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Structural integrity analysis and site measurement for the RPV of Qinshan NPP

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ABSTRACT: This paper summarizes the general guideline for the structural integrity analysis and the site measurement on the RPV of Qinshan NPP. The analysis research includes loading combination, transient stress analysis, fatigue analysis, fracture evaluation, earthquake calculation, thermal shock analysis, interface parts analysis and pressure-temperature limits determination. Thus, the structural integrity is expounded and proved from the view of mechanical aspect. The site measurement shows that the limits and the evaluations given by software system are reasonable.

1. INTRODUCTION

A reactor pressure vessel (RPV) is one of the key components to a nuclear power plant (NPP). Because the RPV is not replaceable during the service life-time of the NPP and contains inside an irradiative high temperature and high pressure working media, its operating requirements are very strict. Therefore, under specified operating conditions, the RPV should have those features of its tightnessn assurance, of its loading ability to sufficiently prevent elastoplastic failure, of its anti-fatigue,anti-brittle fracture and anti-seismic failure abilities and its endurance to an irradiative enviroment. Thus, it is necessary to determine various loading conditions which are moderately conservative, to carry out an integral and reliable analysis, to give a reasonable stress limits and thereby, to perform a complete evaluation.

To carry out such a mechanical analysis aiming at ensuring the structural integrity of the RPV, the primary consideration is to form a logically complete general guideline and to establish a concept of integrity on the basis of a thorough study on a rule system, on a loading system and on a software system. And then, to make clearly the conservative margin in the analysis, some site measurements should be performed, making the engineering and the research aspects depend on each other. Thus,a logical system of research-analysis-site measurement-software which takes the rule system, the loading system and the analysis system as its main contents is then completed.[1]

2. RULE SYSTEM

A rule system is a complete logical system which includes laws, guidelines, standards, Codes and review plan.

From the investigation to the rule system, it should noted that the requirements of design by analysis in subsection NB of ASME Code III can only conditionally ensure the structural integrity of a RPV. Some complements which are not included in the Code should be added,such as the completeness consideration for operating conditions and loading combinations and the deformation limits and the analysis for tightness members, which reflect the containing ability of the working media.

The working media containing ability for a RPV and the relevant deformation limits present as rotation and seperation of the flange mating surfaces. When it is difficult to measure the direct characteristic quantities , some related quantities, such as the rotation angles of the outer wall of the flange, can be taken to make deduction and judgement[2]. The bolt loading variation under different transients is directly related to the RPV tightness and to the general loading endurance ability and belongs to primary stress loading. However, in ASME Code, there is no relevant criteria on bolt loading calculation, therefore, it is necessary to carry out experiments to accumulate the measuring data.

It should be pointed out that to a nuclear vessel design, satisfying the Code requirements is only a necessary condition, not a sufficient one. To ensure the structural integrity, some complement evaluations based on local enviroments and media experiments are sometimes indispensable, otherwise a sever consequence may occur under certain circumstances.

The structural integrity assrance should be based on the completeness concepts. It means that there should be a complete material, welding and examination assurance and a good enviromental effect test condition. Then, on the above basis, a complete comprehensive characteristic analysis can be carries out. To a mechanical analysis, the called "completeness" includes at least four contents: complete operating conditions and loading conditions, complete interfaces, complete functional failure criterion and complete stress limits. Accidents caused by the lack of the one of four integrities are occasionally reported .

3. LOADING SYSTEM

The design transients are enveloped following the principles of conservativity, moderation and conformance of stipulations. The transient loadings and the accident loadings are added to or combined in SRSS with the continuous loading, taking into account their transient effect and dynamic effect. There are some uncertainties in three loading conditions: bolt loading, temperature loading and nozzle loading. The bolt loading one of the fundamental loadings similar to pressure and temperature. It directly relates to the tightness of the RPV, to the fatigue behaviour of the bolt and to the stress and fracture analyses. The temperature lag of the bolt loading may cause the bolt over-loaded or relaxed, the former affecting the fatigue strength of the tightness member while the latter resulting in leakage of the multi-phase thermal conductivity and the thermal boundaries and thermal lag determination, it is still difficult to precisely calculate the increment of bolt loading caused by the thermal effect and to carry out site non-destructive measurement. Therefore, it is necessary to develop a measurement research [3].

The temperature loading determination depends on the system temperature curves both on the hot and cold legs, the thermal boundaries, the heat exchange coefficients of the media , the thermal conductivities of the material and etc., therefore, some uncertainties exist. If some temperature measurement points are arranged at internal and external walls of the RPV during hot commisioning of the NPP, then the heat exchange coefficients of the media and the exact thermal conductivity for the RPV material can be obtained, which is of significance to accumulate engineering data and then to deduce to a thermal analysis.

To the nozzle loading, having only calculated results is not sufficient and the calculated results should be verified by the site measurement taken in the commisioning procedure. The system hydraulic test should be taken not only as a means for engineering examination but also as an important way to verify the loading conditions and the calculated results. Strain and displacement measurement should be arranged during the commisioning and some important technical parametres such as the internal pressure loading curve, the temperature loading curve, the variation of bolt loading increment, the main bolt-stud engagement efficiency and the effective bolt length, the flange raise and the rotation angle of flange outer wall, and the temperature distributions at some characteristic points, should be obtained from the site measurement.

Besides the site measurement durimg commisioning, it is of great engineering significance and technical importance to arrange a transient monitoring system and to establish a site measured loading spectrum. Thus, the conservative margin for analysis can be obtained and the life-time management for the RPV can be carried out.

4. ANALYSIS SYSTEM

As one of the safety analysis aspects,the transient stress analysis is a bound limit analysis which is applicable for engineering evaluation and has some conservative margin rather than a real stress analysis. Some conservative substitutions for operating conditions and loading conditions are allowed to simplify the analysis. When performing analysis, the calculation model, such as one-body model, thermal analysis model and nozzle model, should be thoroughly analyzed and compared.

Stress evaluation is then undertaken. Its essence lies in providing stress evaluations for three kinds of strength of the vessel: general strength, i.e. general membrane stress intensity, limit is S_m; local strength, limits are 1.5Sm for primary stress considering local plastic failure, and $3S_m$ for secondary stress considering shakedown failure, and fatigue strength considering fatigue damage accumulation caused by peak stress.

The ASME Code adopts linear damage accumulation criteria to perform the fatigue analysis, which is suitable for high stress case, and considers the interference between different alternative stresses having different amplitudes. This fatigue analysis method takes into account the maximum stress difference range for the whole service operating conditions in the whole history, thus,it is conservative. The problems lie in that only the total life-time is considered, not dividing the different damage stages, and the fundamental experiment which is taken as the base the $\Delta\sigma$-N curve was carried out in air rather than in corrosive water. Therefore, some fundamental researches have being undertaken.

Actually, before the completion of the whole fatigue analysis, it is often required to provide a simplified fatigue estimation. Then a dual-factor fatigue estimation is provided, taking into account only the main operating conditions and the main peak stress points in the first five terms of the damage accumulation factor [4,5].

The fracture analysis method recommended by the ASME Code is based on linear fracture mechanics, which is suitable for a fundamental hypothesis that before the crack begins to propagate, the size of the plastic zone at the crack tip is much less than the size of the crack. Actually, however, owing to the ductility of metal material, the plastic zone has often the similar size as the crack before the crack propagation, thus, in fact, there is no case which totally satisfies linear elastic fracture mechanics. Therefore, it can be concluded that the ASME method is from the view of safety consideration. The ASME's hypothesis for crack length as $a=t/4$ in Code III App. G conforms substantially the condition of the linear elastic fracture mechanics, but the condition of $a/t \leqslant 0.1$ in Code XI App. A does not satisfy the above requirements. In addition, to closure head high stress zone, the fracture toughness requirements of IV A.2 in 10CFR 50 App. A is reasonable, however, comparing with these requirements, those in ASME Code III App. G G-2222(C), which only mention the adjustment value rather than the requirements for raising temperature, are not sufficient for under critical condition [6].

The interface parts stress analysis and fatigue analysis aims at ensuring the structural integrity on interface boundaries. Some points should still be noted, such as the dynamic loading of CRDM, the uncertainty of interference fit and the weld effect [7].

Computer program is the main means to implement the analysis and evaluation. During the analysis some software have been developed, such as the sealing analysis program SMEC, the dynamic peak point selecting fatigue evaluation program FATIGU [8,9]. A general structural program SYSTUS has also been used.

A RPV pressure-temperature limit curve was established to consider the long-time irradiative effects for the core belt zone of the vessel. (see Figure 1)

For thermal shock analysis, some typical accident transients were adopted to obtain the temperature gradient and to calculate the thermal stress response.

5. SITE MEASUREMENT

The site measurements were carried out during the site hydrostatic test and the NPP's commisioning under hot condition, aiming at obtaining some key parametres for mechanical analysis through strain and displacement measurements and bolt loading increment measurement. The main results are shown in Figure 2 to Figure 4.

According to the measured strain and displacement for the main bolt, the average engagement efficiency can be obtained as:

$$\eta = H'/H = 52\% \qquad (5.1)$$

Here, H is the engagement length, H' is the effective engagement length. The average effective bolt length L_e can be written as:

$$L_e = L_f + \eta H \approx H/2 + L_f \qquad (5.2)$$

Here, L_f is the bolt connection distance, i.e. flange thickness. Figure 3 shows the bolt engagement effect versus the acting pressure.

The relationship between the measured flange pre-tight rotation angle and the pre-tight loading is shown in the curve in Figure 4. From this curve, the bolt loading pressure increment, which is a very practical technical parametre, can then be deduced[10].

The bolt loading can be divided into three parts: main bolt pre-tight loading F_0, loading increment caused by pressure ΔF_p and loading increment caused by thermal effect ΔF_T:

$$F = F_0 + \Delta F_p + \Delta F_T \qquad (5.3)$$

Mechanical measurement and ultrasonic measurement were implemented for ΔF_p and ΔF_T under a heat-up and a leakage test conditions (see detail in [11] and Figure 5,6).

The summarized conclusions of the site measurement for the RPV of Qinshan NPP are listed on the follows:

(1) The RPV of Qinshan NPP is a type A vessel, i.e. its bolt loading increasing with the increasing of internal pressure [9]. The analysis results carried out by the computer programs conform well to the measured results and the conservative margin is moderate.

(2) The calculated maximum displacement on the outer wall of the flange is less than 1mm, the flange rotation angle is less than 8' and the circumferential strain on the outer wall is about 600$\mu\varepsilon$. The measured results are close to the calculated ones, indicating the reliability of the computer programs.

(3) The bolt loading, the bolt engagement efficiency, the bolt effective length and the loading spectrum obtained from the site hydrostatic test are very important technical data and can be taken as a basis for stress analysis and stress evaluation.

(4) The bolt loading increment caused by thermal transient is about 10% of bolt pre-tight loading. To the heat-up condition, the bolt loading increment can be taken as 30% of bolt pre-tight loading.

(5) The ultrasonic measurement for the bolt loading under hot transient was performed for bolts as long as 1.4 m and under a temperature as high as 280 ℃. This had not been before in publication and was a pioneer research.

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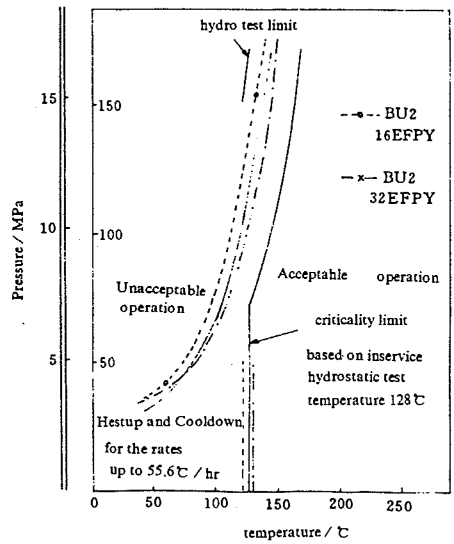

Figure 1 RPV pressure-temperature limit curves for 24 EFPY

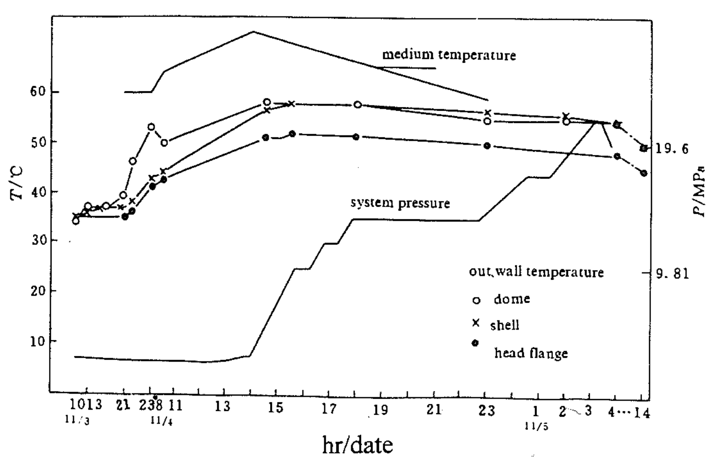

Figure 2 Temperature and pressure curves of system hydrostatic test

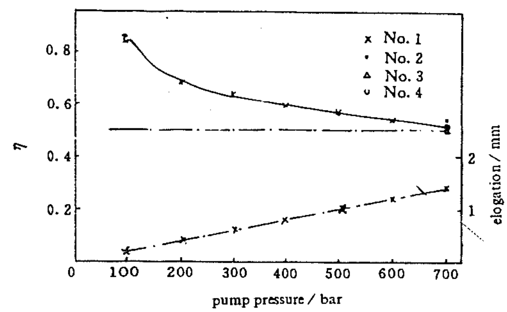

Figure 3 Bolt engagement effect versus the acting pressure

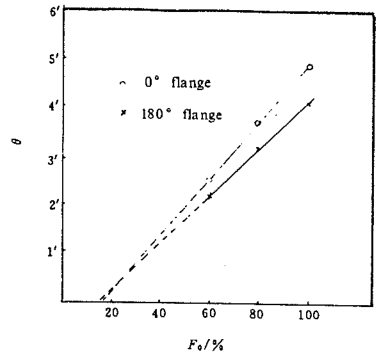

Figure 4 Relationship curve of flange rotation angle and pre-tight loading

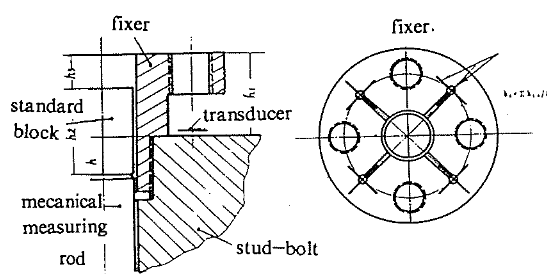

Figure 5 Fixer of transducer

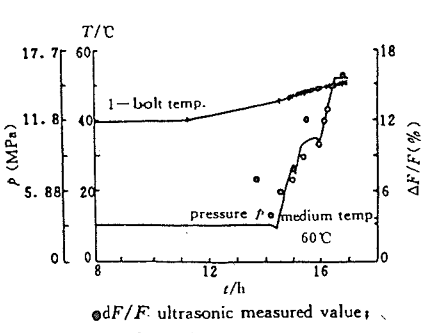

Figure 6a Stud-bolt loading increment under leakage test

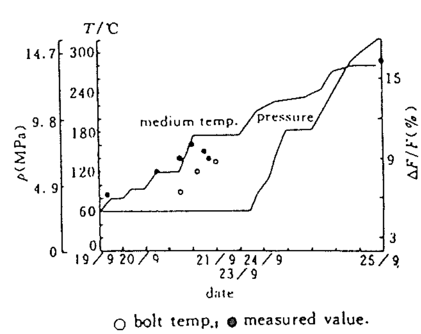

Figure 6b Bolt loading increment under heat-up condition