

# Research Progress of Safety Assessment Technology of Pressure Vessel Pipeline with Defects

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## ABSTRACT

Pressure vessel is widely used in the energy industry, military industry, scientific research and many other fields, the importance of its safe operation is self-evident, the safety of pressure vessel and pipeline has been an important research topic. For the safety assessment of defective vessels and pipelines, this paper firstly introduces the research results of the latest standards of defective equipment and pipelines, gives the latest progress of defect assessment theory, briefly reviews the application status of safety assessment of defective vessels, and finally proposes the current situation of domestic defect assessment, providing a basis for the safety evaluation of defective vessels and pipelines.

## KEYWORDS

Pressure Pipe; Service Life; Defect Assessment; Extended Service.

## 1. INTRODUCTION

In recent years, with the continuous expansion of China's industrial construction scale, the use of pressure vessels and pipelines has become increasingly widespread. Due to the flammable and explosive nature of the media they often contain, ensuring the safe operation of these equipment is of great significance to factories [1-2]. However, these equipment often operate continuously under harsh conditions, such as high temperature and high pressure, and some pipelines are buried underground for long periods, making them susceptible to external forces, corrosion, and other factors that can lead to the formation of micro-cracks. These cracks can cause local stress concentration during use, leading to equipment failure and serious accidents. According to records from the State Administration for Market Regulation, from 2012 to 2022, a total of 674 accidents involving pressure vessels and pipelines occurred nationwide. Apart from operator errors, the majority of these accidents were caused by equipment failure. Therefore, the government has issued a series of standards for the safety assessment of pressure vessels, pipelines, and other special equipment. However, due to the complexity of the assessment process and the numerous parameters required, the efficiency of equipment inspection and assessment is low, and the process is time-consuming and labor-intensive [3-5].

Currently, research on defect assessment systems in China is limited, and some assessment systems lack comprehensive content [8-12]. Moreover, with the update of GB 19624-2019, some assessment systems have become outdated [13-18]. Therefore, the author has compiled the latest version of GB 19624-2019, which includes three methods: simplified assessment, routine assessment, and fatigue assessment, as well as multiple appendices (G, H, I, etc.) for the safety assessment of pressure pipelines. This standard can assess various types of planar and volumetric defects, enabling engineering assessors to quickly and accurately complete the assessment of pipelines under inspection.

## 2. INTRODUCTION TO THE SYSTEM PROCESS

Fracture mechanics initially emerged to address the frequent occurrence of low-stress brittle fracture in pressure vessels. It originated from Griffith's energy theory, but it did not gain much attention. Since Irwin introduced the concept of stress intensity factors, linear elastic fracture mechanics began to take shape. Later, to address the issue of large-scale or complete yielding of materials, plastic zone corrections were introduced, leading to the establishment of elasto-plastic fracture mechanics. Elasto-plastic fracture theory primarily encompasses two methods: the Crack Opening Displacement (COD) method and the J-integral. Since the 1980s, due to the J-integral theory's applicability to both linear elastic and elasto-plastic theories and its greater reliability compared to the COD method, countries worldwide have conducted in-depth research on the J-integral theory and formulated various defect assessment codes. Examples include ASME and API579 in the United States, R6 and BS7910 in the United Kingdom, SINTAP in Europe, and GB/T19624 and NB/T20013 in China. Adopting the latest assessment standards to evaluate the safety of defective pressure piping has become a current trend.

In China's GB/T 19624-2019, a complete defect assessment process can be roughly divided into the following five steps: defect characterization, stress analysis, determination of material performance parameters, selection of assessment method, and completion of assessment. Specifically, they are as follows:

### (1) Defect Characterization

During the actual production process of pipelines, some tiny cracks may develop. These cracks often have irregular shapes due to various factors such as stress concentration and corrosion fatigue. For ease of distinction, the standards classify defects into two categories based on their geometric shapes: volumetric defects and planar defects. Planar defects are further divided into surface cracks, buried cracks, and through cracks, depending on their location within the object. Assessors can choose appropriate classification rules to characterize defects based on the measured location, size, and other information of the defects, thereby completing the regularization of defects.

### (2) Stress Analysis

Due to the varying environments and operating conditions of different pipelines, the forces acting on them also differ. Therefore, the standard outlines the loads and stresses that need to be considered for safety assessments. These stresses are classified into primary stress (P) and secondary stress (Q) based on their regions of action and nature. Assessors can complete the corresponding calculations using relevant stress calculation formulas or finite element simulation software. It is worth noting that the classification of certain stresses (such as thermal stresses) under different operating conditions may vary and needs to be determined according to corresponding rules.

### (3) Determination of Material Performance Parameters

Multiple material properties are involved in the pipeline assessment process, primarily including mechanical properties (yield strength, tensile strength), physical properties (elastic modulus E, Poisson's ratio), and fracture toughness. Corresponding data for these properties can be obtained through mechanical tests. Regarding the measurement of fracture toughness, the most commonly measured values are CTOD (Crack Tip Opening Displacement, the displacement of the crack tip before and after fracture) and J-integral fracture toughness (the energy integral calculated around the crack tip). When actual measured values for the material are not available, fracture toughness can also be obtained using corresponding alternative methods and engineering experience formulas outlined in the standard.

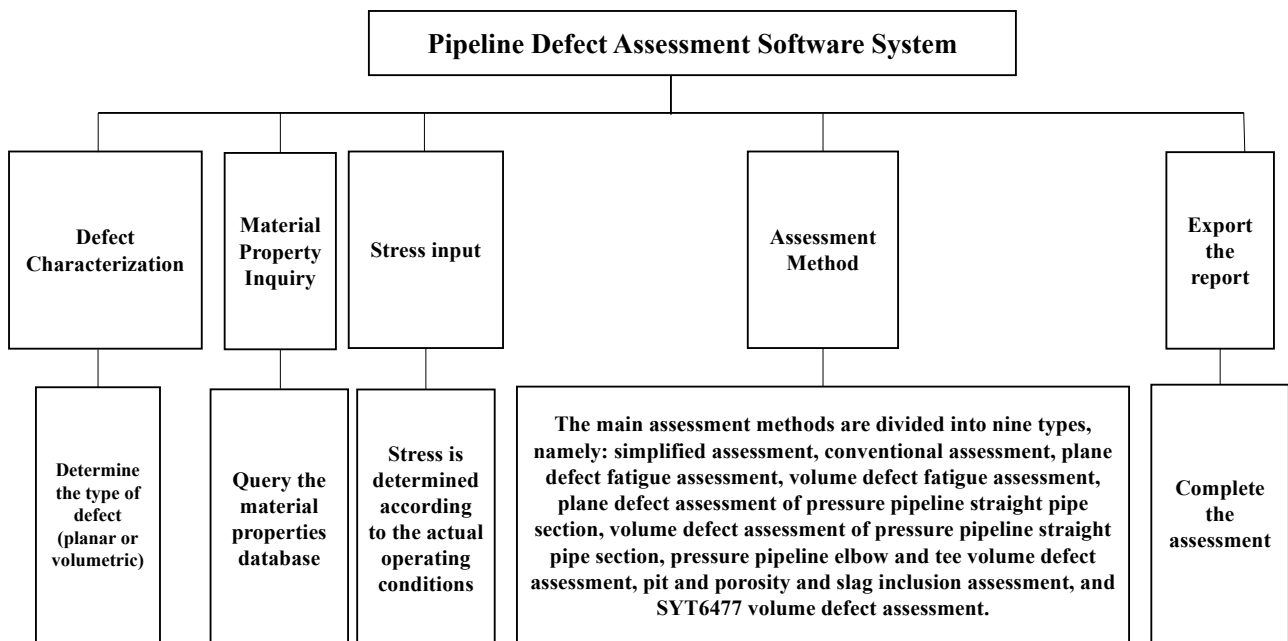
### (4) Selection of Assessment Methods

In GB/T 19624-2019, there are multiple assessment methods. Based on different failure modes, these methods can be roughly divided into three categories: fracture failure, plastic failure, and fatigue failure. For safety assessments targeting fracture and plastic failure modes, the standard provides four

assessment methods, primarily divided into conventional and simplified assessments for planar defects, as well as assessments for volumetric defects such as pits, pores, and slag inclusions. For fatigue failure assessments targeting cracks, the standard also provides two methods for assessing volumetric or planar defects. In addition to providing corresponding methods for the safety assessment of pressure vessels, the standard also outlines three assessment methods for pipelines, categorized based on defect types and locations, facilitating assessors in evaluating defects in straight pipe sections, tee joints, elbows, and other parts of pipelines. These nine different assessment methods are independent yet interrelated. For instance, if a defect passes the conventional assessment but fails the simplified assessment for planar defects, the defect is considered acceptable. If the assessment result for some volumetric defects is unacceptable, re-assessment can be conducted as planar defects. Therefore, assessors need to flexibly select assessment methods based on different environments and defect types to make the assessment results more reasonable.

### 3. SYSTEM OVERVIEW

This system is a safety assessment software developed on the Visual Studio platform using the C# programming language. It incorporates the assessment methods outlined in GB/T 19624-2019 (Safety Assessment of In-Service Pressure Vessels Containing Defects) into the software in the form of formulas. Additionally, the software stores the assessment environments required for each assessment method, such as tables, formulas, and diagrams. To facilitate user experience, this system has also compiled a case database and a material property database, allowing users to quickly query and retrieve data. Considering the impact of temperature on material properties, this system references part of the material property data tables from API 579-2021 and stores them in an SQLite database. In terms of stress processing, the system has also incorporated stress classification rules and calculations for some secondary stresses into tables, providing convenience for assessors in stress calculations. This system can effectively complete safety assessments for both planar and volumetric defects. Users only need to input specific data on defects, material properties, and equipment geometry, and the system can quickly and accurately provide conclusions. The specific modules are as follows:



**Figure 1.** The main modules of the assessment system

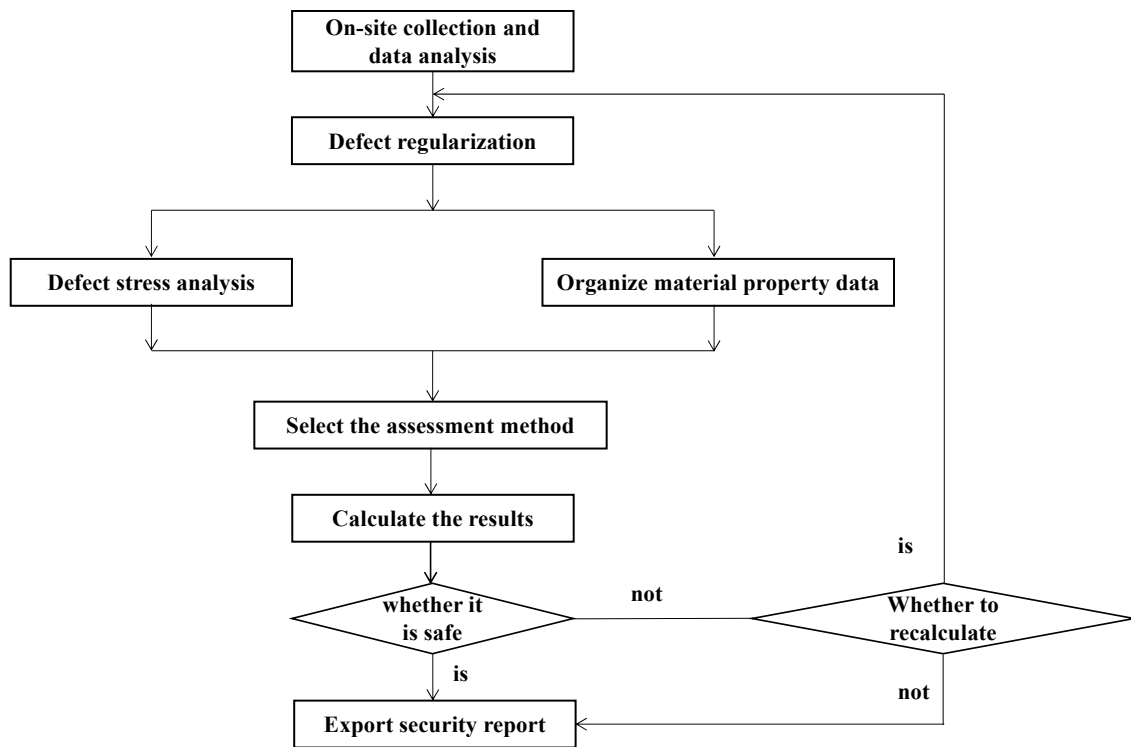
This system focuses on pipelines with defects, conducting calculations and analyses on cracks, pits, and other defects that may arise during service or operation. Its core processes are as follows:

**Data Input and Defect Characterization:** Users input the measured data of the pipeline through the system interface, including the geometric dimensions of the defects (such as length, depth, etc.). The system then standardizes the representation of these defects to provide standardized input for subsequent calculations.

**Material Property Parameter Acquisition:** The system extracts material property parameters such as tensile strength and yield strength from its built-in database or user-inputted field data. It also comprehensively analyzes these parameters in combination with the actual stress conditions of the pipeline (such as primary membrane stress, secondary membrane stress, and bending stress).

**Selection and Calculation of Assessment Methods:** Based on the defect type and pipeline operating conditions, the system supports the selection of multiple assessment methods, including simplified assessment, conventional assessment, and assessment for straight sections of pressure pipelines, to perform safety assessment calculations on defective pipelines.

The system's programming logic and process design are illustrated in the figure below, ensuring the scientific nature and efficiency of the assessment process.

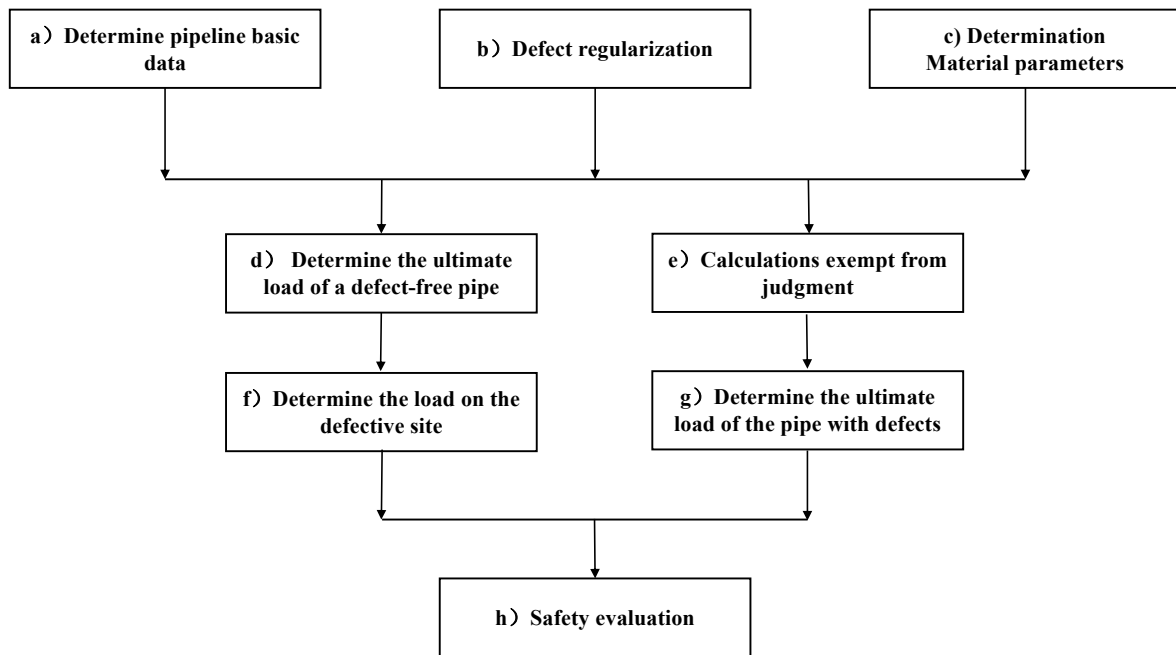


**Figure 2.** Evaluation flow chart

1)Composition of the Main Interface: The main interface of the assessment system primarily adopts a modular design, encompassing eight submenus: File, Tools, Help, Defect Characterization, Material Properties, Stress Analysis, Defect Assessment, and SY/T 6477 Standards. Upon successful login, users can access this interface and select the corresponding functional modules based on their specific needs to perform core functions such as defect assessment, stress analysis, and report generation. The system integrates a multi-standard material property database, allowing users to query relevant material parameters as required. The database covers key mechanical properties data such as tensile strength and yield strength from API standards, as well as material properties like elastic modulus from GB150 standards. Users can quickly search and retrieve the required material data through the query interface shown below, providing accurate material performance support for defect assessment.

2)Composition of the Material Database: The material data function of the assessment system systematically summarizes and categorizes common material parameters in industrial production, facilitating users to quickly query and directly apply them in subsequent calculations. To meet users' personalized needs, the system supports manual addition or deletion of material data, ensuring that the assessment work is highly aligned with actual engineering requirements. In the allowable stress query module, users can obtain the corresponding allowable stress values by selecting parameters such as steel type, steel grade name, design temperature, and nominal thickness. The material data in the system are sourced from the GB/T 150-2011 standard, ensuring the authority and accuracy of the data. The material data of the assessment system is imported through Navicat for SQLite, a visual management tool for SQLite. The specific operation steps are as follows: 1. Database connection configuration: Create a connection with the local SQLite database in Navicat for SQLite, ensuring that the database file path matches the system configuration. 2. Data import: Through the visual interface of Navicat, import material parameter data in a structured format (such as CSV or Excel) into the SQLite database, ensuring data integrity and consistency. 3. Data validation: After import, verify the accuracy of the data through SQL query statements to ensure that the material parameters can be correctly invoked by the system. The system integrates material data from the GB/T 150-2011 standard, with some fields in the database, including material type, steel grade, design temperature, nominal thickness, and allowable stress, ensuring data integrity and queryability.

3)Composition of Assessment Methods: This section divides defect assessment methods into nine types, with the specific classification shown in Figure 1. Each assessment method is designed based on its specific data flow and implemented through automation calculations within the system. The detailed data flow of each method is shown in Figures 3 and 4, ensuring the scientific and standardized nature of the assessment process.



**Figure 3.** Safety assessment process for volume defects in the straight section of a pressure pipeline

Based on the aforementioned data flow diagrams, the system streamlines and formulates various assessment methods, encapsulating them within the software as shown in the figure below. Users only need to input the measured data of the defective pipeline, and the system will automatically invoke the corresponding assessment algorithm to quickly generate accurate assessment results. This design significantly enhances the efficiency and reliability of assessments while reducing the complexity of manual calculations.

4)Exporting Defect Assessment Reports: After users have completed the calculations, they can select the option to export the assessment report from the File menu. This assessment report will

comprehensively present details such as user-input parameters, calculation results, safety evaluations, and failure assessment diagrams.

In this article, the specific development interface content utilized is outlined in the table below:

**Table 1.** Secondary development APIs for Word

Interface object	function
Application	Control or return application-wide properties, adjust the appearance of application windows, or other aspects of the object model.
Document	Open, create, add content, save, activate, print, or close files.
Range	Specify an area in the document and work on that area (such as inserting text or applying formatting).
Selection	Respond to user-selected content, such as text or areas, and manipulate it, such as formatting or inserting new content.
OMath	Use the Add (Range) method of the OMaths collection to create a calculation formula and add it to a document, selection, or range.

5)Creation and Integration of Help Documentation: To facilitate user operation, this system provides detailed help documentation that covers system function descriptions and parameter input guidelines. The steps for creating and integrating the help documentation are as follows: Users can access the documentation through the Help menu on the main interface to obtain system usage instructions and operational guidance.

Document Compilation: Use the Sublime text editor to create an HTML file and write the content of the help documentation using HTML markup language, ensuring that the document structure is clear and the content is complete.

Project Creation: Create a help documentation project using HTML Help Workshop software, import the compiled HTML file, and set the document title and homepage routing.

Document Compilation: Complete the compilation of the help documentation to generate a CHM format file and place it in the bin/debug directory of the project files.

System Integration: Add a HelpProvider control in the WinForm project, and in the load event of the main form, add the following code:

```
HelpProvider1.HelpNamespace = Application.StartupPath + "\\WordHelp.CHM";
```

This integrates the help documentation into the system, allowing users to easily access it when needed.

## 4. CASE STUDY

Case Description:During the regular inspection of a chemical pipeline at a certain company, an incomplete penetration defect was found at its weld seam. Due to the impossibility of directly conducting large-scale repairs on the pipeline, the assessment method for volumetric defects in straight sections of pressure pipelines outlined in GB19624—2019 was adopted. The basic information of the pipeline is as follows:

**Table 2.** Basic Information of the Pipeline

Pipe diameter, nominal wall thickness/mm	Design pressure/MPa	Design temperature/°C	Pipe material
1016× 14.6	8 MPa	room temperature	X70 steel

**Table 3.** Basic information on defects

Measured defect length	Measured defect depth	The closest distance the defect is from the surface of the plate $p_2$
6mm	2mm	9mm

Conventional Assessment Method:

### 1)Determination of Defect Characterization Size

The measured surface defect is characterized and regularized as an elliptical buried crack (coplanar crack) with dimensions of  $c = L/2 = 2.6\text{mm}$ ,  $a = h/2 = 1\text{mm}$ . According to Table 5-1 in the GB/T19624 specification, a safety factor  $K=1.1$  is introduced, resulting in dimensions of:  $c = 3.3\text{mm}$ ,  $a = 1.1\text{mm}$ .

### 2)Determination of Stress

The stress used in the assessment is the principal stress at the defect location. The specification stipulates the use of elastic calculation methods during the calculation process and assumes that there are no defects in the structure.

(1) The primary membrane stress at the defect location is caused by internal pressure and is calculated based on the theory of momentlessness.

$$\text{Thus, } P_m = \frac{PD}{4t} = (8 \times 1016)/(4 \times 14.6) = 139.18\text{MPa}$$

The primary membrane stress is considered to vary uniformly along the wall thickness, so the primary bending stress is 0 MPa.

(2) Secondary stresses include secondary bending stress, residual stress, thermal stress, etc. In this case, only welding residual stress is considered.

The residual stress generated by welding is considered as a secondary stress. The welding residual stress has not been measured in this project's research work. According to Table 5-2 in the GB/T 19624 specification, a value is taken to obtain the secondary membrane stress caused by welding residual stress:

$$Q_m = 0.3\sigma_s, \quad Q_b = 0$$

$$Q_m = 0.3\sigma_s = 0.3 \times 485 = 145.5\text{MPa}$$

In this case, there is no secondary bending stress. After applying the stress partial safety factors from Table 5-1 in the GB/T19624 specification, with  $K=1.25$  for primary stress and  $K=1.0$  for secondary stress, the stresses are calculated as follows:

$$P_m = 173.97\text{MPa}, \quad P_b = 0\text{MPa}, \quad Q_m = 145.5\text{MPa}, \quad Q_b = 0\text{MPa}$$

### 3)Determination of Material Performance Data

The mechanical properties of 0Cr18Ni9 stainless steel at room temperature are shown in Table 4. By consulting relevant materials, the pipeline material properties are obtained as follows:

**Table 4.** Basic properties of materials

Yield Limit $\sigma_s$ /MPa	Tensile limit $\sigma_b$ /MPa	Elastic modulus E/MPa	Poisson's ratio $\nu$
485MPa	570MPa	210000	0.3

See references [19]:

$$K_{IC} = 1.75 \times [149.47e^{-2.98 \times 10^4(T+273.15)}] = 193.92 \text{MPa}\sqrt{\text{mm}} = 6132.50 \text{MPa}\sqrt{\text{mm}}$$

#### 4) Calculation of stress intensity factor

In the calculation of the stress intensity factor, the deepest point and the shallowest point of the surface crack are calculated respectively (denoted as points A and B), and the  $K_I$  values of points A and B are obtained, and then the danger point is determined. The  $K_I$  values used in the calculations a, c, and the introduction of safety factors are taken.

Stress intensity factor of pipeline with elliptical buried cracks:

$$K_I = \sqrt{\pi a}(\sigma_m f_m + \sigma_b f_b)$$

Check GB/T19624 Appendix Table D.1-4, obtain:

$$f_m^A = \frac{1.01-0.37a/c}{\left\{1-\left(\frac{2a/B}{1-2e/B}\right)^{1.8} \left[1-0.4\frac{a}{c}-\left(\frac{e}{B}\right)^2\right]\right\}^{0.54}} = 0.92$$

$$f_b^B = \frac{(1.01-0.37a/c)[2e/B+a/B+0.34a^2/(cB)]}{\left\{1-\left(\frac{2a/B}{1-2e/B}\right)^{1.8} \left[1-0.4\frac{a}{c}-\left(\frac{e}{B}\right)^2\right]\right\}^{0.54}} = 0.42$$

$$f_b^A = \frac{1.01-0.37a/c}{\left\{1-\left(\frac{2a/B}{1-2e/B}\right)^{1.8} \left[1-0.4\frac{a}{c}-0.8\left(\frac{e}{B}\right)^{0.4}\right]\right\}^{0.54}} = 0.90$$

$$f_b^B = \frac{(1.01-0.37a/c)[2e/B-a/B-0.34a^2/(cB)]}{\left\{1-\left(\frac{2a/B}{1-2e/B}\right)^{1.8} \left[1-0.4\frac{a}{c}-0.8\left(\frac{e}{B}\right)^{0.4}\right]\right\}^{0.54}} = 0.24$$

Where:  $e = B/2 - p_1 - a = 2.7$

$$(K_I^P)_A = \sqrt{\pi a}(P_m f_m^A + P_b f_b^A) = 297.70$$

$$(K_I^S)_A = \sqrt{\pi a}(Q_m f_m^A + Q_b f_b^A) = 248.98$$

$$(K_I^P)_B = \sqrt{\pi a}(P_m f_m^B + P_b f_b^B) = 297.23$$

$$(K_I^S)_B = \sqrt{\pi a}(Q_m f_m^B + Q_b f_b^B) = 243.57$$

The stress intensity factor of point A is much higher than that of point B, so the safety assessment can be carried out at the deepest point of the crack A.

#### 5) Calculation of the fracture ratio $K_r$

The surface crack defect fracture ratio is calculated as follows:

$$K_r = \frac{G(K_I^P + K_I^S)}{K_P} + \rho = 0.13$$

Because there is no coplanar crack, the coefficient of interference effect,  $G=1$ .

The safety factor  $K=1.2$  was taken from Table 5-1 of GB19624, and the fracture toughness for evaluation was :  $K_P = K_C/1.2 = 5110.42$ .

Since  $\frac{K_I^S}{\sigma_s \sqrt{\pi a}} = \frac{K_I^S}{\sigma_s \sqrt{\pi a}} = 0.28$ , the specification figure 5-14 is at time of  $L_r = 0.37 < 0.8, \rho = 0.023$

#### 6) Calculation of load ratio

It is the abscissa of the failure assessment diagram FAD, which is an indicator of the plastic failure of the defective structure.

Calculated from the crack loading ratio on the upper surface of the internal pressure cylinder in Appendix C:

$$L_r = \frac{(3\xi P_m + P_b) + \sqrt{(3\xi P_m + P_b)^2 + 9[(1-\xi)^2 + 4\xi\gamma]P_m^2}}{3[(1-\xi)^2 + 4\xi\gamma]\sigma_s} = 0.37$$

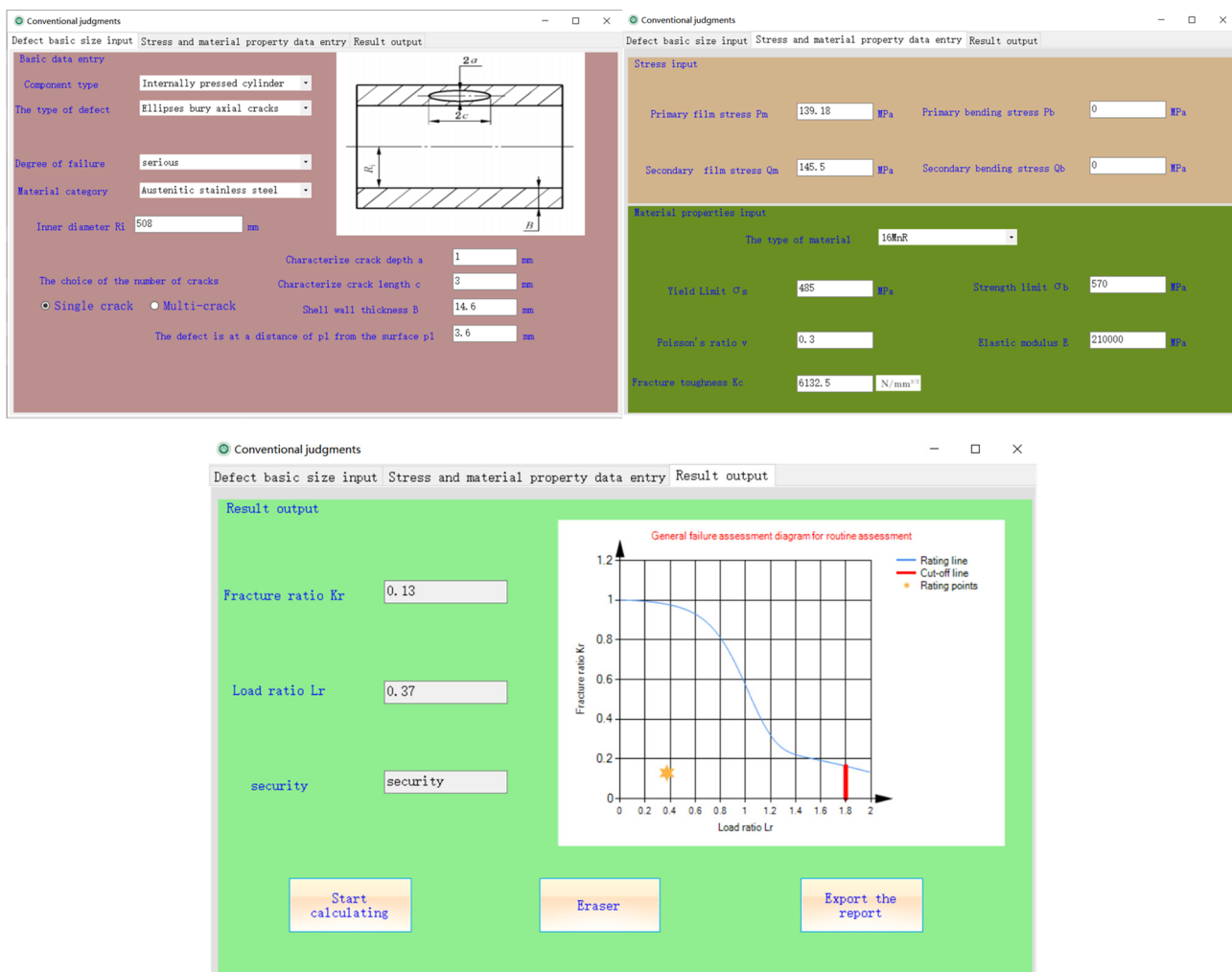
Where:  $\xi = \frac{2ac}{B(B+c)} = 0.028$ ,  $\gamma = \frac{p_1}{B} = 0.25$

### 7) Safety assessment

The values calculated in steps 5 and 6 are fused and formed to form a rating point  $(K_r, L_r)$ , i.e., a point (0.14, 0.26). Drawn in the general failure assessment diagram of conventional assessment, as shown in the following figure: the assessment point is located in the safety zone, so the defect is assessed to meet the requirements of use.

### 8) Systematic assessment calculations

In the safety assessment system, the component type was selected as the internal pressure cylinder, and the defect type was elliptical buried axial crack. Select the consequences of the failure of the destruction as "Critical". After that, enter the relevant material parameters and container parameters in the input column of stress parameters and material parameters, and the specific parameter input and defect type selection are shown in Figure.



**Figure 4.** Diagram of routine evaluation results

Comparing the evaluation results of the two calculations, the error does not exceed 1%, and both calculation results  $(K_r, L_r)$  are located within the safe area enclosed by the cut-off line and the

evaluation curve. Therefore, the defects evaluated this time are considered safe. This demonstrates the high calculation accuracy of the system.

## 5. CONCLUSION

Through the investigation and review of domestic and international standards, a systematic development process from requirement analysis, architecture design to functional implementation has been completed, ultimately constructing an efficient, reliable, and user-friendly safety assessment system. The main research conclusions are as follows:

- 1) The evaluation system can quickly address the safety issues of planar and volumetric defects such as pits, preventing the blind use or waste of defective pipelines, which could lead to significant economic losses. The software is capable of automating the processing of various defects and generating reports.
- 2) The user interface is friendly, the operation is simple, and the system is easy to expand. The calculation process is reliable, and the results are highly accurate. Furthermore, the feasibility of the system for safety assessment analysis of in-service pipelines has been verified through case studies, providing a new option for the evaluation of pipelines with defects.

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