The material comparison design of penstock pipe for a hydroelectric pumped storage station

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Abstract - Penstock pipe belongs to special pressure equipment, which has the risk of explosion. Therefore, it is necessary to strengthen the analysis of common accident damage forms and causes of penstock pipe, and do a good job in quality inspection to ensure the safe operation of penstock pipe. This paper mainly studies the penstock pipe of hydraulic storage power station. In the two kinds of steel, the more suitable steel structure is selected by semi elliptical crack analysis and FAD evaluation. According to the experimental data, steel B is more suitable for this structure. Because the failure time of the material, we make thickness correction with MATLAB. Finally, according to the analysis results, it is more appropriate to select steel B as the material of the penstock.

1. Introduction
Hydropower stations use water that falls from high to low levels to generate electricity. The middle penstock pipe is the pipe downstream of the main inlet valve, the length diameter ratio of penstock pipeline is very large, and it is easy to lose stability. The fluid flow state in penstock pipeline is complex, the buffer space is small, and the change frequency of working conditions is higher than that of pressure vessel. In this paper, the more suitable steel B is selected by semi elliptical crack analysis and fad evaluation, and the corrected wall thickness is obtained by MATLAB. Finally, the B-steel is selected as the material of penstock pipe [1]-[3]. In addition, this analysis method can be used for the selection of other penstock pipeline materials and specifications in engineering.

2. Fracture assessment

2.1 Types of the defect geometry
The defect geometry is defined in the mission requirements, it is a semi elliptical crack parallel to the pipe axis, which is a real crack.

In order to analyze the pipeline, the failure assessment diagram (FAD) is used to assess whether the structural defects will fail, the detailed analysis steps of this method are as follows[4]-[13].

2.2 Semi-Elliptical Crack

2.2.1 Steel A
In the realistic situation, the shape of the crack is a shallow surface with breaking semi-elliptical crack lying parallel to the axis of the pipe. Furthermore, in this situation, what needs to be concentrated on is
the deepest point of the crack. Additionally, to make the most serious case, the assumption has been made that the crack length $c$ is infinite compare to the deepest crack size $a$, shown in figure 1[14]-[21].

![Figure 1. Model of semi-elliptical crack](image)

Therefore, it can be obtained that

$$\frac{a}{c} = 0$$  \hspace{1cm} (1)

To calculate the factor $Y$, it is necessary to look up in the relevant handbook, For A-steel, it can get

$$\frac{a}{t} = 0.2$$  \hspace{1cm} (2)

Therefore, the geometry factor for A-steel is

$$Y = 1.4$$  \hspace{1cm} (3)

By calculation, the relevant parameters can be obtained from TABLE 1. To calculate the value of $L_r$, it can be obtained by the following equation.

$$L_r = \sigma_{hoop} / \left( \sqrt{\frac{a^2}{t^2}} \right) = 0.698$$

**TABLE 1. FAD DATE SUMMARY FOR STEEL A UNDER SEMI-ELLIPTICAL SIZE**

| $K_{IC}$ (Mpa$\sqrt{m}$) | $K_r$ | $L_r$ | $L_{max}$ | $(L_r, K_r)$ | $K_r^2$ |
|--------------------------|------|------|-----------|-------------|--------|
| 128                      | 0.565| 0.698| 1.071     | (0.698, 0.565) | 0.086  |

Thus, the FAD curve and relevant assessment points can be obtained below.

![FAD of steel A](image)

Figure 2. Failure Assessment Diagram of steel A for semi-elliptical crack size
It can be calculated from this figure that the safety factors are

\[ n_{res} = 1.275 \quad n_{n_{res}} = 1.348 \quad (5) \]

2.2.2 Steel B

Similar to the steps for A-steel, the safety factor can be obtained as follow.

\[ n_{res} = 1.498 \quad n_{n_{res}} = 1.61 \quad (6) \]

2.3 Comparison and remark

It can be seen from the two pictures that the safety factor of B-steel is greater than that of A-steel in the semi elliptical crack model. Therefore, B-steel is more suitable for this structure.

3. Sensitivity analysis concerning NDT methods

The Non-destructive testing (NDT) is to detect the internal and surface defects of various engineering materials by using the changes of thermal, acoustic, optical, electrical, magnetic and other physical quantities caused by the abnormal internal structure or defects of materials without damaging the tested objects.

It can be obtained from the handbooks that there are five kinds of NDT methods to detect the crack size[22]-[27].

3.1 The type of NDT

3.1.1 Penetrant testing

Shown in figure 3, it is mostly used to the surface of the pre-cleaned component.

3.1.2 Magnetic particle testing

The ferromagnetic material component is suitable to conduct this kind of test, shown in figure 4.
3.1.3 Radiographic testing
X-ray is used to search the structure and detect the crack size by proving the relevant images.

3.1.4 Eddy current testing
The magnetic field can be produced by applying an electrical current to make it pass through a coil, and the electrical current will change as it near a conductive material. Therefore, the crack can be detected by this approach.

3.1.5 Ultrasonic testing
By using this NDT method, the feedback can be obtained when sending the high frequency sound waves to the material, and through the feedback, the material can be judged, shown as figure 5.

3.2 NDT sensitivity analysis
By research process, the ultrasonic testing can be selected as the NDT method to detect the crack, however, the error might occur during the process of this test. Thus, the detectable crack size may be larger than 4mm if this error exists.

In order to continue this analysis, the assumption has been made to assume that accurate detectable will increase from 4mm to 8mm.

Based on the previous calculation, the following table can be obtained containing the relevant parameters based on different values of a based on the material of B-steel. The analysis results are shown in TABLE 2.
TABLE 2. DATA SUMMARY OF THE NDT SENSITIVITY ANALYSIS

| a     | Y     | $K_{pl}^P$ | $K_{pl}^S$ | $K_R$   | $K_R^S$  | $L_r$   | $L_r^{max}$ |
|-------|-------|------------|------------|---------|----------|---------|-------------|
| 6mm   | 1.08  | 28.99      | 10.38      | 0.512   | 0.135    | 0.657   | 1.21        |
| 8mm   | 1.09  | 33.79      | 12.09      | 0.597   | 0.157    | 0.698   | 1.21        |

Therefore, the relevant FAD and assessment points of the crack size 6mm and 8mm can be plotted below.

![FAD of steel B](image)

Figure 6. NDT sensitivity analysis

It can be concluded from this figure that the safety factor will obviously decrease with the increase of the crack size $a$, therefore, it will be the negative effect to the structure if the error of NDT is too distinctive.

4. Life time assessment

By the means of Paris law, the cyclic times from the detectable crack size to critical crack size can be anticipated. Additionally, it can be assumed that the geometry factor $Y$ is approximately constant when using the formula of Paris law[28]-[30].

4.1 Steel A lifetime

To calculate the critical size, the MATLAB programming is introduced to coordinate the variation of factor $Y$ with A-steel. Therefore, the critical size of A-steel is

$$a_c = 7.8\text{mm} \quad (7)$$

By using the Paris law

$$\int_0^{N_f} dN = \frac{1}{C Y^m \Delta \sigma^m \pi^2} \int_{a_i}^{a_f} \frac{m}{a^2} \, da$$ \quad (8)

With the material constant that has been obtained

$$C = 10^{-11} \quad m = 3 \quad (9)$$

The cyclic times with the defect shape of semi-elliptical to the critical size is
It can be obtained from requirement that the cyclic times for each year is 7500. Therefore, the time to failure for A-steel is

\[ N_f = \frac{2}{\sqrt{\pi^2 A_0^3 \gamma^{1.5}}} [\alpha_0^{0.5} - \alpha_c^{0.5}] = 1925.72 \]  
\[(10)\]

Therefore, the suggested interval inspection time is 3 months, and thus this material with the chosen wall thickness is not qualified if the interval inspection time is 5 years obtained from the requirement.

**4.2 Steel B lifetime**

Similar to the process in A-steel, the time to failure is

\[ T_f = \frac{N_f}{N} = 0.257 \text{year} \]  
\[(11)\]

Therefore, the interval inspection time should be less than 2.54 years for B-steel which is also less than the required time that is 5 years.

Therefore, it can be concluded that the B-steel is more suitable than A-steel, however, to both materials are not qualified when conducting the life assessment. Therefore, further revise for the wall thickness is required to continue.

**5. Revise of the wall thickness**

**5.1 Steel A**

It can be acquired from the requirement that the interval inspection time is 5 years, thus, the wall thickness need to be modified in order to make the failure time of both materials lager than 5 years.

Due to the huge amounts of calculations, the MATLAB programming is used to calculate the suitable wall thickness, and the relevant program can be found in appendix. The result shown as TABLE 3.

**TABLE 3. RESULTS OF THE REVISED WALL THICKNESS AND RELEVANT PARAMETERS**

| Thickness | Critical size | \( Y \) | \( N_f \) | Inspection time |
|-----------|--------------|--------|---------|----------------|
| 49mm      | 13.4mm       | 1.11   | 46325.25| 6.17 years     |

Therefore, it can be concluded from this figure that if the wall thickness is increased from 20mm to 49mm, the lifetime assessment will be qualified to the current requirement.

To check whether this thickness is qualified to the FAD assessment, the relevant parameters are acquired by furthering MATLAB programming, shown as TABLE 4.

**TABLE 4. DATA SUMMARY TO PLOT FAD FOR STEEL A WITH THE REVISE OF WALL THICKNESS**

| \( K_{1c}(\text{MPa}\sqrt{\text{m}}) \) | \( K_f^2 \) | \( K'_f \) | \( K_f \) | \( L_f \) |
|-------------------------------|------------|-----------|--------|-------|
| 128                           | 0.1552     | 0.068     | 0.2232 | 0.2483 |
| \( K_{1c}(\text{MPa}\sqrt{\text{m}}) \) | \( K_f^2 \) | \( K'_f \) | \( L_f^{\text{max}} \) |
| 19.8607                       | 8.7102     | 1.07      |

Therefore, the FAD assessment can be plotted below.
Therefore, the structure of steel A is qualified with revising the wall thickness.

5.2 **Steel B**

Similar to the step for steel A, after the relevant MATLAB programming, the revised results shown as TABLE 5.

| Thickness | Critical size | Y | Inspection time |
|-----------|--------------|---|-----------------|
| 47mm      | 21.2mm       | 1.2 | 40343          |

Thus, the wall thickness of B-steel can be modified from 40mm to 47mm to achieve the qualified interval inspection time which is 5 years.

By continuing the calculation, the relevant parameter to plot FAD shown as TABLE 6.

| $K_{IC}(MPa \sqrt{m})$ | $K_p^b$ | $K_f^s$ | $K_r$ | $L_r$ |
|-------------------------|---------|---------|-------|-------|
| 128                     | 0.1552  | 0.068   | 0.2232| 0.2483|
| $K_f^{s}(MPa \sqrt{m})$ | $K_f^{s}(MPa \sqrt{m})$ | $L_r^{max}$ |
| 19.8607                 | 8.7102  | 1.07    |

Therefore, the FAD assessment for B-steel shown as below.

Figure 8. Failure assessment diagram of steel B with the revise of wall thickness
6. Conclusion
In this essay, the wall thickness is roughly selected according to the diameter, water pressure and other requirements under known conditions. In order to make the analysis more practical, the defect geometry of semi ellipse shape is introduced. The results show that the geometric shape of semi elliptical defects will reduce the safety factor, and steel B is more reliable than A-steel. In addition, the sensitivity of NDT is analyzed. By increasing the value of detectable crack size, the error of detectable crack size is assumed. This shows that with the increase of non-destructive testing error, the risk of structure also increases. In addition, fatigue analysis was performed to estimate life and inspection interval inspection time. The results show that the two kinds of materials cannot be preserved for 5 years before they reach the standard failure crack size. Therefore, it is necessary to modify the wall thickness to meet this requirement. The modified wall thickness can be calculated by MATLAB programming. Finally, the 47mm steel B is selected as the more suitable material for penstock. At the same time, this method can be used as a means of material selection for important parts in engineering.

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