A Framework for Calculating the Failure Probability of Natural Gas Pipeline

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Abstract: Reliability based design and assessment (RBDA) technique is a developing direction of natural gas pipeline design method. In this paper, a framework for calculating the failure probability of natural gas pipeline is proposed. First, Java reflection mechanism is used in the management of the limit state functions, which enables the separation of the limit state algorithms and the calculations of the failure probability. Under this framework, more newly developed equations can be add into the library of the software readily. Second, a Monte Carlo reliability analysis algorithm capable of incorporating the basic input parameters and limit state functions is used to calculate failure probability of pipelines. Third, a post data processing algorithm is used to improve the efficiency. Finally, an example on natural gas pipeline is presented to illustrate the availability and effectiveness of the software. Experimental results indicate the ability of the proposed framework for pipeline quality control.

Keywords: Natural gas pipeline, Limit state, Reliability based design, Failure probability.

1. INTRODUCTION

Natural gas is becoming one of the most widely used sources of energy in the world due to its environmental friendly characteristics and low price. In most countries, the more that pipeline systems are expanded and natural gas consumption increases, the more their economies become dependent on the stable, continuous and safety of the pipeline networks [1]. In order to improve the capacity of the pipeline and to reduce the cost, high-strength large-diameter pipe for long-distance high pressure gas pipeline is the trend of pipeline technology. API X70 and X80 grade pipe steel is widely used [2]. The use of high strength steel grades such as X100 and X120 for high pressure gas pipeline in the arctic is currently being considered [3].

With the newly existing material and design program, the reliability problem is not neglectable in the manufacture, design, construction and operation progress. For example, the high yield-to-tensile strength ratio problem is considered in [4, 5]. Most of the popular design codes specify that the allowable stress is either solely or partially dependent on the yield strength. The safety objectives are achieved by using the allowable stress design approach in piping codes and standardsB31.8. Safety against failure in this approach is based on a factor set to compensate for the uncertainties associated with structural systems. Thus, reliability based design and assessment (RBDA) approach is proposed to take into account the detail information in the pipeline project and get a probabilistic safety measurement.

RBDA method has already been extensively applied in offshore structures (*e.g*. [6-9]) and nuclear containment structures [10], etc. It aims at finding out the potential accidents, analysis on the causes as well as the improvements to reduce the risk. It is important to realize that decision-making regarding reliability combines the technical aspect, political, psychological and societal processes.

To a particular limit state category, reliability is defined as the probability that a given length of the pipeline will not reach any limit states within that category for a specified period of time. From the definition, one can see that the reliability based methods are particularly useful for pipelines involving large uncertainties, application of new materials and technologies, unique loading situations and severe consequences. The approach results in more consistent safety levels and leads to optimal use of resources in achieving the highest possible safety levels. The release of ISO standard on reliability based limit state methods for pipelines ISO16708 [11] and the non-mandatory Annex O in the 2007 version of the Canadian Standards Associations pipeline design

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standard Z662 [12], indicates that RBDA method is a developing direction of natural gas pipeline design method. Reliability with respect to a particular limit state category is defined as the probability that a given length of the pipeline will not reach any limit states within that category for a specified period of time. From the definition, one can see that the reliability based methods are particularly useful for pipelines involving large uncertainties, application of new materials and technologies, unique loading situations and severe consequences. The approach results in more consistent safety levels and leads to optimal use of resources in achieving the highest possible safety levels.

Different from the classical safety factor design method which only depends on several basic parameters, RBDA method needs to select the limit state equations and the corresponding parameters first. Then, the probability of failure of each equation is calculated, which means the process performed by finite element analysis as in [13] is not suitable for system assessment. The probability for rare event, which is common in natural gas pipeline, increases the complexity of the calculation.

Therefore, in order to help decision-makers and designer tackle this problem, this paper gives a short introduction of RBDA method and the limit state equations as well as the basic parameters. Then, based on the Java reflection mechanism, the limit state functions, the uncertain variables and different kinds of distributions are decoupled as different function modules. With the implementation of Monte Carlo simulation process, a software framework is presented for the failure probability calculation. Finally, an example is designed to demonstrate the usefulness of the framework and the software.

2. RELIABILITY BASED DESIGN AND ASSESSMENT METHOD

The essence of RBDA method is to use reliability of the natural gas pipeline as the primary measure of safety, where reliability is defined as the probability that a certain length of pipeline (typically 1km) will not reach any of the applicable limit states for a certain period of time (typically 1year). The use of the reliability based method shall include:

1) data gathering and development of probabilistic models for basic variables,

2) failure mode analysis and determining limit state functions,

3) determining the safety target,

4) reliability calculation,

5) safety assessment.

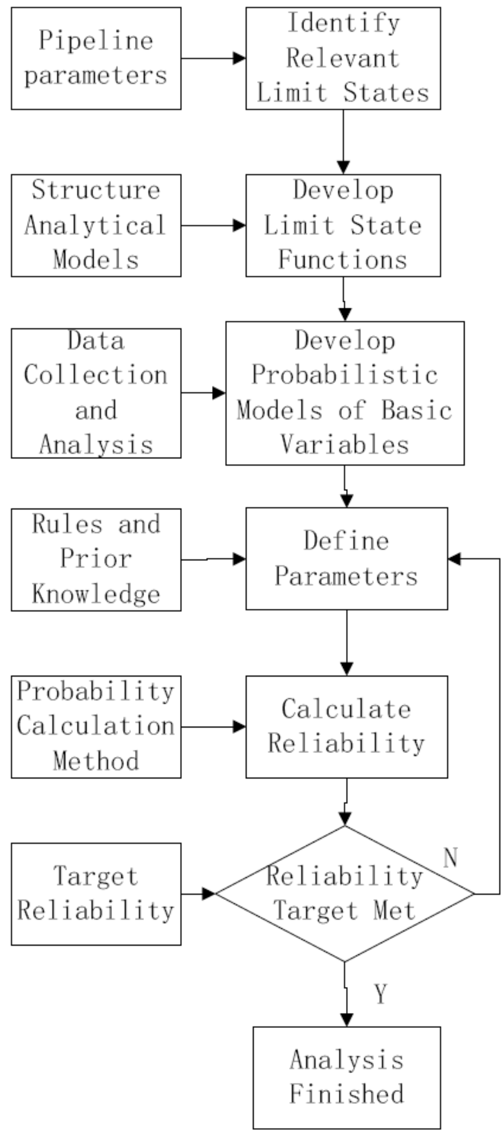

Figure 1: Steps Involved in Implementing RBDA.

The steps give in [11] and [12] may be different in wording and can be illustrated in Figure **1**, where the estimation of the probability of failure for a given function is the core of the method. Reliability is related to the probability of failure by $R = 1\text{-}p_f$. The failure probability for a given limit state is calculated as the probability that the load effect will exceed the corresponding resistance (*i.e*. combined probability of overload and under resistance). From the Annex A of [14], one can see that all the functions are in the explicit form of

$$g = r - l\ ,$$

and the probability failure can be expressed as

$$p_f = p(g = r - l \leq 0).$$

The load effect and resistance distributions are usually estimated from other (more basic) variables using analytical models.

2.1. Limit State Functions

The limit states for natural gas transmission pipelines shall be classified into three categories: ultimate limit state (ULS), leakage limit state (LLS) and serviceability limit state (SLS). Limit state functions are readily available for many key limit states for natural gas pipelines. In [12], there are 9 equations related to 3 key failure causes, which are yielding and burst of defect-free pipe, equipment impact and corrosion. And in [14], 8 failure causes are listed in Annex A.

In this paper, the basic format of limit state functions is from Annex A [15]. Here, only the main part of the equations are given in Table **1**, and please check [14] for detailed information about the meaning of variables. The functions in one category are for different conditions. For example, the limit state function for puncture given in [12] was calibrated for values of wall thickness between 4 and 12.5mm, diameter between 168 and 914mm, and steel grades up to 483, which is not suitable for the analysis of X80 steel pipeline. And with the enlargement of basic experimental data, more functions will be developed for new situations. So, the number of functions in the library of the RBDA software is varying with the development of the studies.

In order to manage the function efficiently, Java reflection mechanism is introduced to link the calculation of the failure probability and the limit state functions. Java reflection can be used for observing and/or modifying program execution at runtime. A reflection-oriented program component can monitor the execution of an enclosure of code and can modify itself according to a desired goal related to that enclosure. This is typically accomplished by dynamically assigning program code at runtime. Reflection allows inspection of classes, interfaces, fields and methods at runtime without knowing the names of the interfaces, fields, methods at compile time. It also allows instantiation of new objects and invocation of methods. In the

Table 1: The Limit State Functions for Key Failure Causes

Failure Causes	Types of Failure	Limit State Functions
Defect-Free Pipe	Yielding of Defect-free Pipe	$g_1 = 2B_1\sigma_y t - pD_i$
	Burst of Defect-free Pipe	$g_2 = 2B_2\sigma_u t - pD_i$
Excessive Plastic Deformation	Deformation	$g_1 = \varepsilon_y - \varepsilon_{eff}$
	Excessive Plastic Hoop Strain	$g_2 = 1.3\% - \varepsilon^k{}_{ph}(k = 10)$
Restrained Thermal Expansion	Local Buckling	$g = \varepsilon_{cirt} - \varepsilon_{th}$
Seam Weld Defect	Small Leak	$g_1 = t - d_{\max}$
	Rupture	$g_2 = B_1 p_c + (1 - B_1)p_0 - B_2 p_0 - p$
	Through-wall	$g_3 = B_3 p_{c1} - p$
Equipment Impact	Puncture	$g_1 = r_a - q$
	Dent-gouge	$g_2 = \sigma_c - \sigma_h$
	Rupture	$g_3 = S_{cr} - \sigma_h$
Corrosion	Small Leak	$g_1 = t - d_{\max}$
	Rupture	$g_2 = B_1 p_b + (1 - B_1)p_0 - B_2\sigma_u - p$
	Through-wall	$g_3 = B_3 p_b - p$

prototype of the RBDA software, Java reflection mechanism is an important technology to improve flexibility of the software, by which the limit state functions and the calculation are separated in the arithmetic, which enables the decoupling of the distributions, the parameters and the equations, as well as the pipeline segmentation. With this technique, more functions can be added into the computational framework. In this way, a comprehensive reliability analysis of pipeline can be conducted. Here, the algorithm model for the yielding and burst of defect free pipe is taken as an example as in Figure **2**. Other functions are implemented similarly.

2.2. Basic Parameters

Besides the complexity of the limit state functions, the basic parameters are another key issue as described in [12]. The input variables in the limit state functions are probabilistic. Each uncertain variable used in calculating reliability is assigned probabilistic models in different conditions. The possible sources of uncertainty for these variables are classified into four categories, *i.e*. random variations, measurement uncertainty, model uncertainty and statistical uncertainty.

The prototype of the software's function library consists of 16 functions related to 6 key failure causes, The basic variables used in the limit state functions above include 31 parameters, which can be grouped into 6 categories:

1) General attributes of pipeline. These are some basic design parameters of the pipeline, including the steel grade, diameter, wall thickness, design pressure and location class.

2) Material properties. These include yield strength, flow stress, tensile strength, Charpy energy of pipe body and seam weld, yield-to-tensile ratio, strain hardening coefficient, the shape of pipe stress-strain curve. These 8 parameters reflect the quality of the steel of the pipe.

3) Seam weld defect. These include the seam weld defect densities, length and depth, the imperfection and the offset of the two cross-sections immediately on either side of a girth weld.

4) Corrosion defect. With in-line inspection data or the historical data, the corrosion defect density, length and depth, growth rate at length and depth direction are for the corrosion analysis.

5) Method to prevent third party damage. These include the depth of burial, above ground alignment markers, buried alignment markers, dig notification requirement, surveillance interval, dig notification response, right-of-way indication, public awareness level. These approaches or indexes are used to quantify the chance of excavator hitting on the pipeline.

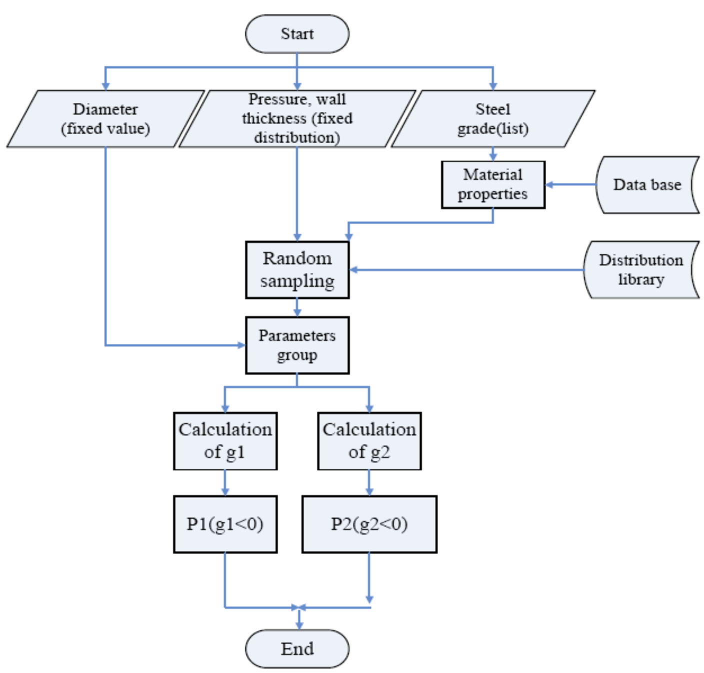

Figure 2: the Algorithm for Failure of Probability of Defect-Free Pipe.

6) Others. Besides the parameters listed above, other parameters such as environmental temperature during construction and operation are necessary for some functions.

It is noted that, model error factors and other fixed variables, such as excavator characteristics etc., are directly coded in the function algorithm that are bounded with the equations. The limit state functions and their correlated input variables matrix are given in Table **2**.

The values of function parameters in Table **2** are usually not directly typed into the software but by different ways. As list in Table **3**, there are three ways: directly input values or distributions, built-in codes of limit state functions, mapping with predefined fix-distributions.

3. FRAMEWORK OF THE SOFTWARE OF RBDA

In any case, estimating the probability of failure using analytical techniques requires a background in probability and statistics. But with Monte Carlo simulation technique, the process is simple and the method is also robust. The simulation method can provide estimation for any problem whereas analytical methods may not always converge in their iterations. With the advancement in computer technology, it is easy to develop a specific software for the calculation of fail-probability of the limit state equations. Based on the essential elements of Monte Carlo simulation

Table 2: The Parameters of The Limit State Functions

Failure Causes	Yielding And Burst of Defect-free Pipe	Excessive Plastic Deformation	Local Buckling of Restrained Thermal Expansion	Failure of Seam Weld Defect	Failure of Equipment Impact	Failure of Corrosion
Number of Parameters	5	9	5	10	15	11
List of Parameters	Diameter	Diameter	Diameter	Diameter	Diameter	Diameter
	Wall Thickness	Wall Thickness	Wall Thickness	Wall Thickness	Wall Thickness	Wall Thickness
	Pressure	Pressure	Pressure	Pressure	Pressure	Pressure
	Yield Strength	Yield Strength	Yield Strength	Yield Strength	Yield Strength	Yield Strength
	Tensile Strength	Imperfection at Body	Strain Hardening Coefficient	Tensile Strength	Tensile Strength	Tensile Strength
	*	Offset of Two Cross-Sections	*	Defect Density	Charpy Energy of Pipe Body	Defect Density
	*	Temperature During Construction	*	Defect Depth	Location Class	Defect Depth
	*	Shape of Pipe Stress-Strain Curve	*	Charpy Energy of Seam Weld	Method To Prevent Third Party Damage	Growth Rate of Defect

Table 3: the Input Methods of Parameters

Parameters	Input Method	Default Value	Remarks
Steel Grade	Combo List	X80	X52/60/65/70/80/90/100
Diameter	Directly Input	1219	Deterministic Value
Wall Thickness	Directly Input	18.4	Input Based Distribution
Pressure	Directly Input	10	Input Based Distribution
Location Class	Combo List	Class 1	Class 1/2/3/4
Welding	Combo List	SAW	SAW/HFW
Coating	Combo List	Enhanced	Regular/Enhanced
Buried Depth	Directly Input	1.0	Deterministic Value
others	Combo List& Directly Input		Puncture rate

technique, the algorithm is as following (Figure **3**). Since the method is independent from the equations, the simulation can be folded as a single block that is decoupled from the limit state function library.

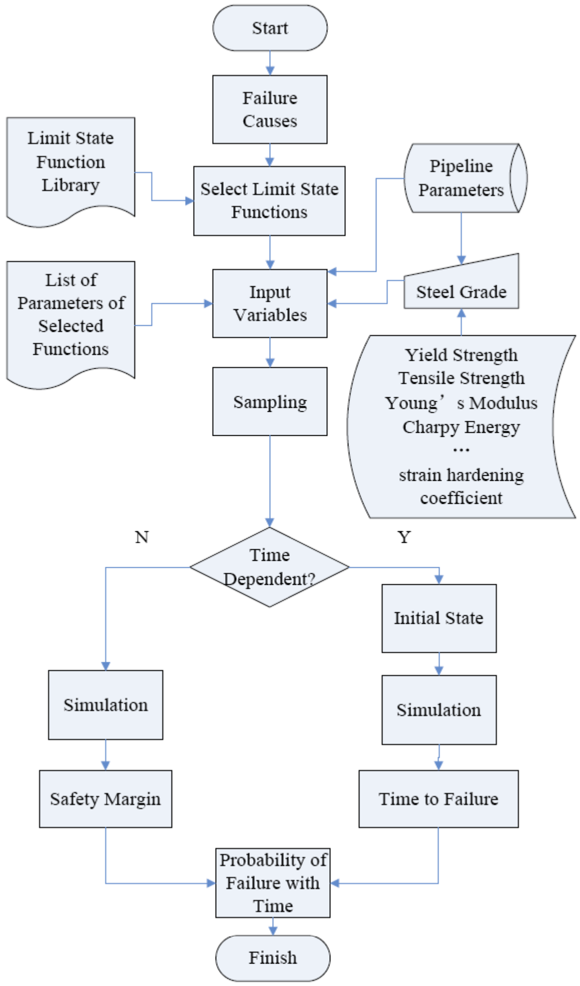

Figure 3: the Algorithm of Monte Carlo Simulation

From Figure **3**, the key issue that arises in estimation of the probability of failure involves setting the probability distributions for the basic variables and solving the limit state equations for the specific causes. The premises of the calculation are the preparation of basic data and limit state equations. In our project, these informations are built into the software as the fundamental database and the limit state equations library. Each limit state function is an independent class performing similar operations, i.e. the Monte Carlo simulation. Java reflection is used to adapt the software to different functions and situations dynamically. Without reflection-oriented programming, the simulation might be hard-coded to call method names of every class. However, using the reflection-oriented programming paradigm, the software could be designed and written to utilize reflection in order to invoke methods in each class without hard-coding method names. Reflection-oriented programming almost always requires additional knowledge, framework, relational mapping, and object relevance in order to take advantage of more generic code execution. Hard-coding can be avoided to the extent that reflection-oriented programming is used. Although it is often used as part of software testing, it is borrowed to achieve the flexibility of the software.

Following the work before, the limit state functions and parameters are saved in one Microsoft Excel sheet. And the framework of RBDA software is as in Figure **4**. The software is extensible in the basic input level, function parameters level and limit state functions level. Since each function is a single function block decoupling the calculation process. With the explicit parameters mapping of the function, the newly developed functions are easy to add to the library. Allowing researchers to devote their time to limit state functions rather than dealing with the entire process, the framework reduces overall development time. It

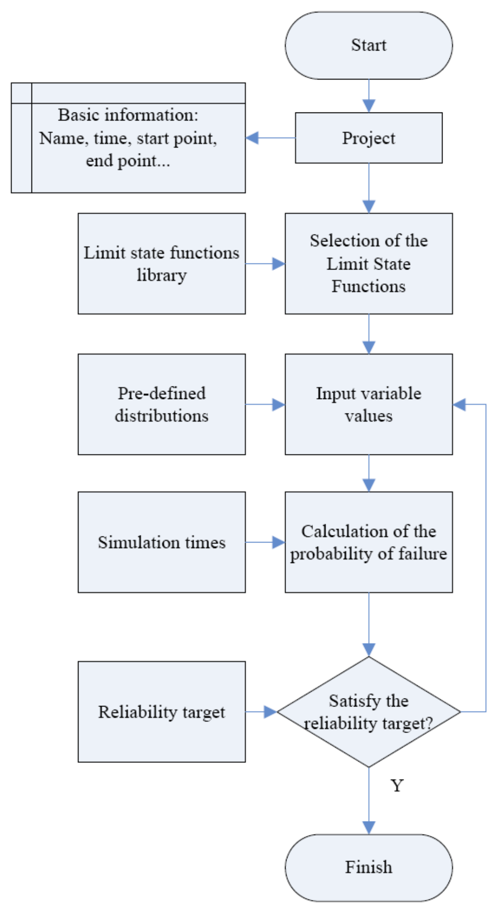

Figure 4: the Architecture of the Software.

Table 4: The Basic Parameters of the Pipeline

Diameter	Wall Thickness	Design Pressure	SMYS
1219mm	19.1mm	12MPa	630MPa

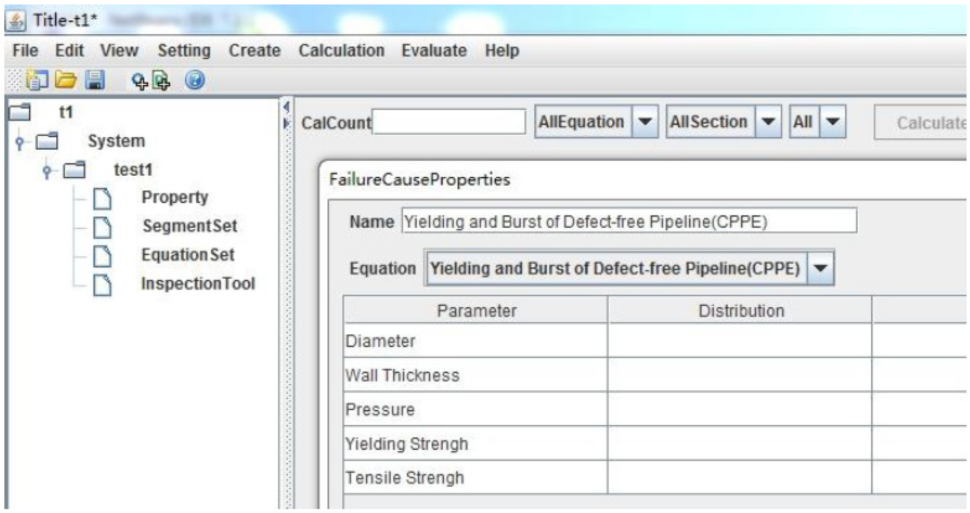

Figure 5: The Interface of the Software.

also reduces the requirement of programming techniques.

4. RESULTS

As the prototype of the software, its main functions are the management of the parameters and limit state functions, the implementation of Monte Carlo simulation and the post process of original results of the limit state functions. Since RBDA method suits to new material, X90 pipe steel is checked for the probability of failure of yielding and burst of defect-free pipe and local buckling due to restrained thermal expansion.

The basic parameters of the pipeline are assumed as in Table **4** and the distribution used in the calculation of the failure probability is generated following Annex B in [14]. The interface of the software is as following (Figure **5**). The distributions of the result of each equation are illustrated as in Figures **6** and **7**.

5. DISCUSSION AND CONCLUSION

By post processing of the data, the estimated probability of failure of each limit state is given in Table **5**. The failure probability can be analyzed for different parameters. Each variable in the limit state functions is a random variable with specific distribution. The variation of their mean values around the standard condition values shows the sensitivity of probability of failure to the variation of the input parameters. The influence of the parameters to the failure probability is reflected from the results, which indicates the directions of quality control of the pipeline material.

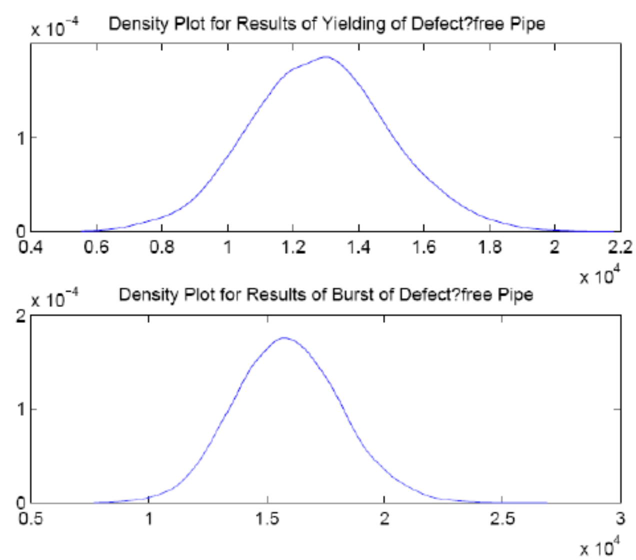

Figure 6: Density Plot for Results of Limit State Equations of Defect-free Pipe.

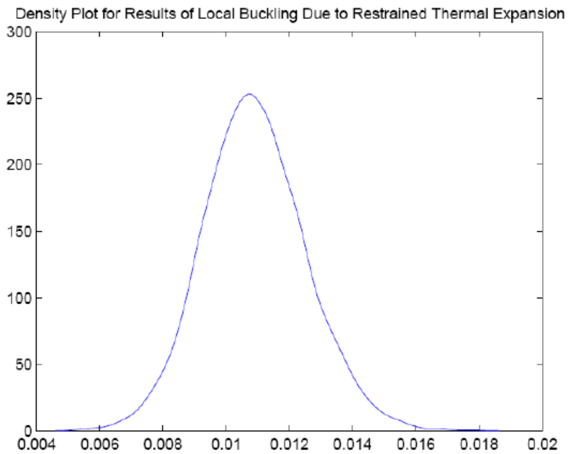

Figure 7: Density Plot for Results of Limit State Equations of Local Buckling Due to Restrained Thermal Expansion.

Table 5: the Probability of Failure of Limit State under Standard Parameters

Limit State	Failure Probability
Yielding of Defect-free Pipe	2.18E-09
Burst of Defect-free Pipe	8.25E-13
Local Buckling Due to Restrained Thermal Expansion	1.08E-11

Reliability based design and assessment method is a developing direction of natural gas pipeline design method. The main objective in using reliability-based methods is to provide consistent safety by accounting for uncertainties which are not explicitly considered by deterministic safety factors. The core of the method lies in the collection of the fundamental data, the development of the limit state equations and the calculation of the probability of failure. Since the explicit expression of the limit state equations, the Monte Carlo simulation is implemented based on Java reflection mechanism to unify the input variable mapping relationship, the basic parameters management and the limit state equations library. A flexible framework of the software is proposed which enables the modification and extension of limit state equations. Thus, more equations can be added into the computational framework and the use of RBDA method on the analysis of natural gas pipeline becomes more convenient.

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