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Key code R&D of LBB design for pipeline in reactor

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ABSTRACT: Leak before break (LBB) analysis code is an important tool for LBB design of high-energy piping in reactor, and it can ensure the accuracy of designed pipeline. This paper proposes a software embodied with a LBB code. LBB design technical background, R&D actuality of the Crack Stability code, Crack-Opening Displacement (COD) and leak rate code are first introduced. Numerical results are employed to demonstrate that the presented software can obtain more accurate results than the available ones for the same problems. Thus, this software can further be applied to practical engineering.
Keywords: LBB design; code development; crack stability; crack-opening displacement; leak rate

1 Background of LBB Design

In the traditional high-energy piping design of nuclear reactor, it is assumed that the pipeline break situation is a double-ended-guillotine-break (DEGB). However, nuclear power plants operating experience and experiment studies have shown that DEGB in large diameter pipeline has very low probability to occur. On the other hand, pipe fracture mechanic tests have also proved that there is a long fatigue crack growth period before the fast rupture of high-energy pipeline, which is called leak before break behavior. These research results have led to a new pipeline design technology, i.e., LBB design technology. LBB design technology can reduce the project cost by taking the advantages of the material properties and simplifying the piping system, and can further provide guide for the maintenance. Thus, LBB design has been regarded as an advanced technology, and has been extensively applied to nuclear power plant design and technology improvement.In the LBB design procedure, the key issue is to prohibit the disastrous double-ended rupture accident, which may be caused by unstable crack propagation, using fracture mechanics and leak rate analysis. The corresponding core technology is fracture mechanics analysis and leak rate analysis. Fracture mechanics analysis includes the critical crack length calculation, crack stability analysis and crack-opening displacement calculations, which are complementary with leak rate results. Fracture mechanics calculation and leak rate calculation decide whether the LBB criteria can be used in piping design or not. Critical crack length calculation, crack stability analysis and crack-opening displacement calculation are mechanical problems and are simple; but the leakage rate calculation is more complex than fracture mechanics analysis. Many uncertain factors can affect the leakage rate result, such as the crack geometric shape, flow path length, the friction effect and the thermal dynamics of fluid passing through the crack. Leak rate calculation is one of the most difficult parts in the LBB analysis.

Many professional LBB design codes have been developed and have been utilized to solve fracture mechanics and leakage rate analysis problems during the LBB design procedure based on the experiment and theory research in America, Russia, etc. However, In China, the application of LBB concept is slower than the developed countries, and there are no available credible codes developed by ourselves. Therefore, developing a recognized LBB design code is significant. This paper focuses on showing the presented LBB design code. The paper is organized as follows. The background of the fracture mechanics analysis, COD calculation and leak rate calculation are briefly introduced firstly, and then the R&D situation of the key code is introduced.

2 R & D of fracture mechanics analysis code for LBB design

LBB fracture mechanics analysis plays an important role in the procedure of LBB analysis, which is used to verify the resist capability of the cracked pipe crack to external loads. A series of fracture mechanics tests on full-size cracked pipe have been carried out by some international pipeline integrity research projects, and some LBB fracture mechanics analysis codes have been developed and verified by the experimental data and numerical analysis, such as FLET, NRCPIPE, FRACTURE and PICEP. In addition, some nonlinear finite element methods including ANSYS and ABAQUS have also been applied to LBB designs owing to their significant advantages in solving fracture mechanics analysis of the complex structures with complex loads.

There are various LBB fracture mechanics analysis codes, mainly including the simplified engineering methods and the refined elastic-plastic fracture mechanics analysis methods. The former consists of the Net-Section-Collapse criteria method, the plastic limit-load analysis method, and the flow stress criteria method. The simplified engineering methods can easily obtain the important information of LBB fracture mechanics analysis, such as the critical crack length. But the results are commonly conservative, which are usually used in the Level 1 LBB procedures. The latter includes the J-integral Tearing modulus intersection method (J-T) and R6 failure assessment diagram method (R6 method). The elastic-plastic fracture mechanics approaches are accurate and reliable for LBB fracture mechanics analysis, but these methods are time-consuming because they require the stress-strain curve and JR curves as input parameters, which are often applied to Level 2 LBB procedures. Therefore, LBB fracture mechanics analysis code usually consists of the simplified engineering methods and elastic-plastic fracture mechanics approaches in order to fulfill the requirements of LBB design in the first-level and second-level analysis.

The overall framework of the code developed by the authors is shown in Figure 1. This code has referred the same code in engineering and the novel trend of related disciplines. Some widely used engineering algorithms and the elastic-plastic fracture mechanics methods have been included in this code.

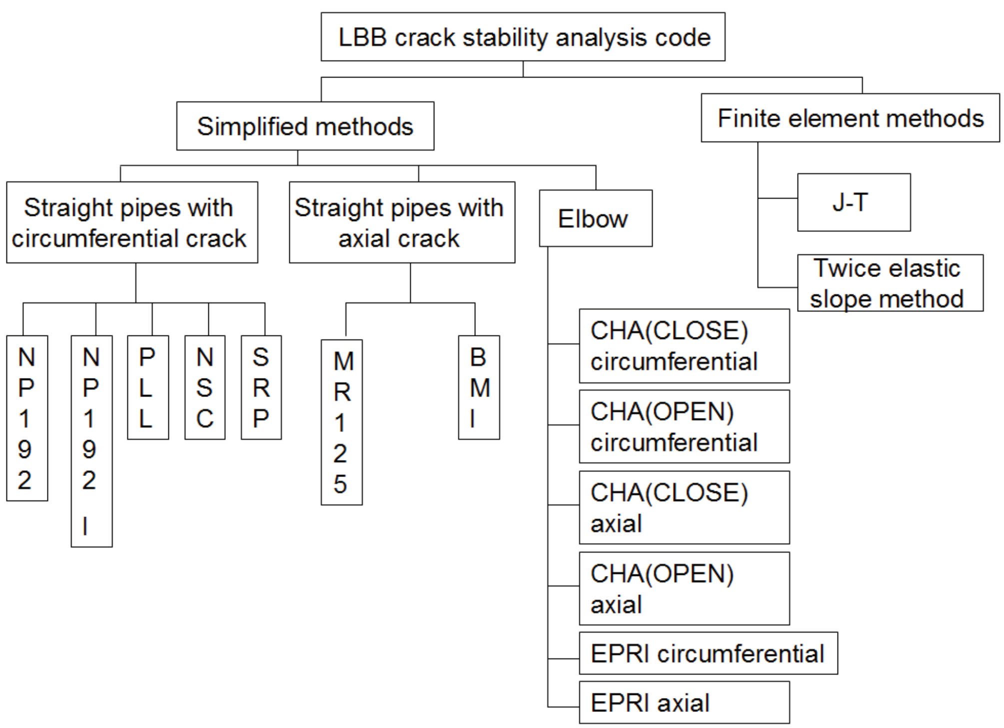

Figure 1. The flow diagram of LBB crack stability analysis code

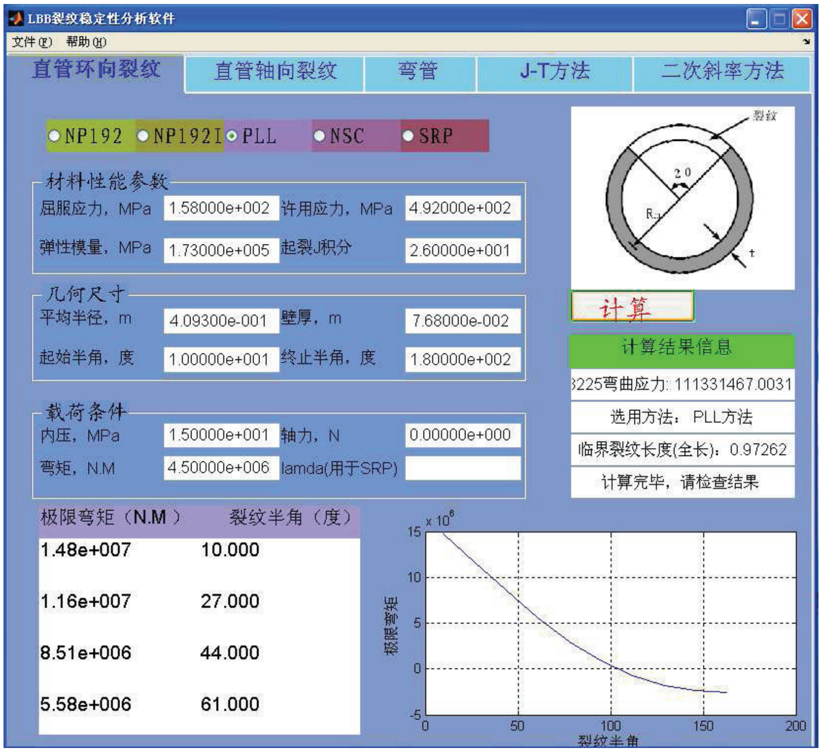

Figure 2 .The interface of LBB crack stability analysis code

The code has a very friendly interface and the code integrates a variety of methods, considering different types of cracks. The developed code has many advantages compared with the available ones. In addition, it has reserved an interface to the elastic-plastic fracture mechanics approach and can be extended to a wider range of application.

3 Development of COD calculation code

The value of COD can affect the results of the leak rate. A great value of COD leads to a great result of the leak rate and the leakage can be easily detected. COD usually depends on the geometry of the crack shape, component geometry, material properties and loading conditions. The corresponding methods include the linear elastic fracture mechanics method, elastic-plastic fracture mechanics method and the finite element method. The elastic-plastic fracture mechanics method and the finite element method can cope with the nuclear grade piping with high toughness. Some available dedicated LBB analysis codes, such as the SQUIRT developed by NRC, PICEP developed by EPRI and Russia's FRACTURE, can compute COD. These codes can calculate the COD of the through wall circumferential crack under the load of simple stretching, pure bending and the combination of them. Meanwhile, the axial COD can be obtained by NP-3596-SR, dimensionless COD curves from Rev.1 and many other methods. Compared with the straight pipes, it is difficult to calculate the COD of elbow pipe, and it requires more research on such topic. LBB analysis for the elbow pipelines has attracted more and more attention because elbow pipes are usually subjected to large moment loads

The results with reasonable accuracy can be obtained by either the linear elastic method or elastic-plastic approach when the loads are small, but the results will have a certain error compared with the accurate ones when the loads becomes large. The elastic-plastic finite element methods can usually result in a satisfied result of COD, but the corresponding computation is heavy. Thus, these methods can not deal with the practical engineering problems. Therefore, a reasonable COD code which satisfies LBB engineering design needs to fulfill the following requirements:(1)calculation methods for COD should contain linear elastic fracture mechanics algorithms and elastic-plastic fracture mechanics algorithms, and they should include sufficient algorithms to check the results;(2)The COD of the elbow pipes should be solved other than the axial and circumferential COD of straight tube.

According to the previous requirements, the presented block diagram has been shown in Figure 3.

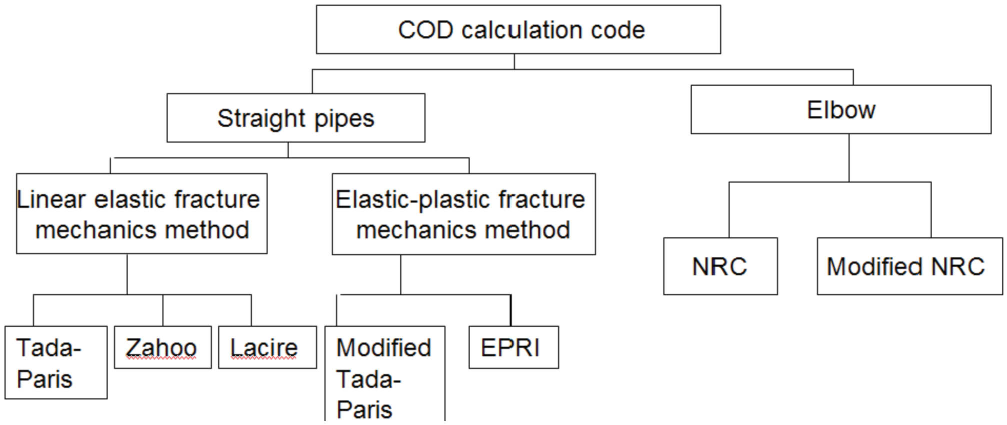

Figure 3. The block diagram of COD calculation code

4 development Fluid leakage rate code for pipe with through wall crack

Value of leak rate can determine the leakage when the pipe has through wall crack under the normal operating conditions of high-pressure fluid, and the leakage is regarded as the criteria for designing the monitoring system. The result of the leakage rate can affect the applicability of LBB design for pipeline. The codes evaluating the leakage rate usually employs the combination of the theoretical approach and experimental studies due to the complexity and the uncertainty of calculating leakage rate.

Two-phase flow theory is used to evaluate the leak rate of the small break dehydration problem in reactor, and there are many models for such problems, such as evenly balanced model, slip model, freezing flow model, unbalanced model and unbalanced two-fluid model. SQUIRT developed by NRC and PICEP developed EPRI are available widely-used leakage rate calculation code, in which corrected Henry two-phase critical flow model is the foundation. This model has many advantages to calculate the leak rate for a small break in the reactor accident. Many researches focus on the effect of the crack morphology parameters on the phenomenon of the thermal fluid. Experiments and numerical simulations reveal that the morphology of flow channel has an important effect on the prediction of leakage. The main morphology parameters of flow channel crack include surface roughness, the number of cracking corners and the ratio of the length of actual flow path to its thickness. NUREG/CR-6004 has explained the crack morphology in detail and has given a quantitative analysis for the effect of crack morphology on leakage.

Several large international research projects on structural integrity, including the aging of pipeline integrity code, international pipeline integrity code and BINP projects, have performed test verification about leak rate procedures for straight pipes, tees and elbows with fatigue crack and stress corrosion cracking. In addition, the study on crack morphology is also conducted accompanied with the leak rate test. The important input parameters such as the local roughness, the global roughness, cracks true length and the inlet morphology are obtained by the anatomical trial to test piece and the crack of true decommissioning pipeline.

According to the available leak rate codes, it is important to consider the effects of the crack morphology parameters on leak rate. Thus, based on the corrected Henry two-phase critical flow model and the combination of the related leak rate tests and the latest international research, the proposed code has the following features:

（1） Consider the effects of geometric shape of crack on the pressure loss.

（2）Introduce the effective roughness, the effective channel length and the effective corner number , and correct the pressure drop of flow path’ s corner as well as provide the sensitivity analysis of individual parameter.

（3）Calculate leakage rate when the entrance is super cooled water, two-phase flow and the super heated steam-gas with the situations of critical flow and un-critical flow.

5 Numerical example of code

Code verification is a very critical part to develop the LBB code, which determines whether the code can be used in practical engineering. Code validation can make use of relevant test data, on the other hand，the calculated results can be compare with the results calculated by internationally sophisticated code .

5.1 Verification of Crack stability analysis code

The proposed code is compared with the FRACTURE for Crack stability analysis shown in Table 1, while it is compared with the FLET for elastic-plastic fracture mechanics analysis summarized in Table 2.

Table 1:Verification of critical crack length of straight pipes circumferential cracks (FRACTURE example)

Proposed code algorithms	NP192	PLL	NSC	SRP
Critical crack length （m）	0.9826	0.9726	0.9886	0.9729
FRACTURE algorithm	NRC	MM	PLL	MR125
Critical crack length （m）	0.9826	0.6246	0.9669	0.9321

Table 2 :Validation of J-T methods and double slope method (FLET example)

Methods	FLET (R6 method)	J-T method	twice elastic slope method
Limit load	2.687×10^4	2.615×10^4	2.271×10^4

Table 1 shows that the presented code has obtained very satisfied results compared with FRACTURE.

Table 2 reveals that the results are conservative compared with R6, especially using twice elastic slope method.

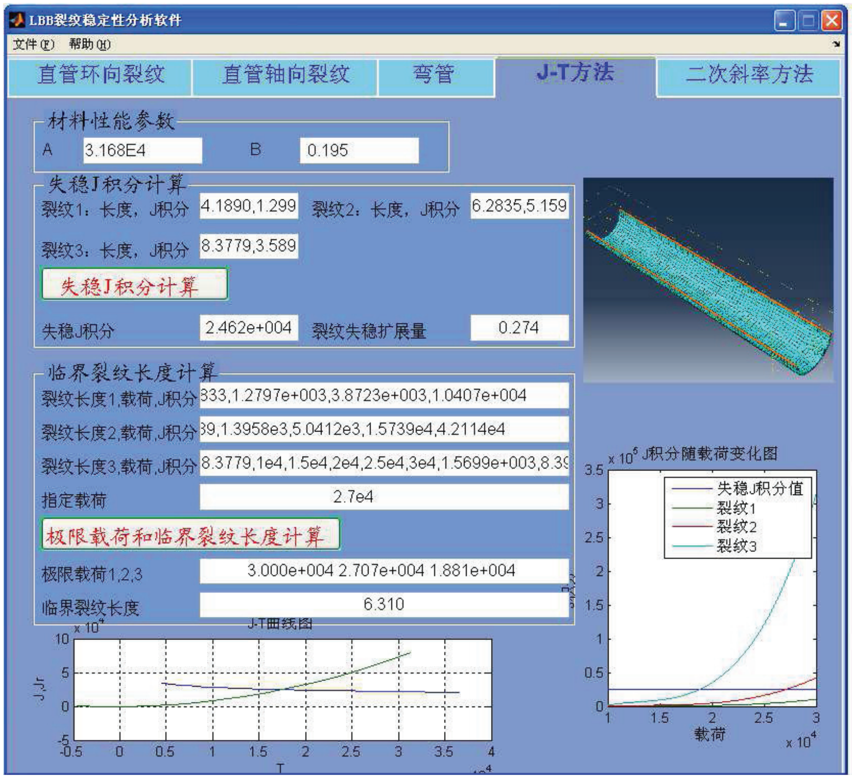

Figure 4. The Screen shot of calculating process of J-T algorithm

5.2 Verification of COD code and leakage rate code

COD and leakage rate calculation code are verified by PIECEP example. In the example, the values of global roughness is decided by NRC' recommendation, while the remaining load and crack morphology information is from PICEP example. Table.3-4 give the results of PICEP and the proposed code , respectively.

Table 3: PICEP Case 1

Crack length（m）	COD（PICEP）（m）	COD（Proposedcode ）（m）	Leakage rate（PICEP）（GPM）	Leakage rate（GPM）
0.04064	2.877e-5	2.824e-5	0.1287	0.1727
0.06096	8.303e-5	8.425e-5	0.8372	0.8693
0.07112	1.264e-4	1.292e-4	1.6598	1.6159
0.08128	1.814e-4	1.827e-4	2.93	2.7734
0.09144	2.489e-4	2.502e-4	4.8	4.5186
0.1016	3.302e-4	3.336e-4	7.4	7.1293

Table 4: PICEP Case 3

crack length （m）	COD （PICEP） （m）	COD （self-code ） （m）	leakage rate PICEP （GPM）	leakage rate （self-code ） （GPM）
0.21336	6.35e-5	6.42e-5	1.0852	1.17

Table 4 shows that the results from the presented code are very close to the ones of PICEP. The leakage rate is conservative when COD is small.

6 Summary

China has been lack of the LBB dedicated analysis code which are recognized by nuclear safety regulatory institute, which has become a constraining bottleneck in the development of LBB design technology. So the relevant work has become very urgent to carry out. In this paper, the work of developing the special code for LBB design has been conducted with the help of the state funded projects. The crack stability analysis code has initially completed at present, COD calculation code and the leak rate calculation procedures have achieved good results. The next work is to refine and validate the procedures using more experimental data and numerical examples, and make code apply in engineering project.

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