Research On Optimization Method of Fatigue Analysis for Nuclear Pipeline

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Abstract. The initial design life of nuclear power plant is 40 years. In 60 year life extending license application, the fatigue of component should be evaluated under the influence of the fatigue factors of the pressurized water reactor coolant environment. Because the original design used a more conservative analysis method, the result could not meet the requirement of Cumulative usage fatigue factor of RCC-M. An optimizing analysis method is studied, and as an example of application, optimizing fatigue analysis of Safety Injection Nozzle of Main Coolant Line is performed. The evaluation results show that the optimized fatigue analysis results meet the requirements of RCC-M.

1 Introduction

The repeated stress changes causing by changing pressures, thermal and mechanical loads acting on metal components can cause fatigue damage under sufficient stress cycles, and ultimately lead to component cracking. The latest research shows that in the reactor coolant environment, metal fatigue can be accelerated under specific temperature, strain rate, dissolved oxygen content and material conditions^[1].

There are researches on fatigue of nuclear grade stainless steel in high temperature water environment at home and abroad^[2-4]. Restricted by calculation technology, in the early design of Pressurized Water Reactor (PWR) nuclear power plants, nuclear-grade pipelines mainly adopted simplified fatigue analysis methods, only calculating the stress value of a scalar (one-dimensional) over time, and for some factors affecting fatigue, envelope method were adopted to calculate stress and fatigue utilization factor. This method has been proven to be conservative in most cases and can be used by designers to get a good judgment, but it is often too conservative and leads to a small design margin. To obtain more accurate and realistic calculation results, it is necessary to study new calculation methods to replace the original simplified formula method.

This paper proposed a fatigue optimization analysis method for the life extension of nuclear power plants, and used the safety injection nozzle as an example to calculate. According to the method specified in NUREG/CR-6909^[5], the influence of the fatigue promotion of the coolant environment was considered, and the fatigue analysis results of the injector nozzle in service for 60 years were obtained.

2 Fatigue analysis optimization method

According to the actual situation of nuclear first-level pipelines of nuclear power plants, the fatigue optimization analysis method is mainly composed of four optimization methods, including three-dimensional analysis method, transient combination optimization, thermal expansion load combination optimization, and using transient times based on actual operation statistics.

2.1 Three-dimensional analysis method

The three-dimensional analysis method uses the three-dimensional finite element method to calculate the pressure stress and thermal stress, which is more accurate than the one-dimensional calculation.

2.2 Transient combination optimization

In fatigue analysis, unless otherwise specified, the most demanding combination results of all transient pairwise combinations are selected. In the actual situation, it is impossible to directly combine some transients. For example, in the transient condition of cold shutdown, it needs to experience the transition transient from cold shutdown to hot shutdown before the transient operation of thermal shutdown and power operation can be achieved. Therefore, the number of transients from cold shutdown to hot shutdown limits the combination of cold shutdown transients, thermal shutdown and power operation transients.

To avoid the transient combination in the fatigue

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calculation process being too conservative, all transients can be divided into three groups:

- The first group: cold state to cold shutdown
- The second group: cold shutdown to hot shutdown
- The third group: thermal shutdown to full power

The transient times of the second group of working conditions limit the number of combinations of the first group and the third group of working conditions. After the number of combinations is exceeded, the first group and the third group will no longer be combined, only combined between internal transients.

2.3 Using thermal expansion load optimization

The thermal expansion load often uses the envelope value, and the calculated stress amplitude is relatively conservative. By adopting the thermal expansion load corresponding to each transient, the stress amplitude can be reduced, thereby obtaining a more accurate cumulative use factor.

2.4 Transient times based on actual running statistics

The operating practice of nuclear power plants shows that the number of design transients is often much larger than the number of transients in actual operation due to conservative assumptions. Through years of operating experience and statistical results of nuclear power plants, it is possible to effectively predict the expected number of transients in subsequent operations.

Using transient times based on actual operating statistics has a more obvious optimization effect on the fatigue analysis results.

3 Environmental fatigue correction factors

The influence of the reactor coolant environment on the fatigue life is expressed by the environmental influence factor F_{en} , and the correction calculation is shown as follows:

$$U_{en} = \sum_{i=1}^n U_i F_{en,i} = U_1 F_{en,1} + U_2 F_{en,2} \cdots + U_i F_{en,i} \quad (1)$$

In the formula, n is the number of transient combinations, $F_{en,i}$ is the environmental impact factor corresponding to the i -th transient combination, and U_i is the cumulative use of fatigue before the i -th transient combination without considering the environmental impact factor.

According to NUREG/CR-6909, the environmental influence factor F_{en} of austenitic stainless steel in the coolant environment is related to the coolant temperature, strain rate and the dissolved oxygen content of the coolant:

$$F_{en} = \exp(0.734 - T' \dot{\epsilon}' O') \quad (2)$$

The definition of $T' \dot{\epsilon}' O'$ can be referred to

NUREG/CR-6909.

4 Examples of fatigue optimization analysis methods

4.1 Model and analysis path

Take the main pipeline safety injection nozzle as an example, using three-dimensional finite element to carry out fatigue analysis, as shown in Figure 1.

Considering 4 fatigue-sensitive positions:

- Position 1: The welding seam position of connecting pipe and auxiliary pipe
- Position 2: The transition position of nozzle thickness
- Position 3: The transition position of the connection between the takeover and the main pipeline
- Position 4: The welding seam position of the connection pipe and the main pipeline

Figure 1 Finite element model

Figure 2 Schematic diagram of the analysis position of the safety injection nozzle

According to engineering experience, during fatigue analysis, the upstream, downstream, and intermediate cross-sections of the coolant flow at all four locations were analyzed by the analysis path for fatigue evaluation. The evaluation path is shown in Figure 2.

4.2 Loads and boundary conditions

- (1) Thermal load and pressure load

The transient frequency of the safety injection nozzle adopted the predicted number of 60 years of service, and the transient frequency took the envelope value of Unit 1 and Unit 2.

The inner surface is subjected to transient temperature load, and the heat transfer between the inner surface and the medium is determined by the medium temperature and heat transfer coefficient; and the outer surface is considered as adiabatic due to the covering of the insulation layer.

The pressure load is applied to the inner surface in the way of unit load, and the end effect caused by the pressure is considered. The stress cloud diagram is shown in Figure 3.

Figure 3 Stress cloud diagram under unit pressure load

(2) Other mechanical loads

Other mechanical loads considered in the fatigue analysis mainly include thermal expansion load, pressure expansion load, dead weight load and OBE load.

4.3 Number of transients

The statistical value of the actual operating transients of the power plant is much smaller than the design transients. For example, the fatigue impact of the safety injection nozzle is the most obvious transient, the safety injection system abnormal startup transient, and the 40-year design transient is 80 times, but according to statistics, it is estimated that the number of occurrences in 60 years is only 4, which is far lower than the design value.

Considering the 60-year transient times predicted based on the actual operating transient statistics of the power plant, the fatigue assessment results have a greater optimization effect.

5 Fatigue assessment

The fatigue assessment adopts the RCC-M standard A-level criteria, and the stress combination method is based on RCC-M ZE200.

According to the requirements of the operation manual of a nuclear power plant: the dissolved oxygen content of the primary circuit coolant is controlled within 0.10ppm, so $O'=0.281$; according to the "Cold Pipe Section Safety Injection (6 in) Nozzle" 60 years of service transient prediction times fatigue analysis, the average value of the maximum temperature corresponding to the two transient combinations in the stress cycle of the contacting liquid surface should be less than 325°C, so the conservative value is $T'=1$; corresponding to the effect of strain rate on environmental fatigue, the conservative value should be $\dot{\epsilon}' = \ln(0.0004/0.4) = -6.91$ (3)

According to formula (2), the environmental fatigue correction factor F_{en} of austenitic stainless steel is:

$$F_{en} = \exp(0.734 - T' \dot{\epsilon}' O') \quad (4)$$

Regardless of environmental fatigue, the evaluation results of the cumulative fatigue use factor of each sensitive position of the safety injection nozzle are shown in the third column of Table 2. The position with the largest cumulative use factor appears in the upstream section of the transition position between the connection pipe and the main pipeline, and the maximum cumulative use factor is 0.036, which meets the specification requirements.

Considering environmental fatigue, the cumulative fatigue use factor evaluation results of each sensitive position of the safety nozzle are shown in the 5th column of Table 2. The position with the largest cumulative use factor appears in the upstream section of the transition position between the connection pipe and the main pipeline, and the largest cumulative use factor is 0.523, which meets the specification requirements.

It can be seen from Table 1 that the position with the largest cumulative use factor appears in the upstream section of the transition position between the connection pipe and the main pipeline. Take this section as an example, the use factors generated by the first 5 transient combinations under the 60-year forecast times and the usage factors generated by 1.5 times the 40-year design transient times are compared in Table 1.

Table 1 Assessment of the cumulative use factor of environmental fatigue under the 60-year transient prediction times of the safety injection nozzle of the cold pipe section

Sensitive location	section	Fatigue cumulative use factor (CUF)	Environmental fatigue correction factor (F_{en})	Environmental fatigue accumulative use factor (CUF_{en})
Position 1: The welding seam position of the connecting pipe and	Upstream section	0.002	14.52	0.029

auxiliary pipeline	Middle section	0.001	14.52	0.015
	Downstream section	0.002	14.52	0.029
Position 2: Take over the thickness transition position	Upstream section	0.000	14.52	0
	Middle section	0.001	14.52	0.015
	Downstream section	0.008	14.52	0.116
Position 3: The transition position of the connection between the takeover and the main pipeline	Upstream section	0.036	14.52	0.523
	Middle section	0.011	14.52	0.16
	Downstream section	0.027	14.52	0.392
Position 4: The welding seam position of the connecting pipe and the main pipeline	Upstream section	0.000	14.52	0
	Middle section	0.000	14.52	0
	Downstream section	0.001	14.52	0.015

Table 2 The use factors and comparison of the top 5 transient combinations under 60-year forecast times

Transient combination*	Unit recycling factor	60-year forecast of transient times		1.5 times the number of design transients in 40 years	
		Number of combinations	Use factor	Number of combinations	Use factor
68-52.2	0.002574	1	0.002574	4	0.010296
17.2-52.1	0.002012	4	0.008047	120	0.24144
17.2-52.1	0.001969	4	0.007875	120	0.23628
17.2-52.2	0.00195	1	0.00195	30	0.0585
17.2-54	0.00176	1	0.00176	15	0.0264
		Cumulative use factor	0.022206	Cumulative use factor	0.572916

*Note: Transient 68, primary circuit hydraulic test: single hydraulic test

Transient 52.2, the takeover of the safety injection system (RIS) in the cold section: abnormal pressure drops in the primary circuit (RIS transient)

Transient 17.2, exhaust after the primary circuit refueling

Transient 52.1, abnormal start (RIS transient)

Transient state 54, shutdown from normal operation state (RIS transient state)

It can be seen from Table 3 that because the 60-year forecast times are much less than 1.5 times the 40-year design transient times, resulting the calculation result of the fatigue cumulative use factor is significantly optimized compared with the 40-year design transient times.

6 Conclusion

The safety injection nozzle of the cold pipe section of the nuclear power plant bears the hot and cold transients in the main coolant loop system. The large temperature difference leads to large thermal stress, and the three-way structure causes stress concentration, which is a metal part with high fatigue accumulation factor and small evaluation margin in the fatigue analysis. In the life extension project of operating nuclear power plants, the cumulative use factor evaluation reported by the original designer for 60 years of service will be too conservative.

Through the study of various factors that affect the fatigue calculation, the optimized method was used to calculate the cumulative use factor of the safety nozzle fatigue, the influence of environmental fatigue was corrected, and the calculation result satisfied the requirements of the specification. The analysis method in this paper was successfully applied to the fatigue analysis project of a certain nuclear power plant life-extending metal components, ensuring the smooth development of the nuclear power plant life-extending project. This method can be extended to be used in the subsequent fatigue analysis of in-service nuclear power plants and the fatigue analysis of high-temperature and high-stress metal components at the design stage.

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