Study on the Reliability of Mechanical Components of Squib Valve in Passive Nuclear Power Plant

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Abstract. The action principle of squib valve employed in passive nuclear power plant was introduced and the main factors affecting the reliability of the mechanical components of the squib valve were analyzed, and the shear cover material of the squib valve was subjected to different strain rates at normal temperature, 155°C and 350°C. The parameter distribution of Johnson-Cook constitutive model was obtained by fitting the test data, and the impact velocity, material properties and failure strain of the squib valve piston were selected as random variables, and the reliability of the mechanical components of the squib valve was calculated by the joint simulation of ABAQUS+NESSUS. The results show that the reliability of the squib valve is high, and the mechanical performance of the shear cap material is the biggest impact on the mechanical reliability of the squib valve. The mechanical reliability of the squib valve is positively related to the impact speed of the piston. This study provides a reliable basis and reference for quantitative assessment of the overall reliability of the squib valve and the application in passive nuclear power plant.

1. Introduction
As the key equipment of passive core cooling system in new generation nuclear power plant, squib valve is mainly used in the fourth-level automatic pressure relief system, low-pressure safety injection circuit and containment recirculation circuit. Its reliability has always been the industry’s concern focus. The cost of reliability test for the squib valve is relatively high, and the commonly used reliability analysis methods cannot meet the needs of its reliability analysis. The data available for the reliability analysis of the squib valve is limited.

In this paper, by analyzing the action principle and failure mode of the mechanical components of the squib valve, the main factors affecting the reliability of the mechanical components are obtained. A model for interactive calculation of the reliability of the mechanical components based on the reliability software NESSUS and the finite element analysis software ABAQUS is proposed. The reliability of the mechanical components of the single-side shear squib valve is obtained. The research of this paper provides a basis for the reliability of the squib valve machine, and lay a foundation for quantitatively evaluating the reliability of the squib valve, which has important reference significance for the establishment of the reliability database of nuclear power equipment in China.
2. Action principle
The squib valve can be divided into two structures: single-side shear and double-side shear. As shown in the Figure 1 and Figure 2, and mainly composed of cartridge driving device, tension bolt, piston, shear cover, valve body and valve cover. The action principle of the two kinds of squib valve is similar: the igniter detonates after receiving the ignition command, the high temperature and high pressure gas is instantaneously generated, the tension bolt is pulled off, the piston is driven to accelerate downward movement, the shear cover is broken, and the flow channel is established.

![Figure 1. Single-side shear squib valve.](image1)
![Figure 2. Double-side shear squib valve.](image2)

3. Failure mode analysis
According to the action principle of the squib valve, its failure modes can be divided into five situations: failure of the driving device, failure of the tightening bolt, failure of the piston function, failure of the shear cover, and failure due to manufacturing tolerances. The failure of the mechanical components mainly refers to whether the shear cap can be successfully sheared after the piston hitting, which is mainly related to the material mechanical property of the shear cap and the impact speed of the piston. Therefore, in order to study the reliability of the mechanical components of the squib valve, the dispersion of the mechanical property of the shear cover material should be studied first.

4. Determination of random variables
4.1. Shear cover material properties test
In order to obtain the discrete distribution of the mechanical properties of the shear cover material (INCONEL 690), a large number of tests were carried out. The quasi-static test of the material was completed by the MTS universal material testing machine, and the dynamic test was completed by the Split Hopkinson Tension Bar (SHTB). The Johnson-Cook (J-C) dynamic constitutive model is used to fit the plastic mechanical property. The Johnson-Cook model is a pure empirical model, and the specific form is:

$$\bar{\sigma} = \left[ A + B\varepsilon_p^n \right] \left[ 1+C \ln\dot{\varepsilon} \right] \left[ 1 - T^m \right]$$

The J-C model contains five undetermined empirical functions: A, B, n, C and m, where A is the yield strength, B and n are strain strengthening parameters, C is the empirical strain rate sensitivity coefficient, and m is the temperature softening effect. The curve of stress with strain rate obtained is shown in the Figure 3. It can be seen that the material stress increases with the increase of strain rate, materials exhibit typical strain rate strengthening effects.
Figure 3. Typical true stress–strain curve of INCONEL 90 at different rates.

The elastic modulus obtained from the quasi-static mechanical test, the elastic modulus is counted, as shown in the Figure 4, it can be seen that the material elastic modulus distribution is relatively concentrated.

In addition, the failure strain is also a key parameter. By statistically analyzing the failure strain of the material obtained from the test, as shown in the Figure 5, it shows that the failure strain distribution of the material is relatively concentrated and presents the typical normal random distribution characteristics.

The normal hypothesis test was carried out on E, A, B, n, m and C, and the verification result was normal distribution, the mean and standard deviation of the material parameters were obtained. The summary is shown in Table 1.

Table 1 Material parameter normal distribution.

| No | Parameter | Mean       | Standard Deviation |
|----|-----------|------------|--------------------|
| 1  | STRAIN    | 0.56       | 0.12029            |
| 2  | V         | 20819.4mm/s| 490.2mm/s          |
| 3  | E         | 207.1Mpa   | 17.58Mpa           |
| 4  | A         | 269.5Mpa   | 27.65Mpa           |
| 5  | B         | 1282.4Mpa  | 42.12Mpa           |
| 6  | C         | 0.1329     | 0.018              |
| 7  | n         | 0.762      | 0.029              |
| 8  | m         | 1.216      | 0.275              |

4.2. Piston impact speed test results

The speed before the piston hitting the shear cap is based on the results of the squib valve machine test, and the distribution can be seen in the Figure 6, the speed distribution of piston is very concentrated, with the minimum velocity of 20m/s and the maximum velocity of 21.6m/s. The impact velocity of the piston conforms to the normal distribution, with an average value of 20.81935m/s and a standard deviation of 0.48221m/s.
5. Reliability model and results

5.1. Reliability model

ABAQUS is used to analyze the whole movement process of the squib valve from the piston impact until the shear cap is completely separated, which is the important index of the reliability of the mechanical components. The squib valve is a symmetrical structure, and its 1 / 2 finite element numerical model is taken, which mainly includes four parts: piston, shear cover, upper clamping block and lower clamping block, as shown in the Figure 7.

![Figure 7](image)

**Figure 7.** 1/2 model of single-side squib valve.

The results are shown in the Figure 8, the displacement of the squib cap in the impact direction at 0.51ms, 0.81ms and 1.5ms are given respectively. Crack have been generated at the position of shear cover ring section at 0.51ms, complete crack on the shear cover have been generated at 0.81ms, the shear cap has been completely separated from the shear cover body at 1.5ms. The results show that the shear cap has been separated from the shear cap body at 0.81ms. Furthermore, the displacement curve of shear cap is obtained, as shown in the Figure 9. The results show that the vertical displacement of shear cap is 9.88mm when the time is 0.81ms.
Figure 8. The displacement of the shear cover in the impact direction with time.

Figure 9. Displacement curve graph of shear cover node.

The reliability judgment function and judgment value are set for the reliability analysis:

\[ \text{Verify} = U - U_2 \]  \hspace{1cm} (2)

\[ U_2 = f_e(\text{STRAIN}, V, E, A, B, C, n, m) \]  \hspace{1cm} (3)

Where: \textbf{Verify} is the reliability judgment function; \textbf{U2} is the displacement of the shear cover; \textbf{U} is the judgment value; \textbf{TRAIN} is the failure strain of the shear cover material; \textbf{E} is the elastic modulus of the shear cover material; \textbf{A, B, C, n, m} are parameters of the Johnson-Cook.

The reliability of the mechanical components of the squib valve calculated by the joint simulation...
of NESSUS and ABAQUS using the Advanced Mean Value method (AMV) is 0.999999712895, which is extremely high.

5.2. Reliability Sensitivity
In addition, the Sensitivity Levels of each random variable and its influence on the effect on the final result are obtained, as shown in the Figure 10 and Figure 11. It can be seen from the figure that the mechanical properties of the shear cover material have a great impact on the reliability of the mechanical components of the squib valve, especially the failure strain of the material is large and negatively correlated; the impact speed of the piston also has a great impact on the reliability of the mechanical components of the squib valve, and it is positively related.

Furthermore, the Importance Levels of each random variable are obtained, as shown in Figure 12, similar results can be obtained from the figures, the mechanical properties of materials have a very important impact on the reliability of the mechanical components of the squib valve, especially the failure characteristics and dynamic performance of the materials.

6. Conclusion
Through a large number of material mechanical property tests, the discrete distribution of mechanical properties of shear cover material is obtained. Further, the reliability of mechanical components of one-sided shear squib valve is simulated and analyzed by using NESSUS and ABAQUS. The reliability of mechanical components of one-sided shear squib valve is 0.999999712895, which is extremely reliable. Furthermore through the sensitivity and importance analysis of each random variable obtained by reliability calculation. The results show that: the mechanical properties of materials is the most important factor affecting the reliability of the mechanical components of the squib valve, and it is negatively correlated. The impact speed of the piston also has an important and positive correlation on the reliability of the mechanical components of the squib valve.
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