1.01
30	3.5	1.04	1.09	1.31	1.01	1.04	1.10	1.17	1.01	1.04	1.09	1.10	1.01
30	2.5	1.05	1.08	1.30	1.01	1.05	1.09	1.17	1.01	1.04	1.08	1.10	1.01
40	6	1.05	1.07	1.31	1.01	1.05	1.08	1.17	1.01	1.05	1.08	1.10	1.01
40	4.5	1.06	1.10	1.30	1.01	1.06	1.11	1.17	1.01	1.06	1.09	1.10	1.01
40	3.5	1.07	1.10	1.30	1.01	1.07	1.11	1.17	1.01	1.06	1.10	1.10	1.01
40	2.5	1.08	1.09	1.30	1.01	1.08	1.09	1.17	1.01	1.08	1.09	1.09	1.01

Table 4.4 Approximated Partial Safety Factors

s_m (mm)	t_m (mm)	Reliability level =4.75				Reliability level =3.09				Reliability level =2.0			
		PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P
$s_m \leqq 20$	$t_m \geqq 4.5$	1.01	1.06	1.31	1.01	1.01	1.07	1.18	1.01	1.02	1.06	1.11	1.01
	$2.5 \leqq t_m < 4.5$	1.01	1.08	1.31	1.01	1.01	1.08	1.18	1.01	1.01	1.07	1.10	1.01
$20 < sm \leqq 40$	$t_m \geqq 4.5$	1.04	1.08	1.31	1.01	1.05	1.09	1.17	1.01	1.04	1.08	1.10	1.01
	$2.5 \leqq t_m < 4.5$	1.06	1.09	1.30	1.01	1.06	1.10	1.17	1.01	1.06	1.09	1.10	1.01

Chapter 5. Application of Sensitivity Analysis

5.1 Introduction

The probabilistic sensitivity measures the dependence of variation of variables on probability of failure. As introduced in chapter 2, the probabilistic sensitivity can be produced by FORM.

In chapter 5, a sensitivity analysis is performed on the example tee pipe containing local metal loss at discontinuity. It aims to quantify the importance of variations of variables, which contains regarding tensile strength, the geometries of metal loss and working pressure. By neglecting the variation of variable (PSF equals to 1.0) with low sensitivity, it is possible to reduce both the data collecting cost and complexity of safety check expression.

5.2 Results of sensitivity analysis

5.2.1 Relation between probabilistic sensitivity and geometries of metal loss

Figure 5.1 shows the relationship between probabilistic sensitivity and remain thickness of main pipe.

For the tensile strength, it has the greatest sensitivity, and barely changes along with the different geometries of metal loss. It suggests that the tensile strength has the dominant influence on the probability of failure. Both of the amount of data and the accuracy of data in tensile strength is requested in a reliability analysis.

For the main pipe remain thickness, it has second greatest sensitivity, which means remain thickness also has huge influence on the probability of failure. The decrease of sensitivity happens when there is a larger remain thickness of main pipe. This indicates that if the metal loss is shallow, the data of remain thickness becomes less important, and the uncertainties in measurement of remain thickness might not influence the evaluation results. For the width of metal loss, the sensitivity stays a very low value when the metal loss is narrow one. With the increase of nominal value of itself, the sensitivity of width starts to increase and becomes an unneglectable factor. These conclude that when the metal loss is large (deep and wide), it is important to measure the dimension precisely; while when the metal loss is in a small size, a rough measurement is also allowable.

For the working pressure, the working pressure maintains a low level of sensitivity for all the cases. This suggest that the variation of working pressure has too little influence to evaluate the results precisely. It might be possible to neglect the uncertainties in working pressure during normal operation.

5.2.2 Relation between probabilistic sensitivity and reliability level

Figure 5.2 shows the relationship between probabilistic sensitivities and reliability level. It concludes that for the tee pipe, which is requested to maintain a high level of reliability, is important to clarify the uncertainties in tensile strength, and reduce the uncertainties as much as possible.

5.3 Re-definition of safety check expression

As concluded in 5.2.2 that the variation of working pressure has too much little influence on evaluation results, it is possible to treat the working pressure as a constant in the safety check expression. Therefore, the calculation of the partial safety factor of working pressure becomes unnecessary.

Based on the results of sensitivity analysis, in the safety check expression of Eq.(4-5), the PSF_P is 1.0, and it is simplified as

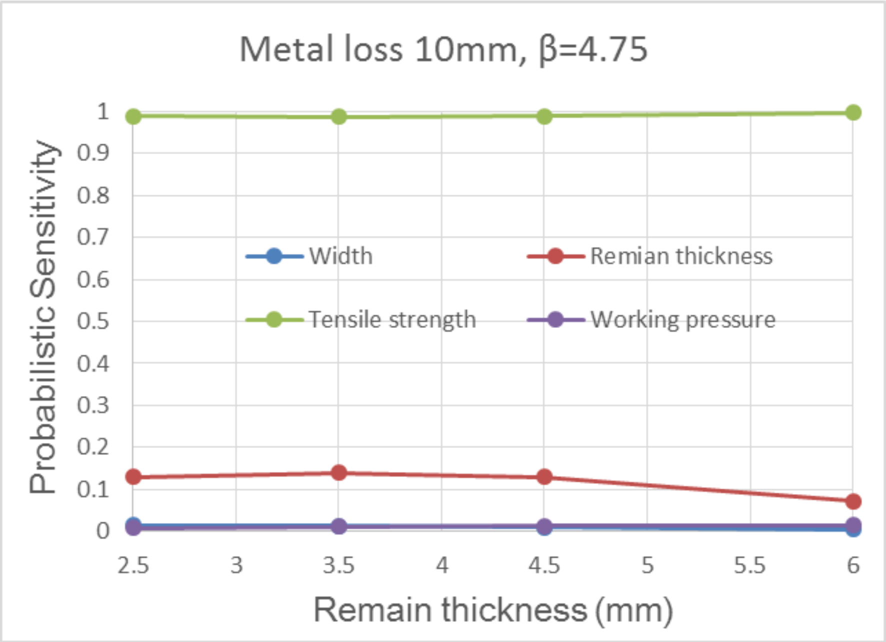
$$P\left(s_{mm} \cdot PSF_s, \frac{t_{mm}}{PSF_t}, \frac{\sigma_{tsm}}{PSF_\sigma} \right) \geq P_{Wm} \qquad \text{Eq.(5-1)}$$

.Reasonableness of the re-defined safety check expression associated with approximate values of PSF is examined in this chapter in Table 4.4.

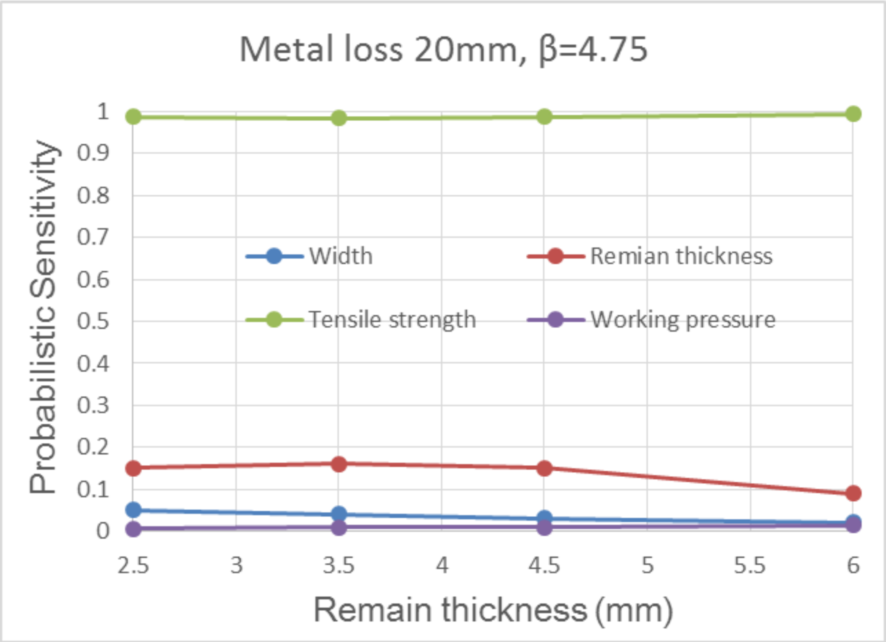
Firstly, the mean values of metal loss width, main pipe remain thickness and tensile strength are putted into Eq(5-1) to calculate the maximum of working pressure satisfying Eq(5-1). This working pressure is recorded as P'_W. Then put the P'_W into the Eq.(4-3) and the limit state function to evaluate the reliability level of P'_W is shown as follow in Eq.(5-2).

$$g = P\left(s_m, t_m, \sigma_{ts}\right) - P'_W \qquad \text{Eq.(5-2)}$$

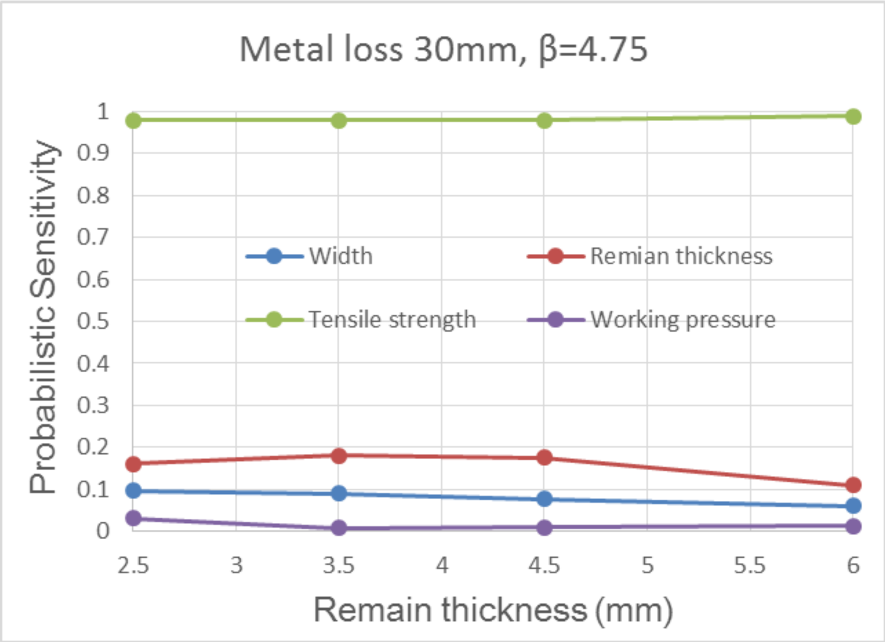
First order reliability method is performed to evaluate the reliability of P'_W. If the reliability is near the target reliability, then the reasonableness of re-defined safety check expression and approximate values of PSF can be proved.



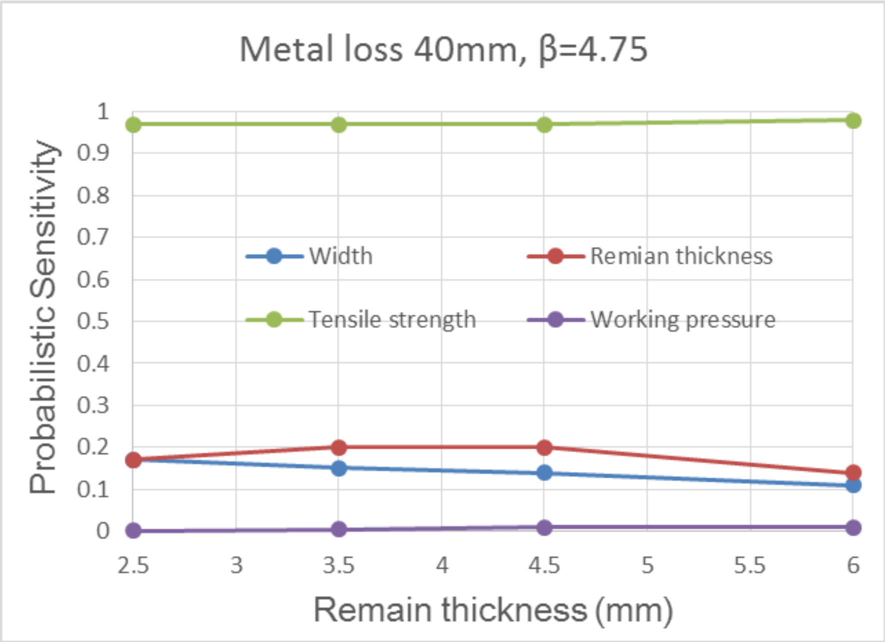
(a) Metal loss = 10mm, Reliability= 4.75



(b) Metal loss = 20mm, Reliability= 4.75

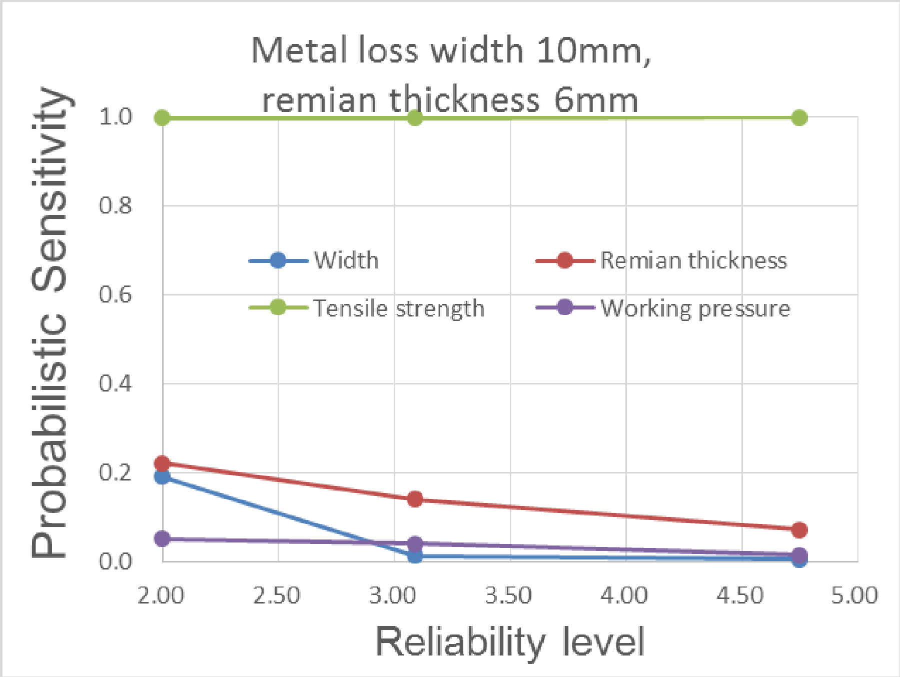


(c) Metal loss = 30mm, Reliability= 4.75

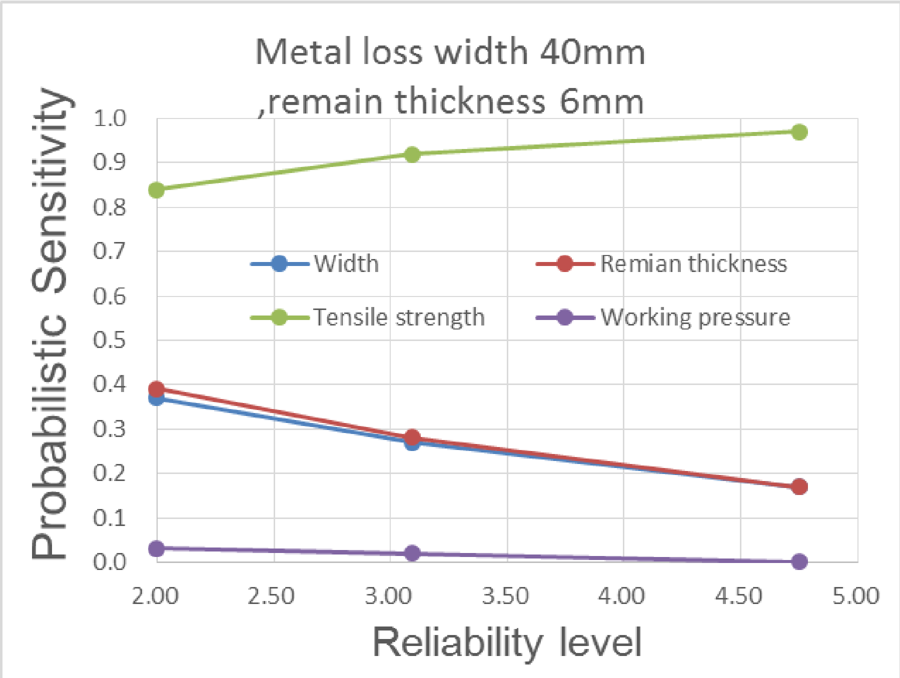


(d) Metal loss = 40mm, Reliability= 4.75

Figure 5.1 Relation between probabilistic sensitivities and remain thickness of main pipe



(a) Small size of metal loss



(b) Large size of metal loss

Figure 5.2 Relation between probabilistic sensitivities and reliability levels

In Fig 5.3, the reliability indices evaluated by re-defined safety check expression and approximate value of PSF in the examination are plotted against the target reliability. The error bar shows the absolute error of reliability evaluated in the examination. In Fig 5.4, the axis are the corresponding probability of failure of the evaluated reliability and target reliability.

Both of the Figures show that, the reliability and probability of failure are evaluated accurately by the re-defined safety check expression and approximate PSF. This proved the reasonableness of both the treatment of low sensitivity variables and the approximate approaches of PSF used in chapter 4.

5.4 Influence of different level of coefficient of variation

The probabilistic sensitivity has directly dependence on the variation. In Table 4.1, the COV of working pressure and tensile strength are assumed as 0.03 and 0.05. However, API579 standard [18] recommends that when the COV of working pressure or tensile strength is unknown, the evaluation should be performed under the assumption of COV=0.1. In this part, the reliability analysis and sensitivity analysis is perform for the case of tensile strength COV=0.1 and working pressure COV=0.1 respectively.

Figure 5.5 shows the probabilistic sensitivity when metal loss width is 40mm, reliability index is 4.75, COV of tensile strength is 0.1. Comparing to Fig.5.1 (d), it can be observed that for the case of larger COV of tensile strength, the sensitivity of other variables decreases remarkably. Figure 5.6 shows the sensitivity of the case metal loss width =40mm, remain thickness =6mm, COV of tensile strength =0.1. Compared with Fig 5.2 b), in all level of reliability index, the sensitivity of tensile strength nearly reaches the value of 1.0, and sensitivity of width and remain thickness decreases to a lower value.

For the case of working pressure’s COV=0.1, the sensitivity is plotted in Fig 5.7 and Fig 5.8. From both of the figure, it can be seen that, the sensitivity of working pressure barely changed from the case of COV=0.03 (shown in Figure 5.1d and Figure 5.2b). This indicates that, the variation of working pressure can be neglected even if it is unknown.

In API579 standard, the MAWP is recommended to be used in the FFS assessment. In chapter 4, the reliability level of MAWP by API579 is calculated, and it is showed that the MAWP by API579 produces too much conservative results. This conclusion is obtained based on the assumption of COV of tensile strength is 0.05. However, in US and EU countries, the material standard might be different from Japan, and the variation of material properties might be a higher level. The reliability level of MAWP by API579 is investigated for the case of COV of tensile strength equals to 0.1. The limit state function and process are as same as part 4.5.

Figure 5.9 and 5.10 show the different reliability level of MAWP from API579 for 2 cases of COV of tensile strength when metal loss width is 10 mm and 30mm. It can be observed that, for the COV=0.1 case, the reliability level is lower than the medium level 3.09. This indicates that, the API579 standard recommended the thickness averaging method and reinforcement area method as a medium reliability level assessment. However, in Japan, with a lower variation of material properties, this assessment method provided by API579 produced too much safety margin, as a result, a proper assessment method must be developed for Japan's conditions.

5.5 Summary and conclusions

In chapter 5, sensitivity analysis is performed. From the results of sensitivity analysis, it is concluded that the working pressure has a negligible sensitivity. As a result, the working pressure is treated as constant when the safety check expression is re-defined. The results of verification by reliability method show that this simplified safety check expression is accurate to evaluate the target reliability. The reasonableness of approximate values of PSF is also proved by the examination. The results of simplified safety check expression and PSFs are shown in Table5.1

From this application of sensitivity analysis, it is shown that the variables with low sensitivity can be considered to be constant, and in the safety check expression the partial safety factor of low sensitivity variables is simplified to be 1.0.

The influence of COV is investigated for 2 cases of different COV of tensile strength and working pressure. It is shown that, the accuracy and amount of data of tensile strength is important for the reliability assessment. On the other hand, the uncertainties in working pressure might not influence the evaluation results.

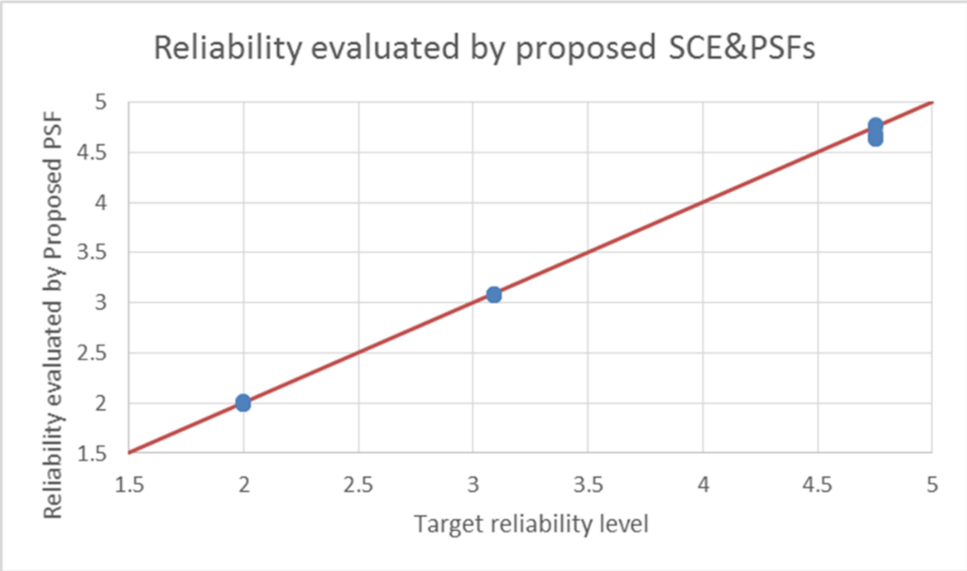


Figure 5.3 Errors for reliability evaluated by proposed safety check expression and values of PSF.

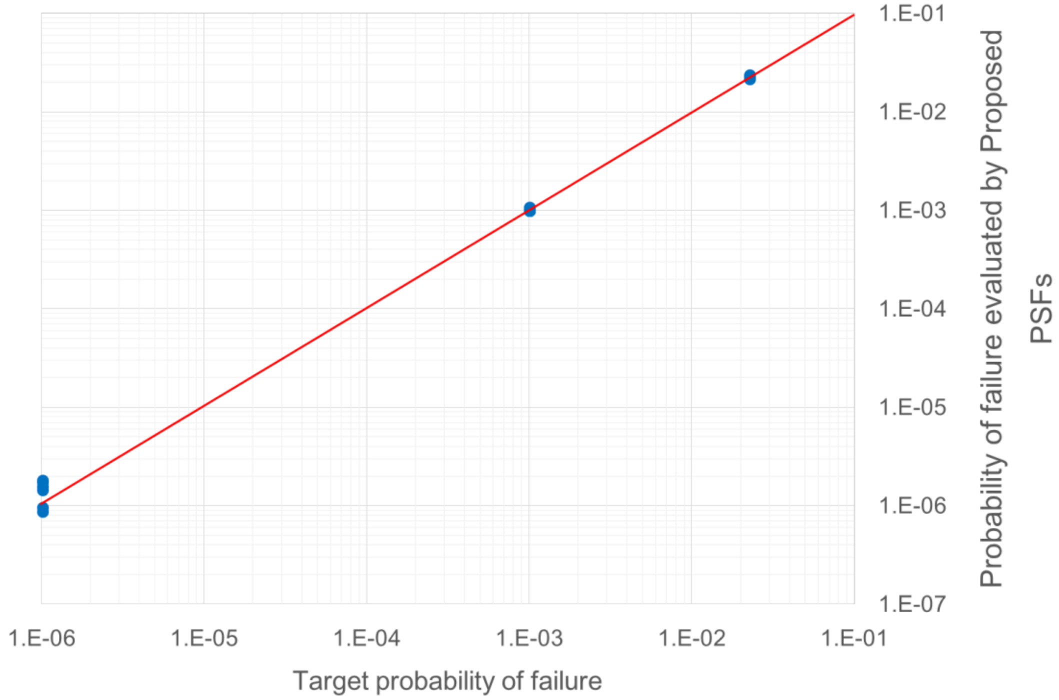


Figure 5.4 Probability of failure evaluated by proposed safety check expression and values of PSF.

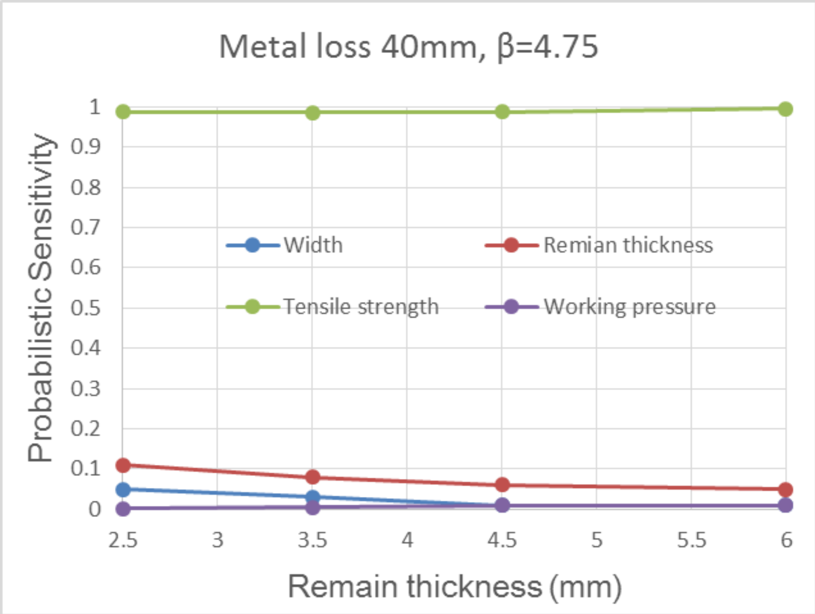


Figure 5.5 Probabilistic sensitivity of the case of metal loss =40mm, reliability index =4.75, COV of tensile strength =0.1

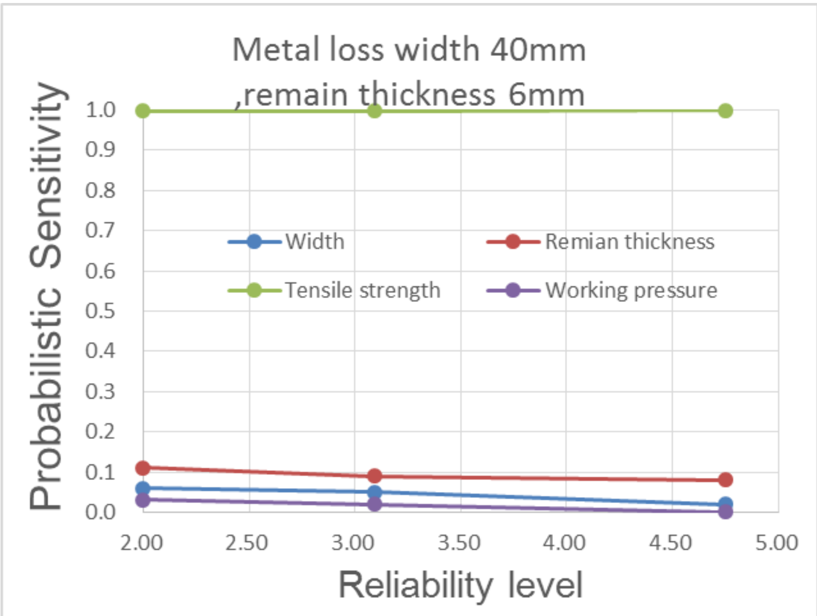


Figure 5.6 Probabilistic sensitivity of the case of metal loss =40mm, remain thickness 6mm, COV of tensile strength =0.1

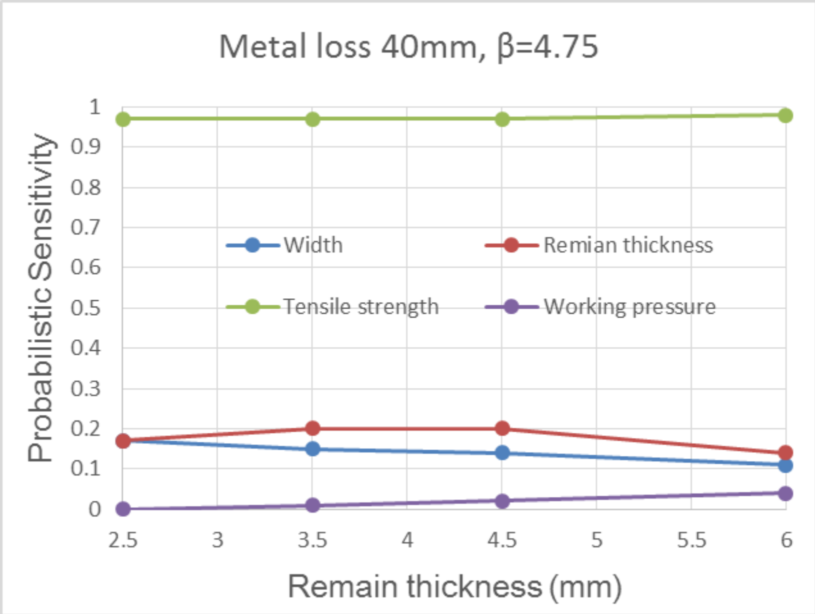


Figure 5.7 Probabilistic sensitivity of the case of metal loss =40mm, reliability index =4.75, COV of working pressure =0.1, COV of tensile strength = 0.05

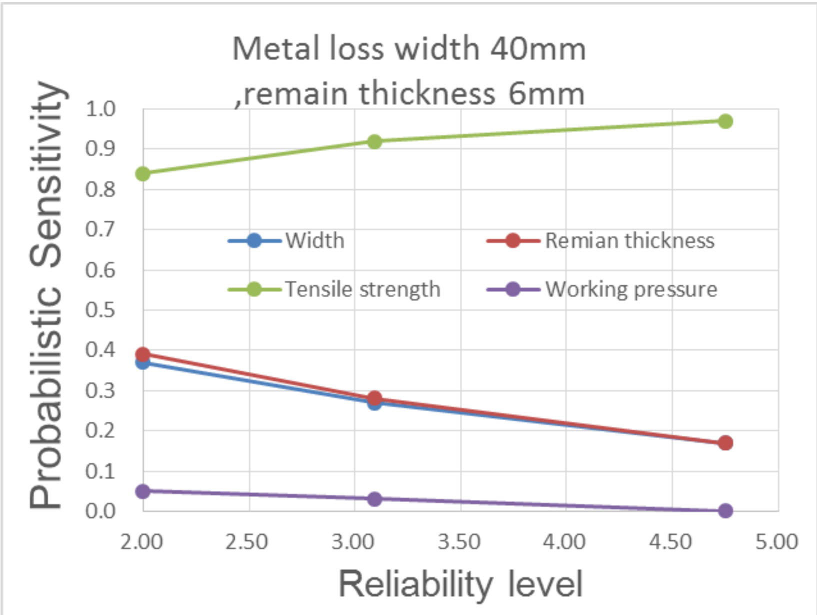


Figure 5.8 Probabilistic sensitivity of the case of metal loss =40mm, remain thickness 6mm, COV of working pressure = 0.1, COV of tensile strength =0.05,

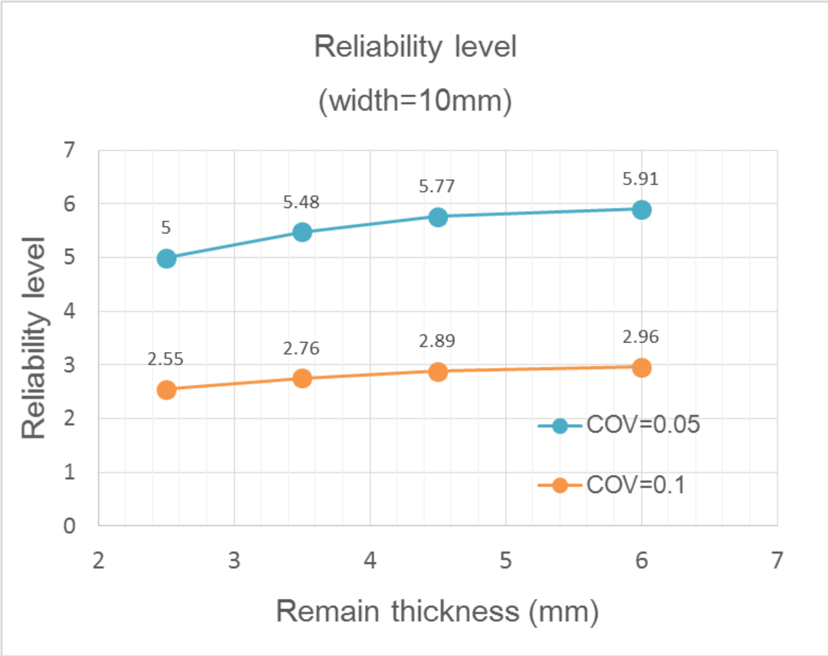


Figure 5.9 Reliability level of MAWP for different COV of tensile strength (Metal loss width = 10mm)

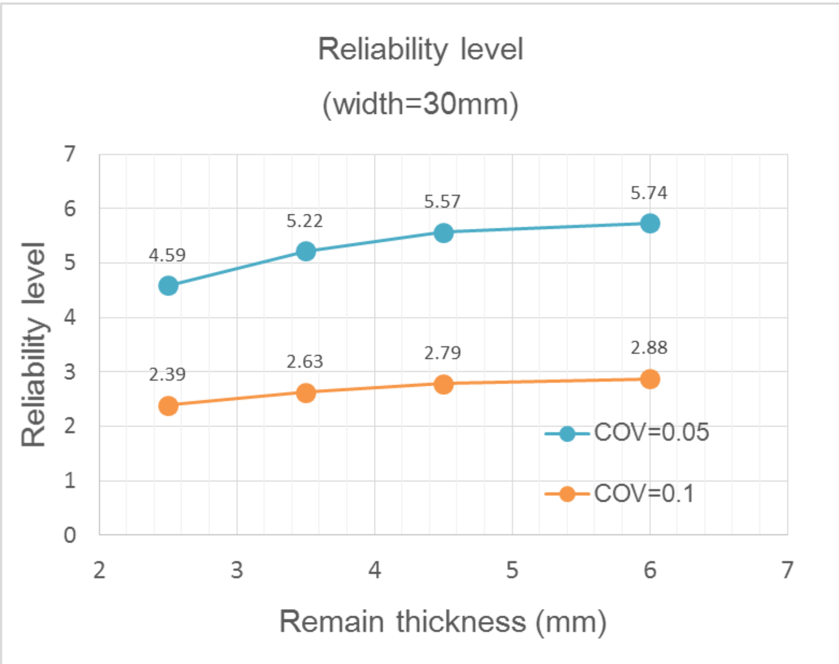


Figure 5.10 Reliability level of MAWP for different COV of tensile strength (Metal loss width = 30mm)

Table 5.1 Safety check expression and partial safety factors proposed in Chapter 6

Safety Check Expression
$P\left(s_{mm} \cdot PSF_s, \dfrac{t_{mm}}{PSF_t}, \dfrac{\sigma_{tsm}}{PSF_\sigma} \right) \geq P_{Wm} \cdot PSF_p$

Partial Safety Factors

s_m (mm)	t_m (mm)	Reliability level =4.75				Reliability level =3.09				Reliability level =2.0			
		PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P	PSF_s	PSF_t	PSF_σ	PSF_P
$s_m \leqq 20$	$t_m \geqq 4.5$	1.01	1.06	1.31	1.0	1.01	1.07	1.18	1.0	1.02	1.06	1.11	1.0
	$2.5 \leqq t_m < 4.5$	1.01	1.08	1.31	1.0	1.01	1.08	1.18	1.0	1.01	1.07	1.10	1.0
$20 < sm \leqq 40$	$t_m \geqq 4.5$	1.04	1.08	1.31	1.0	1.05	1.09	1.17	1.0	1.04	1.08	1.10	1.0
	$2.5 \leqq t_m < 4.5$	1.06	1.09	1.30	1.0	1.06	1.10	1.17	1.0	1.06	1.09	1.10	1.0

Chapter 6. Applicability of Proposed Assessment Method

6.1 Applicability of limit state function and partial safety factors generated from Chapter 5

In Chapter 5, after the simplification by the results of sensitivity analysis, the safety check expression shown as Eq(5-1) and the group of partial safety factors shown in Table 4.4 are proved to be accurate enough to evaluate the metal loss at tee-pipe of which the main pipe external diameter is 216.3mm and branch pipe external diameter is 114.3mm. However, the applicability of this safety check expression and the group of partial safety factors on other size of tee pipe has not been proved. In this part of 6.1, the proposed safety check expression and partial safety factors are applied on an exam tee pipe of a different size, so the applicability will be investigated.

6.1.1 Transformation of proposed limit state function

For standardization, the variable of remain thickness is alternated by remain thickness ratio in the proposed limit state function. The limit state function Eq(4-3) is convert into Eq(6-1a).

$$g = P_{bc} - P_W \qquad \text{Eq(6-1a)}$$

The Pbc is shown as follow

$$\begin{aligned} P_{bc} &= P\left(s_m, r_{tm}, \sigma_{ts}\right) \\ &= -200.56 + a_1 s_m + a_2 r_{tm} + a_3 \sigma_{ts} \\ &\quad + b_1 s_m t_m + b_2 s_m \sigma_{ts} + b_3 r_{tm} \sigma_{ts} \\ &\quad + c_1 s_m^2 + c_2 r_{tm}^2 + c_3 \sigma_{ts}^2 \end{aligned} \qquad \text{Eq(6-1b)}$$

$a_1 = 0.128$; $a_2 = 6.7132$; $a_3 = 0.609$;
$b_1 = 1.1164 \times 10^{-1}$; $b_2 = -4.2471 \times 10^{-4}$; $b_3 = 5.2441 \times 10^{-2}$;
$c_1 = -2.0747 \times 10^{-3}$; $c_2 = -17.499$; $c_3 = -4.3535 \times 10^{-4}$;

where the r_{tm} is the remain thickness ratio.

6.1.2 Determination of size of exam tee pipe

In Japan, the size of pipes is managed by pipe schedule. According to the design pressure and allowable stress, the number of schedule *sch* can be determined by the following expression Eq(6-2) [27].

$$sch = \left(P_d / \sigma_a\right) \times 10 \qquad \text{Eq(6-2)}$$

where the sch is the pipe schedule number, P_d is the design pressure, and σ_a is allowable stress. The nominal diameter of the pipe is determined by the needs of capacity of transport. Once the schedule number and nominal diameter are decided, the value of pipe external diameter and thickness can be found in JIS G 3454 Pipe Thickness/Size Table [27]. As a result, the size of tee pipe are fixed by different combination of pipes from Pipe Thickness/Size Table. The general size of pipe schedules are shown in Table 6.1 [27].

Table 6.1 General pipe schedule products in Japan [27]

Nominal diameter (mm)	External diameter (mm)	Thickness (mm)			
		Sch20	Sch30	Sch40	Sch80
50	60.5	3.2		3.9	5.5
80	89.1	4.5		5.5	7.6
100	114.3	4.9		6	8.6
150	165.2	5.5		7.1	11
200	216.3	6.4	7	8.2	12.7
250	267.4	6.4	7.8	9.3	15.1
300	318.5	6.4	8.4	10.3	17.4
350	355.6	7.9	9.5	11.3	19

In chemical plants, the most widely used combination of main pipe and branch pipe is the case of test tee pipe which has been lift as an example in this research. Another typical size of tee pipe used in chemical plants is the combination of nominal diameters of main pipe 300mm and that of branch pipe 100mm, for convenience, this combination of tee pipe is abbreviated as Case 300/100. As well, the test pipe analyzed in Chapter 3, 4, 5 is abbreviated as Case 200/100.

In order to clarify the applicability, the proposed safety check expression and partial safety factors are applied to the Case 300/100 tee pipe. For simplification, in this research, the applicability is only investigated for different sizes of tee pipe. Therefore, the design pressure, allowable stress and materials are assumed to be same as Case 200/100 tee pipe, which are given in Chapter 3. The schedule number of exam tee pipe (Case 300/100) is sch30 calculated from Eq(6-2). Because the there is no sch30 for branch pipe, the schedule of branch is chosen as sch40 for safety.

Form Table 6.1, the external diameters and thickness of both main pipe and branch pipe are obtained. The external diameter and thickness of main pipe is 318.5mm and 8.4mm; the external diameter and thickness of branch pipe is 114.3mm and 6.0mm.

6.1.2 Results

The FEM analysis is performed to calculate the burst internal pressure of the exam tee pipe. The burst pressure from the FEM analysis and those predicted by Eq(6-1b) are shown in Table 6.2a.

It can be seen that, the burst pressure calculated by FEM analysis is smaller than those predicted by proposed limit state functions. The relative error increases along with the increase of size of metal loss. The minus errors indicate that, the limit state function which is generated from the Case 200/100 leads to an overestimate of the safety, and produces evaluations of dangerous side. The approximate performance of proposed limit state function are also shown in Fig 6.1. The red line is y=x line, the predicted burst pressure are all plotted above. The approximate results are not accurate and safe to be used in the evaluation.

Table 6.2b shows the comparison between real reliability level and the reliability index approximately evaluated for local metal loss at 300/100 tee pipe, by using the limit state function and PSF of 200/100 case. The real reliability levels are higher than those evaluated by 200/100. This means the probability of failure will be underestimated, if 200/100 case LSF&PSF is applied to 300/100 case. It leads a dangerous side of evaluation. However, for some of the cases, the relative error are small and the approximate evaluation results didn’t change from the real value too much. If the error is judged to be acceptable, then it is possible to use 200/100 LSF&PSF to evaluate 300/100 case.

From Table 6.2a and b, it can be concluded that, if the defected tee pipe is approximately evaluated by LSF&PSF from other size of tee pipe, the larger the metal loss is, the greater the relative error will be in both burst pressure and probability of failure. For these cases of approximate evaluations, the error must be noticed.

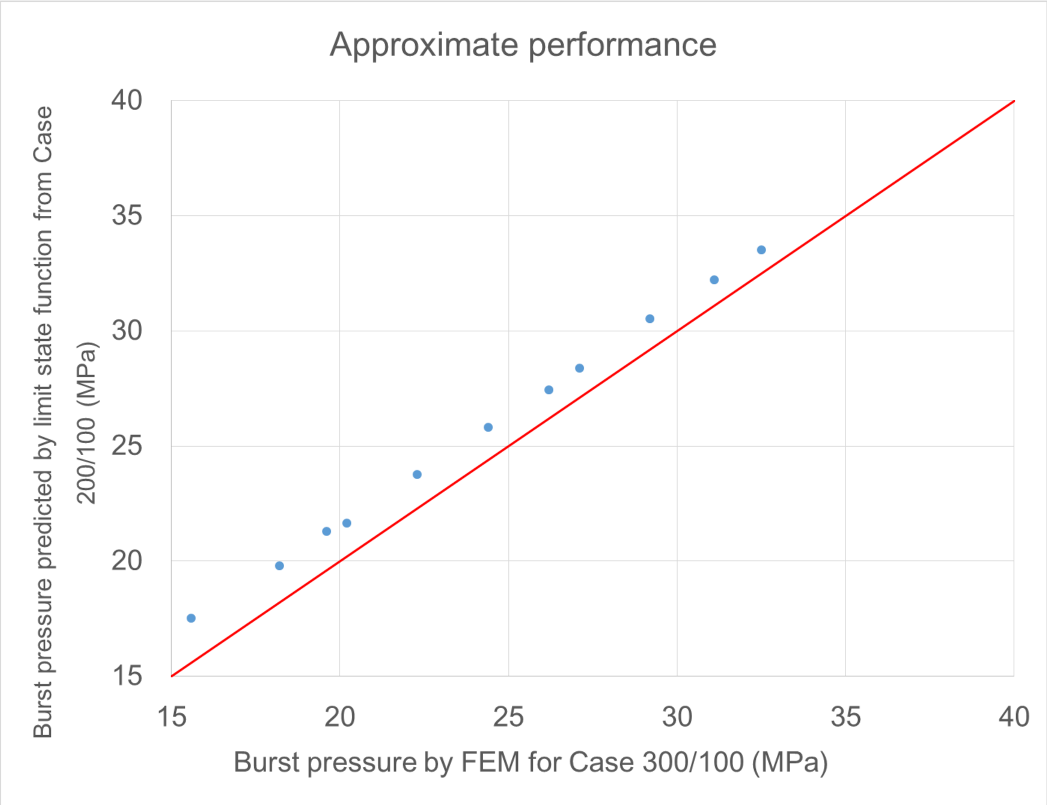


Figure 6.1 Accuracy of approximation of P_{bc} by FEM analysis of Case 300/100 and limit state function of Case 200/100

Table 6.2a. The errors of Pbc between FEA and using LSF & PSF of 200/100 case to evaluate 300/100 case (Tensile strength =671MPa)

Exam No.	Remain thickness ratio	Width of metal loss	Calculated P_{bc} By FEM analysis (MPa)	Predicted P_{bc} By Eq(6-1b) (MPa)	Relative errors
E1	0.8	10	32.5	33.5	-3.1%
E2	0.5	10	26.2	27.4	-4.7%
E3	0.3	10	20.2	21.6	-7.1%
E4	0.8	20	31.1	32.2	-3.6%
E5	0.5	20	24.4	25.8	-5.8%
E6	0.3	20	18.2	19.8	-8.7%
E7	0.8	30	29.2	30.5	-4.5%
E8	0.5	30	22.3	23.8	-6.6%
E9	0.3	30	15.6	17.5	-12.3%
E10	0.8	40	27.1	28.4	-4.8%
E11	0.5	40	19.6	21.3	-8.7%
E12	0.3	40	12.7	14.8	-16.8%

Table 6.2b. The error of Pf when use 200/100 LSF&PSF to evaluate the metal loss located at 300/100 tee pipe (Tensile strength =671MPa)

	Pf (real)	Pf(by 200/100)	Error	Pf (real)	Pf(by 200/100)	Error	Pf (real)	Pf(by 200/100)	Error
E1	1.18×10^{-6}	10^{-6}	-18%	1.10×10^{-3}	10^{-3}	-10%	2.84×10^{-2}	2.3×10^{-2}	-5%
E2	1.30×10^{-6}	10^{-6}	-30%	1.18×10^{-3}	10^{-3}	-18%	2.89×10^{-2}	2.3×10^{-2}	-7%
E3	1.92×10^{-6}	10^{-6}	-92%	1.52×10^{-3}	10^{-3}	-52%	3.16×10^{-2}	2.3×10^{-2}	-17%
E10	1.33×10^{-6}	10^{-6}	-33%	1.20×10^{-3}	10^{-3}	-20%	2.92×10^{-2}	2.3×10^{-2}	-8%
E11	2.10×10^{-6}	10^{-6}	-110%	1.58×10^{-3}	10^{-3}	-58%	3.19×10^{-2}	2.3×10^{-2}	-18%
E12	3.67×10^{-6}	10^{-6}	-267%	2.40×10^{-3}	10^{-3}	-140%	3.51×10^{-2}	2.3×10^{-2}	-30%

6.2 Applicability of proposed reliability based assessment process

In Chapter 2, a flow chat of reliability based assessment process has been proposed. In this part6.2, the proposed process is applied to evaluate the Case 300/100 exam tee pipe. During this process, an exclusive limit state function and group of partial safety factors for Case 300/100 exam tee pipe are developed.

In part 6.1.2, the sampling points of Case 300/100 tee pipe are calculated for the case when tensile strength is 671MPa. In addition, the sampling points for tensile strength equals to 690MPa and 650MPa are also calculated by FEM analysis. With these 36 sampling points, the relation between burst pressure and metal loss width, remain thickness ratio, tensile strength is obtained by response surface method. The relation is shown in Eq(6-3).

$$
\begin{aligned}
P_{bce} &= P_e\left(s_m, r_{tm}, \sigma_{ts}\right) \\
&= -133.85 + a_1 s_m + a_2 r_{tm} + a_3 \sigma_{ts} \\
&\quad + b_1 s_m t_m + b_2 s_m \sigma_{ts} + b_3 r_{tm} \sigma_{ts} \\
&\quad + c_1 s_m^2 + c_2 r_{tm}^2 + c_3 \sigma_{ts}^2
\end{aligned}
\qquad \text{Eq(6-3)}
$$

$a_1 = 0.774$; $a_2 = 15.87$; $a_3 = 0.373$;

$b_1 = 1.213\times10^{-1}$; $b_2 = -1.425\times10^{-3}$; $b_3 = 4.15\times10^{-2}$;

$c_1 = -1.7222\times10^{-3}$; $c_2 = -18.26$; $c_3 = -2.355\times10^{-4}$;

The approximate performance of this expression is shown in Fig.6.2. It is shown that, the predicted burst pressure by Eq(6-3) is nearly plotted on the y=x line. This proved the accuracy of the response values of burst pressure.

Figure 6.3 shows the comparison between response surface of case 200/100 and case 300/100. It can be seen that, for the same width and remain thick ratio of metal loss, the different size of tee pipe will have different burst pressure. For all the cases, the case 200/100 have higher values of burst pressure than the case 300/100. This reduction of burst pressure might be caused by the reason that 300/100 case has a less absolute remain thickness (remain thick ratio × total thickness). It also can be seen that, the difference between 2 response surfaces becomes less when remain thickness ratio decreases. This means when the metal loss is shallow, the burst pressure response surface of case 200/100 provides less error to evaluate tee pipe 300/100. If the error is acceptable, it will be convenient to use response surface of 200/100 to other cases.

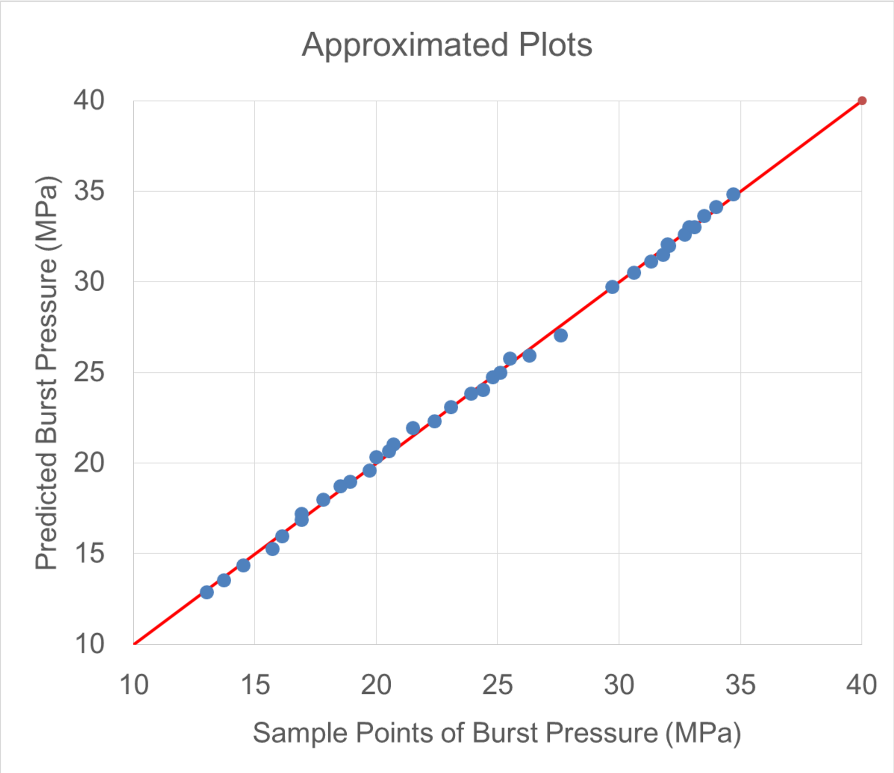


Figure 6.2 Accuracy of approximation of P_{bc} by FEM analysis and response surface of Case 300/100

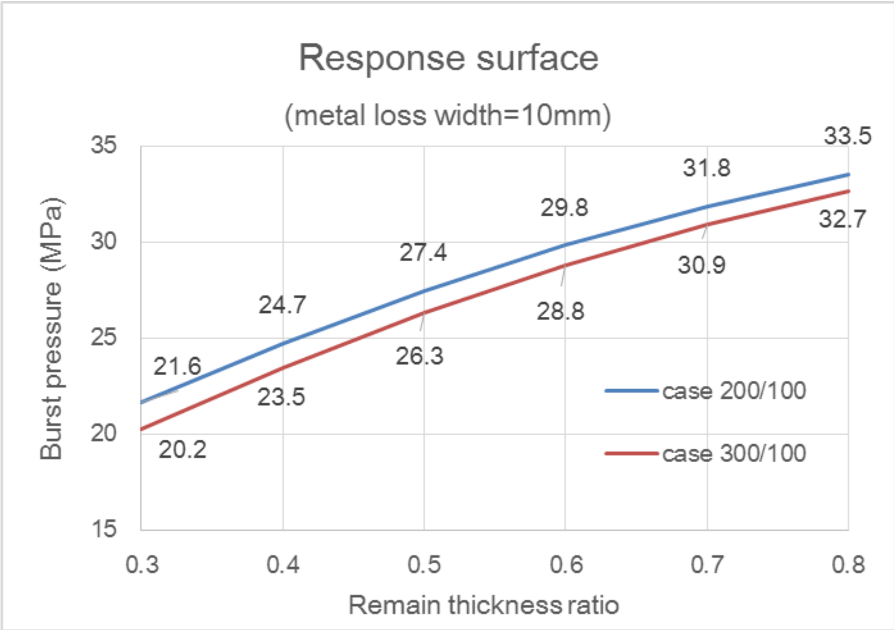
The limit state function of Case 300/100 can be written as

$$g = P_{bce} - P_W \qquad \text{Eq(6-4)}$$

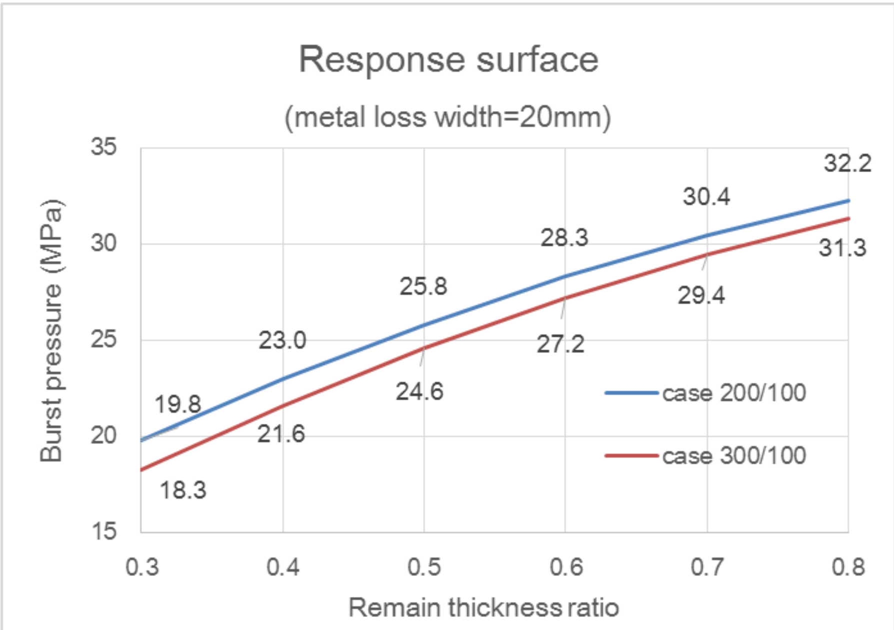
Where the P_{bce} is the expression of Eq(6-3).

If the random distributions of variables are assumed as the same as case 200/100 tee pipe given in Table 4.1 and the target reliability are referenced from Table 4.2. The partial safety factors and the sensitivity of each variable can be obtained by FORM. The partial safety factors are shown in Table 6.3.

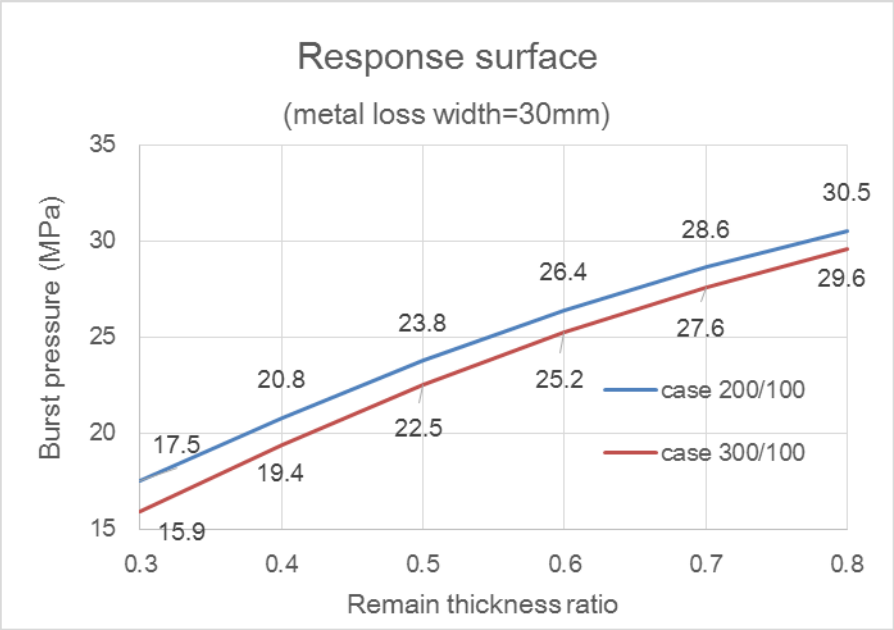
In Fig.6.4, it can be observed that, when the metal loss become wider, the partial safety factor of width increases remarkably. The partial safety factors are also changes with the change of remain thickness ratio. However, when remain thickness ratio is smaller than 0.5, the partial safety factor of each variable keeps same level. In Fig.6.5, it can been seen that, when the metal loss width is smaller than 20mm, the partial safety factors stay stably; when the width of metal loss is greater than 30mm, the changes are relaxed.



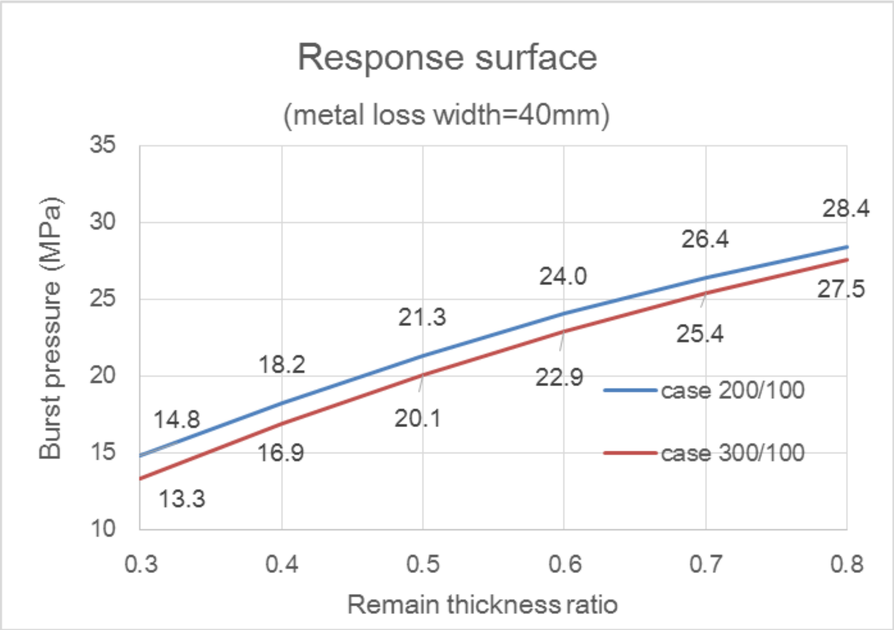
(a) metal loss width = 10mm



(b) metal loss width = 20mm



(c) metal loss width = 30mm



(d) metal loss width = 10mm

Fig.6.3 Comparison of response surfaces between case 200/100 and case 300/100

From the results of sensitivity analysis, as shown in Fig 6.6, it is observed that the sensitivity of tensile strength is dominate, and the sensitivity of working pressure is nearly 0.0. Therefore, the variation of working pressure can be treated to a constant.

According to the change regulation observed from Fig.6.4, the partial safety factors are relatively stable when remain thickness ratio is smaller than 0.5. The group of value of partial safety factors can be divided into 2 area by remain thickness ratio 0.5. From the regulation observed in Fig 6.5, it is reasonably to divide the values of partial safety factors into wide metal loss case, normal metal loss case and narrow metal loss case. In each area, the average value of partial safety factors is taken to be the simplified partial safety factors.

From the conclusion given above, the partial safety factors are regrouped in Table 6.4. The safety check expression of case300/100 are rewritten as Eq(6-5), in which the PSFp is 1.0.

$$P\left(s_{mm} \cdot PSF_s , \frac{r_{tmm}}{PSF_{rtm}} , \frac{\sigma_{tsm}}{PSF_\sigma} \right) \geq P_{Wm} \cdot PSF_p \qquad \text{Eq(6-5)}$$

Where the PSF_S, $PSF_{rt,}$, PSF_σ, PSF_p , are the partial safety factors (PSF) and the s_{mm}, r_{tmm},σ_{mm} and P_{Wm} are the nominal values of metal loss width, main pipe remain thickness, tensile strength and working pressure.

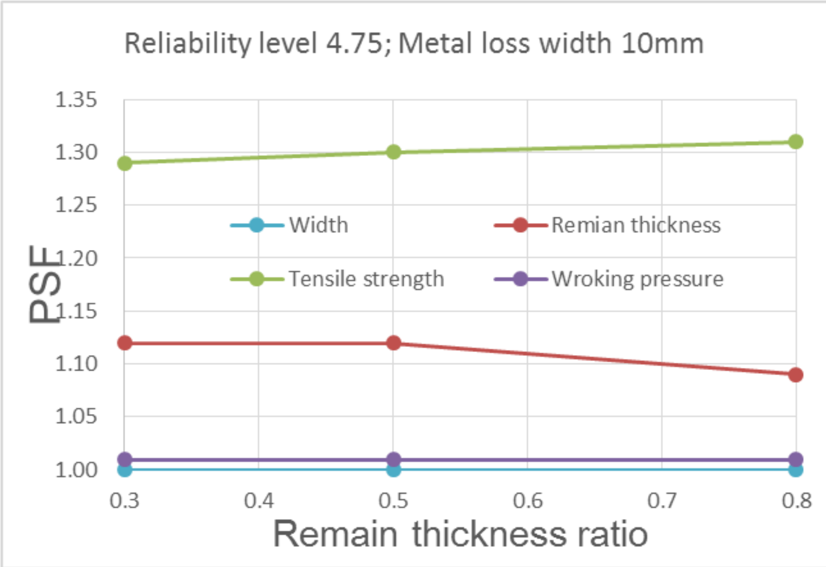
Using the same process as applied in Chapter 5, the applicability of simplified safety check expression for Case 300/100 and regrouped PSF can be investigated. Figure 6.7 shows that, the probability of failure using simplified safety check expression and regrouped PSF are plotted against the target probability of failure of picked PSF. It shows that, the probability of failure are nearly coincident with the target, and the simplified safety check expression and regrouped PSF are accurate enough to evaluate the case 300/100 tee pipe.

6.3 Summary and Conclusions

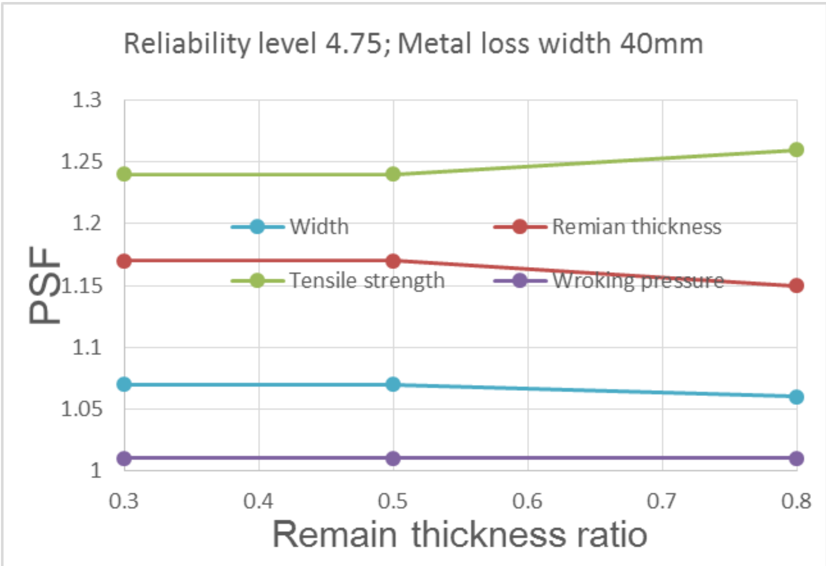
In chapter 6, the applicability of the limit state function and PSF for case 200/100 text pipe is investigated. They are applied on a different size of pipe, and the results showed that, it is not accurate to use the case 200/100 on other size of tee pipe. This indicates that, different size of tee pipes have different limit state functions. The limit state functions for the tee pipe with different combination of main/branch pipe should be developed individually.

In chapter 6, the assessment method proposed at chapter 2 is applied to case 300/100 to develop the limit state function for this case. By using FEM analysis, response surface method and reliability approaches, the limit state function for case 300/100 is developed. In addition, simplified safety check expression and PSF for case 300/100 is also proposed.

Although there are limitation of the usage of developed limit state function, the process of reliability based assessment for local metal loss existing at pipe discontinuities has been proved to be applicable.

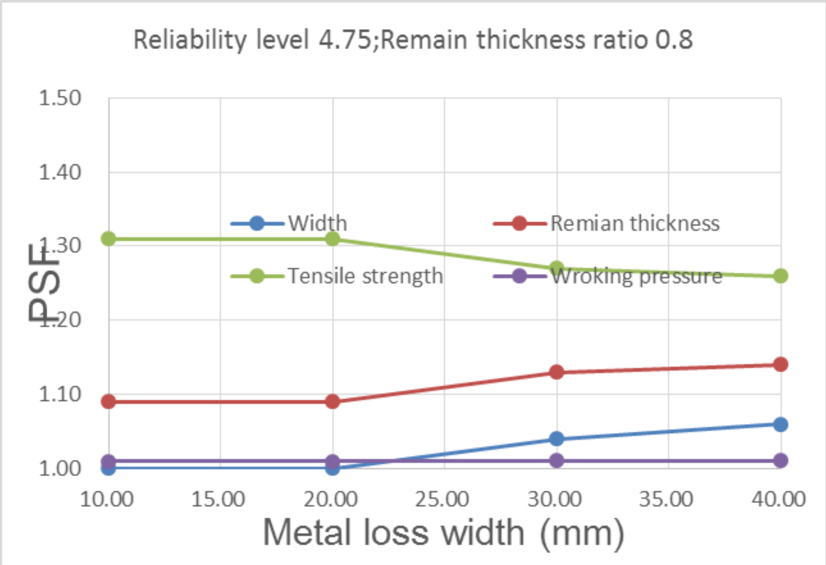


(a) Metal loss width =10mm

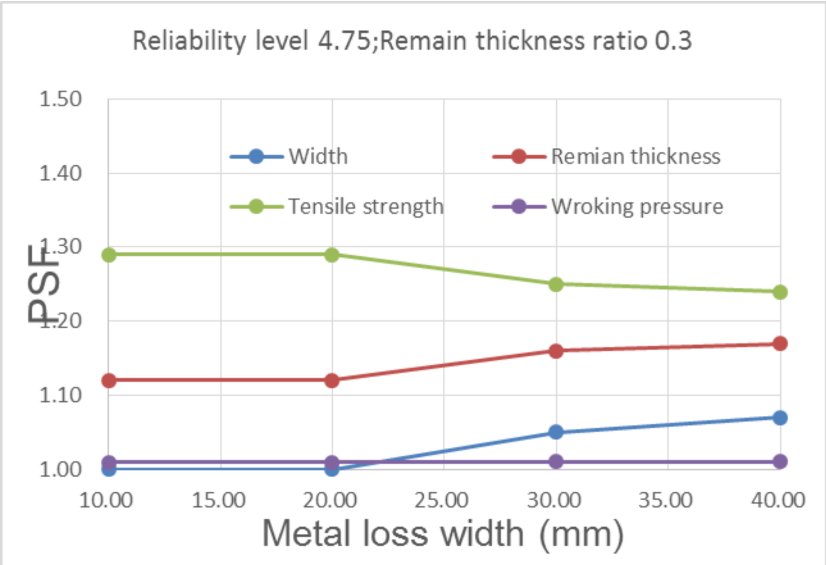


(b) Metal loss width =40mm

Figure 6.4 The relation between PSF and pipe main pipe remain thickness (β=4.75)

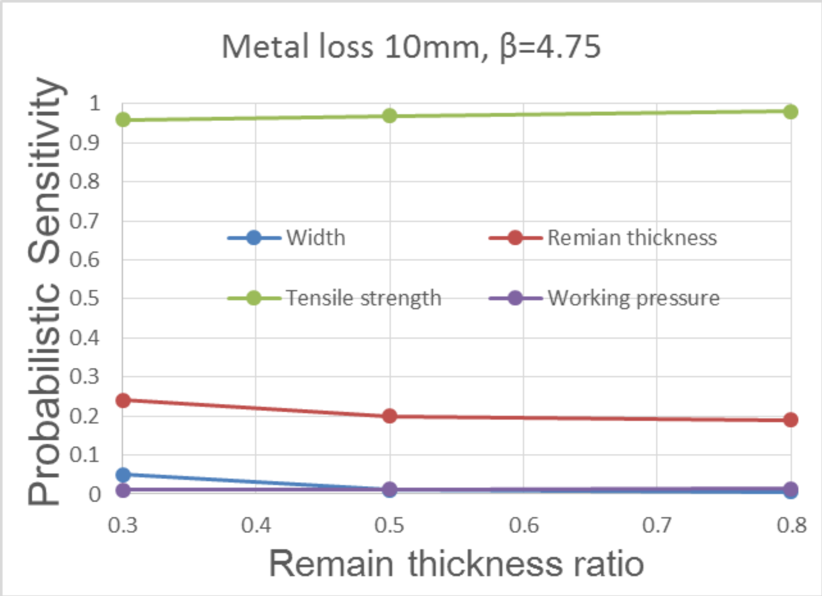


(a) Remain thickness ratio =0.8

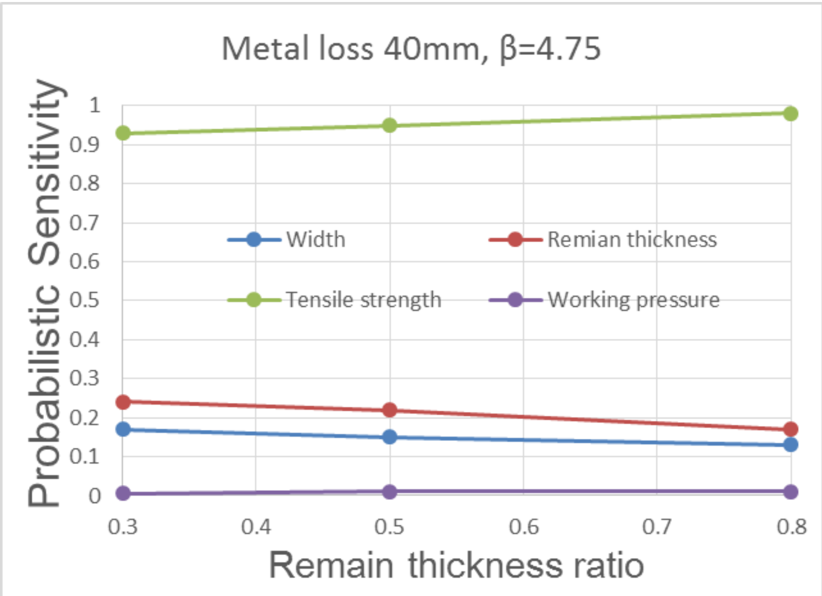


(b) Remain thickness ratio =0.3

Figure 6.5 The relation between PSF and metal loss width (β=4.75)



(a) Metal loss width =10mm



(b) Metal loss width =40mm

Figure 6.6 The relation between Sensitivity and metal loss width (β=4.75)

Table 6.3 Calculated Partial Safety Factors for varied geometries of metal loss

s_m	r_{tm}	Reliability level =4.75				Reliability level =3.09				Reliability level =2.0			
		PSF_s	PSF_r	PSF_r	PSF_P	PSF_s	PSF_r	PSF_σ	PSF_P	PSF_s	PSF_r	PSF_σ	PSF_P
10	0.8	1.00	1.09	1.31	1.01	1.00	1.05	1.24	1.01	1.04	1.05	1.11	1.01
10	0.5	1.00	1.12	1.30	1.01	1.00	1.07	1.24	1.01	1.01	1.07	1.11	1.01
10	0.3	1.00	1.12	1.29	1.01	1.00	1.08	1.24	1.02	1.01	1.07	1.10	1.02
20	0.8	1.00	1.09	1.31	1.01	1.00	1.05	1.24	1.01	1.04	1.06	1.13	1.01
20	0.5	1.00	1.12	1.30	1.01	1.00	1.07	1.24	1.01	1.01	1.07	1.12	1.01
20	0.3	1.00	1.12	1.29	1.01	1.00	1.08	1.24	1.02	1.01	1.08	1.12	1.02
30	0.8	1.04	1.13	1.27	1.01	1.06	1.13	1.22	1.01	1.05	1.10	1.16	1.01
30	0.5	1.05	1.16	1.25	1.01	1.07	1.16	1.20	1.01	1.06	1.11	1.15	1.01
30	0.3	1.05	1.16	1.25	1.01	1.07	1.16	1.20	1.01	1.06	1.11	1.15	1.01
40	0.8	1.06	1.15	1.26	1.01	1.06	1.15	1.21	1.01	1.05	1.12	1.17	1.01
40	0.5	1.07	1.17	1.24	1.01	1.07	1.17	1.20	1.01	1.06	1.12	1.17	1.01
40	0.3	1.07	1.17	1.24	1.01	1.07	1.17	1.20	1.01	1.06	1.12	1.16	1.01

Table 6.4 Approximated Partial Safety Factors

s_m (mm)	r_{tm}	Reliability level =4.75				Reliability level =3.09				Reliability level =2.0			
		PSF_s	PSF_r	PSF_σ	PSF_p	PSF_s	PSF_r	PSF_σ	PSF_p	PSF_s	PSF_r	PSF_σ	PSF_p
s_m≦20	t_m>0.5	1.00	1.09	1.31	1.0	1.00	1.05	1.24	1.0	1.04	1.05	1.11	1.0
	0.3≦t_m≦0.5	1.00	1.12	1.30	1.0	1.00	1.07	1.24	1.0	1.01	1.07	1.11	1.0
20<sm≦30	t_m>0.5	1.04	1.13	1.27	1.0	1.06	1.13	1.22	1.0	1.05	1.10	1.16	1.0
	0.3≦t_m≦0.5	1.05	1.16	1.25	1.0	1.07	1.16	1.20	1.0	1.06	1.11	1.15	1.0
sm>30	t_m>0.5	1.06	1.14	1.26	1.0	1.06	1.14	1.21	1.0	1.05	1.12	1.17	1.0
	0.3≦t_m≦0.5	1.07	1.17	1.24	1.0	1.07	1.16	1.20	1.0	1.06	1.12	1.16	1.0

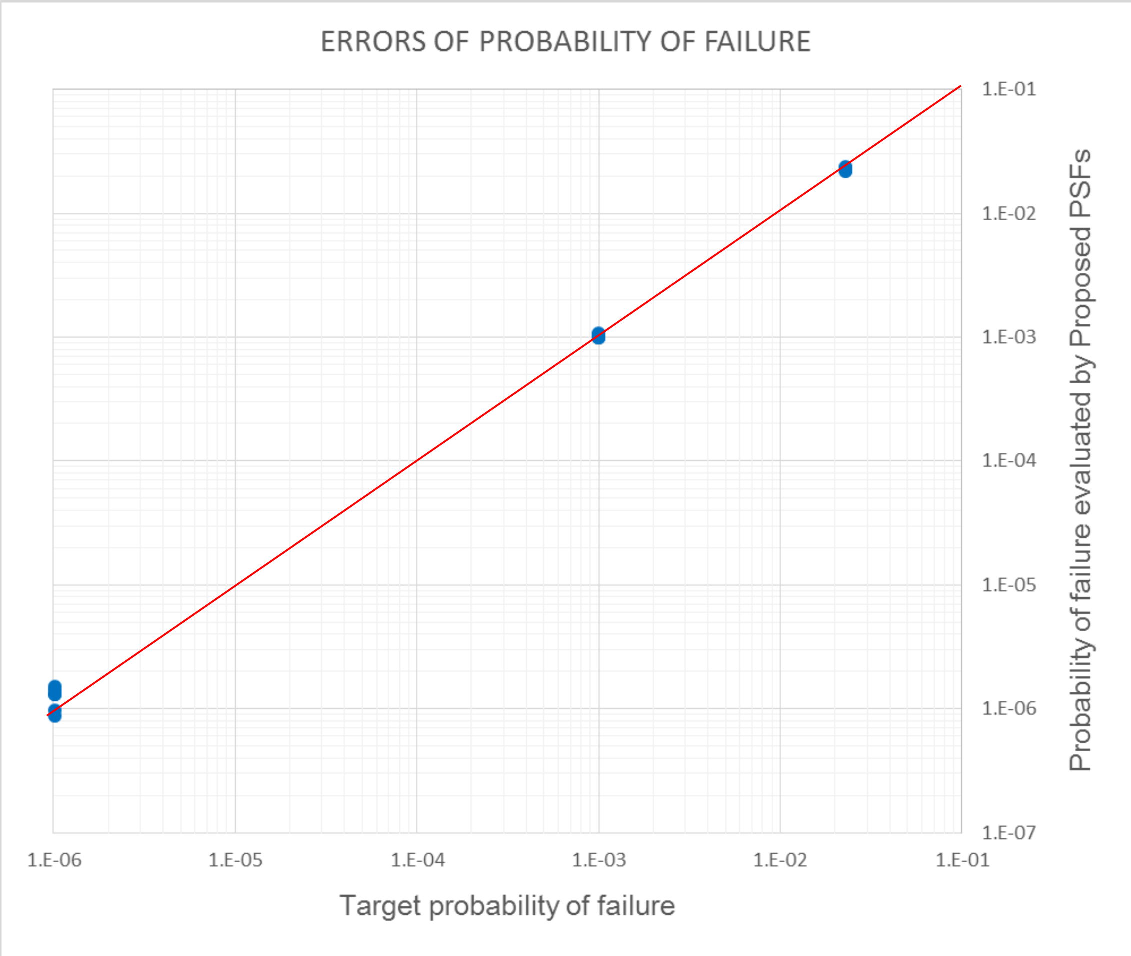


Figure 6.7 Probability of failure evaluated by proposed safety check expression and values of PSF for case 300/100.

Chapter 7. Conclusions and Future Works

7.1 Conclusions

To achieve a proper Fitness-For-Service assessment for pressed pipe containing metal loss existing at structure discontinuity, a reliability based assessment method is proposed in this research.

In proposed reliability based assessment process, firstly, for a nonlinear FEM analysis, the dashpot element is used to solve the incalculable of FEM analysis under an unstable condition of plasticity. For implicit analysis in ANSYS, burst pressure for tee pipe 1 (main pipe of STPG370

200A Sch30 and branch pipe of STPG370 100A Sch40) and tee pipe 2 (main pipe of STPG370 300A Sch30 and branch pipe of STPG370 100A Sch40) containing metal loss at discontinuity are calculated in chapter 3 and chapter 6 respectively by the usage of trilinear true stress-strain curve with vertex of tensile strength and dashpot elements. The result of burst pressure from FEM analysis is agreeing with the experimental result, therefore, the reasonableness of this definition of criteria of burst is proved.

In proposed reliability based assessment process, secondly, a response surface method with a proper surrogate model is proposed to explorer the limit state function for those complex geometries of pipe or metal loss of which the limit state function of P_{bc} doesn't exist. This method reduces the computational time and cost of performing Monte Carlo FEM analysis simulation. In chapter 4 and chapter 6, the application of this proposal is conducted to explore the limit state function of 2 kinds of geometries of tee pipe mentioned above. It showed that the 2nd order polynomial regression surrogate model is accurate to explore the relationship between P_{bc} and geometries of metal loss and tensile strength. This proposal is proved to be an effective way to explore limit state function for complex geometries of pipe or metal loss. It is also the first time to define a limit state function for a tee pipe containing metal loss at nozzle. Response surface method makes it possible to perform reliability method for structures with complex geometries only by a few times of FEM analysis.

In proposed reliability based assessment process, thirdly, the probabilistic sensitivity analysis is proposed to investigate the importance of uncertainties in variable. It contributes to improve the accuracy of evaluation by collecting more data of highlighted variables. It also contributes to reduce the cost of data collection if variable has limited influence on the evaluation accuracy. Thought the application of sensitivity analysis, in chapter 5 and chapter 6, simplified safety check expression and values of PSF are proposed for the assessment of 2 kinds of geometries of tee pipes mentioned above.

7.2 Future works and Perspectives

The welded influence will be considered in the FEM analysis model. Also, the metal loss other than circumferential shape will be investigated in the future works.

In this research, the process of reliability based assessment of pipe containing local metal loss at discontinuity is developed and proved to be applicable. Although limit state function for fixed case has limitation, the number of combination of tee pipe is countable. By using the process proposed in this research, it is possible to generate all limit state function for each case of geometries of tee pipes. Comparing with the recent maintenance methods for local metal loss, this reliability based assessment can evaluate the safety margin more precisely, the repair/replacement is performed more reasonably. As a results, both safety issues and economy save will be achieved.

Due to the high cost, the burst experiment is only performed for 1 case of 300/100 tee pipe containing local metal loss of 30cm width, 4.5mm depth. If the budget is possible, additional experiments for more sizes of tee pipe or local metal loss are expected. These results can verify the accuracy of the FEM analysis results and the response surfaces. The uncertainty caused by the error of FEM analysis should be also evaluated, and the influence of this uncertainty (error of FEA to real results) will be investigated.

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List of achievement

Conference paper

1. Q.QU, S.IZUMI, S.SAKAI, *Applicability of FFS Assessment Using Partial Safety Factors Evaluated by Infinite Plate*, ASME Pressure Vessel and Piping Conference, ASME Pressure Vessel and Piping Conference, PVP2013-97363, 2013

2. Q.QU, S.IZUMI, S.SAKAI, *Development of Reliability assessment Method for Piping Containing Local Metal Moss at Discontinuity,* ASME Pressure Vessel and Piping Conference, PVP2016-63444, 2016

Award

1. Honorable mention award of “Rudy Scavuzzo Student Paper Competition and Symposium, PVP2013”, 2013

2. Honorable mention award of “Rudy Scavuzzo Student Paper Competition and Symposium, PVP2016”, 2016

Workshop

1. Q.QU, Development of Fitness-For-Service Assessment Method Based on Reliability, GMSI-COSM-UT2 (2014)

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August 17st, 2016

Qiang QU