Failure analysis of the rubber expansion joint of fire water system in a nuclear power plant

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Abstract: The rubber expansion joint of fire water system in one nuclear power plant was cracked during service. By means of macroscopic and microscopic analysis, combined with mechanical calculation, the reasons of cracks in this expansion joint were analyzed. And the results showed that: the joint action of concentrated stress caused by improper installation and unqualified rubber material led to the crack source. With the crack propagation, part of the flange was separated from the main body of the expansion joint. Recommendations were then proposed to avoid the recurrence of similar events.

1. Introduction
Compared with common industry fire, fire in a nuclear power plant may not only cause casualties and economic losses, but also a threat to nuclear safety. Therefore, the fire water system of a nuclear power plant should have sufficient reliability.

In order to improve reliability of the fire water system of a nuclear power plant, a design change was performed. In the first year, the upstream and downstream pipes of the butterfly valve were replaced while a expansion joint adhering to the standard HG/T 2289-2017: Flexible rubber joint was added upstream of the valve to absorb pipeline deformation. In the next year, it was found that the expansion joint was broken and fire water was leaking. Operational parameters of the expansion joint are listed in Table 1. This work mainly analyzes the failure reasons of the expansion joint and puts forward improvement suggestions.

Table 1 Operational parameters of the expansion joint

| Name               | Size   | Design pressure | Design temperature |
|--------------------|--------|-----------------|--------------------|
| The expansion joint| DN300  | 1.0MPa          | Outdoor temperature|

2. Physical and chemical test

2.1 Macroscopic examination
Fig. 1 shows the upstream and downstream pipes do not maintain coaxial, therefore the deformation occurs at the rubber expansion joint. Fig. 2 shows the damaged expansion joint, and the flange is separated from the main body of the expansion joint after fracture. In Fig. 3, the separated flange is assembled with the main body, which can be formed to a complete expansion joint. Fig. 4 shows the crack on the main body. The inner rubber layer is cut off and part of the middle fabric layer is sheared.
2.2 SEM analysis of fracture surface

The fracture surface to be observed in Fig. 4 is sprayed with gold, and the fracture morphology is observed under MIRA3 TESCAN electron microscope, displayed by Fig. 5. The parabola shape can be showed in the crack growth area, and the opening direction of parabola is considered to be the crack propagation direction[3]. In the thickness direction, after the 2mm-thick inner rubber layer is cut off, part of the middle fabric layer is also sheared. In the horizontal direction, the crack continues to expand to the flange edge. It can be inferred that area O in Fig. 4 is the starting position of the main crack. With the increase of the main crack length, the crack bifurcates at point M and produces a secondary crack perpendicular to the fracture direction when the product of propagation resistance and propagation velocity exceeds a critical value[4].

2.3 Infrared spectrum analysis of rubber

According to GB/T 7764-2017: Rubber identification infrared spectrometry, the chemical composition of the inner/outer rubber layer of this expansion joint was qualitatively analyzed by Fourier transform infrared spectrometer. The results of Fig. 6 and Fig. 7 shows that both the inner and outer rubber are polyisoprene.
2.4 Mechanical tests

Table 2 Mechanical tests results

| Position       | Tensile strength /MPa | Elongation at break /% | Bond strength /N•mm⁻¹ | Hardness /Shore A |
|----------------|-----------------------|-------------------------|------------------------|------------------|
| Inner rubber   | 6.79                  | 270                     | 3.6                    | 67.6             |
| Outer rubber   | 6.77                  | 280                     | 3.9                    | 69.6             |
| HG/T 2289-2017 | ≥13                   | ≥450                    | ≥2                     | 60±5             |

Mechanical tests results of inner rubber and outer rubber are listed in Table 2 according to GB/T 528-2009[^5], GB/T 532-2008[^6] and GB/T 531.1-2008[^7]. Except for the adhesive strength, results of tensile strength, elongation at break and hardness of the inner/outer rubber do not conform to HG/T 2289-2017. The tensile strength is only about 50% of the standard value, while the elongation at break is reduced to about 60% of the standard value.

3. Mechanical calculation

3.1 Modeling

![Fig. 8 Expansion joint](image1)

![Fig. 9 Deflection angle](image2)

The analysis model is established by measuring the geometric size of the expansion joint, shown in Fig. 8. Solid element is used in the model and rotational degree of freedom is applied to the end of the expansion joint.

The expansion joint is a composite material of natural rubber and nylon cord cloth. Its elastic modulus E=400MPa and Poisson's ratio ν=0.498 are obtained from references[^8].

3.2 Input parameters

Deflection angle of upstream and downstream pipes is 6.9°, taken as the calculation boundary referring to HG/T 2289-2017, displayed by Fig. 9.
3.3 Stress analysis result

The stress contour of the expansion joint is shown in Fig. 10, and the maximum stress area is on the inner rubber layer, which confirms the inference that area O in Fig. 4 is the starting position of the crack.

4. Failure analysis

Through macroscopic examination, SEM analysis of fracture surface and infrared spectrum analysis, this expansion joint consists of 3 layers: the inner rubber (polyisoprene) layer, the middle fabric layer and the outer rubber (polyisoprene) layer. The inner rubber layer is cut off and part of the middle fabric layer is sheared. From the parabola shape of fracture by SEM, it can be inferred that area O is the starting position of the main crack. In addition, the result of mechanical calculation confirms the inference. With the crack propagation, a secondary crack perpendicular to the fracture direction occurs at point M. Finally the flange is separated from the main body of the expansion joint.

As mentioned above, mechanical tests results show that tensile strength, elongation at break and hardness of the inner/outer rubber fail to meet HG/T 2289-2017. Moreover, chapter 8.2.3 of HG/T 2289-2017 points out that the rubber material is decided to be unqualified as long as one of these three tests results is substandard.

5. Conclusions and recommendations

1. The main reason for the rupture of the rubber expansion joint was that the upstream and downstream pipes failed to maintain coaxial, resulting in excessive stress on the inner rubber layer of the expansion joint.

2. According to HG/T 2289-2017, mechanical tests results of tensile strength, elongation at break and hardness proved that rubber material was unqualified. Furthermore, results of tensile strength and elongation at break were far below the standard values.

3. The combined action of excessive stress caused by improper installation and unqualified rubber material led to the crack source. With the crack propagation, the inner rubber layer was cut off and part of the middle fabric layer was sheared. In the end, part of the flange was separated from the main body of the expansion joint.

4. It is suggested to strictly follow the construction procedures to ensure that the upstream and downstream pipes maintains coaxial; At the same time, fixed supports should be added on the pipeline to prevent the large swing of the pipeline during the operation.

5. Material of Rubber expansion joints needs to be reinspected before acceptance.

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