



# Fatigue Life Analysis and Evaluation of Multi-Pipe Water Brakes

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**Abstract.** Based on the S-N curve of the water brake device material, the nominal stress method was used to calculate the fatigue life by comparing the stress concentration coefficient and nominal stress of the structural fatigue danger part, combined with the fatigue damage accumulation theory. Through empirical formula combined with experimental correction, according to the t-distribution theory, the S-N curve of the water brake device material is obtained according to the confidence and error requirements. Combined with finite element simulation analysis, the load spectrum and danger point stress are extracted, and the fatigue simulation and analysis software is used to identify the danger point of the water brake device and calculate the fatigue life.

**Keywords:** Rocket sled · Water brakes · Fatigue life · S-N curve

## 1 Introduction

The rocket sled is a ground equipment powered by a solid rocket motor and taxiing at high speed along a dedicated high-precision track, which can better solve many technical problems that may be caused by high speed and high acceleration in the development process of various aircraft, and complete the research on the aerodynamic, vibration, material, guidance and control characteristics of the test piece [1–4]. The speed of rocket skid rail test is getting faster and faster, to ensure the safe recovery of rocket skid, water braking is used at the end of the track. The principle of water brake is that when the rocket sled enters the brake section, the water brake device passes through the water tank between the tracks and uses the kinetic energy conversion principle to convert the kinetic energy of the rocket sled into the kinetic energy of water to obtain braking power and achieve the purpose of rapid braking [5, 6].

Rocket sled dynamics analysis is becoming increasingly important and popular [7–10]. Ordinary water brake devices are mostly horizontal double-pipe systems, which have efficient and safe braking capabilities for small-mass high-speed rocket skis. However, in the high-mass low-speed rocket skid braking, the braking effect of the double-pipe water brake device cannot meet the short-distance braking requirements, and the multi-pipe water brake device needs to be used for safe braking [11–13]. Test and simulation methods are used to verify whether the structure of the multi-pipeline water brake device is safe and reliable in the environment of large load and high repetitive work [14–16].

In this paper, a certain type of multi-pipeline water brake device is taken as the research object, and the S-N curve of the water brake device material is obtained by experimental correction, and the fatigue life is analyzed by commercial software.

## 2 Fatigue Analysis Based on Nominal Stress Method

The nominal stress method is the earliest formed anti-fatigue design method, which is based on the S-N curve of the material or part, compared with the stress concentration coefficient and nominal stress of the fatigue risk part of the specimen or structure, combined with the fatigue damage accumulation theory, check the fatigue strength or calculate the fatigue life.

The nominal stress method is generally used to calculate the fatigue life by linear fatigue cumulative damage theory. Linear fatigue cumulative damage theory means that under the action of cyclic load, fatigue damage can be linearly accumulated, each stress is independent and unrelated, when the accumulated damage reaches a certain value, fatigue failure occurs in the specimen or component.

Using Miner's theory, the damage caused by  $n$  cycles under variable amplitude load is:

$$D = \sum_{i=1}^n \frac{1}{N_i} \quad (1)$$

where  $N_i$  is the fatigue life corresponding to the current load level  $S_i$ .

Critical fatigue damage  $D_{CR}$ : If it is a constant load, obviously when the number  $n$  of cyclic loads is equal to its fatigue life  $N$ , fatigue failure occurs, that is,  $n = N$ . then  $D_{CR} = 1$ .

Miner theory is a linear fatigue damage accumulation theory, which does not consider the influence of load order, but in fact the loading order has a great influence on fatigue life, which has been extensively experimentally studied. For secondary or few stage loads, the critical damage value  $D_{CR}$  at the time of failure of the test piece deviates greatly by 1. For random loads, the critical damage value  $D_{CR}$  at the time of failure of the test piece is around 1.

Using the S-N curve after average stress correction, the fatigue life  $N_i$  corresponding to each stage of load is obtained, the fatigue damage  $D_i = n_i/N_i$  caused by the load of this stage is calculated, and then the fatigue life of the structure can be obtained according to the Miner linear fatigue damage accumulation theory:

$$C_p = \frac{D_{CR}}{\sum_{i=1}^n D_i} = \frac{1}{\sum_{i=1}^n D_i} \quad (2)$$

## 3 S-N curve of Water Brake Device Material

The material S-N curve of the multi-pipe water brake device was obtained by conservative estimation + experimental correction. The conservative S-N curve can be obtained by fitting the static performance data of the material, and then the fitted S-N curve can be corrected in combination with the test data, so as to obtain a relatively accurate S-N curve as the input for later fatigue life calculation.

## 4 Empirical Equation for S-N Curves

The relationship between the load and the lifetime of the material can be given directly from the experimentally determined S-N curve, but under limited test conditions can also be given by the empirical formula describing the S-N curve obtained by fitting.

The main empirical equations commonly used to describe S-N curves are:

a) Exponential function formula:

$$N \cdot e^{\alpha S} = C \quad (3)$$

where  $\alpha$  and  $C$  are material constants. Taking the logarithm on both sides of formula (3) yields:

$$\log N = a + bS \quad (4)$$

where  $a$  and  $b$  are material constants.

b) Power function formula

$$S^\alpha N = C \quad (5)$$

where  $\alpha$  and  $C$  are material constants. Taking the logarithm on both sides of formula (5) yields:

$$\log N = a + b \log S \quad (6)$$

The exponential function equation and the power function equation are the two most used empirical formulas in the S-N curve, and their advantage is that only less experimental data is required to analyze the curve, while the power function equation requires more data than the exponential function equation, but the accuracy of the fitted S-N curve is higher. Others include Basque's formula, Weibull's formula, and the three-parameter formula are also commonly used formulas in empirical equations.

### 4.1 Empirical Equation for S-N Curves

There are two methods for average stress correction on the S-N curve of the structure, interpolation method and equal life curve correction method. The S-N curves of materials under different load ratios  $R$  can be given, and the structural S-N curves under the average stress corresponding to each stage of load can be obtained by interpolating these curves. Only the material S-N data at a specific  $R$  can be given, and the is lifetime curve can be used to correct it.

Average stress correction formula:

Goodman's formula:

$$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_b} = 1$$

Gerber formula:

$$\frac{\sigma_a}{\sigma_{-1}} + \left( \frac{\sigma_m}{\sigma_b} \right)^2 = 1$$

Soderberg's formula:

$$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_s} = 1$$

In the formula:

$\sigma_a$  – the required stress amplitude,

$\sigma_{-1}$  – the stress amplitude corresponding to the stress ratio  $R = -1$ ,

$\sigma_m$  – mean stress,

$\sigma_s$  – yield limit,

$\sigma_b$  – tensile limit.

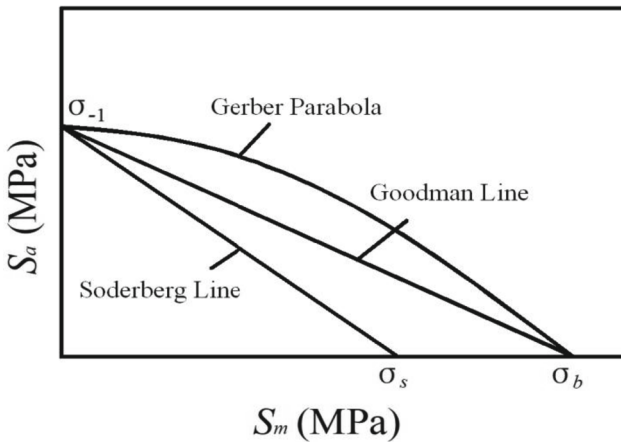


Fig. 1. Schematic diagram of the average stress empirical correction formula.

## 4.2 Empirical Test for S-N Curves

The test piece material is 30CrMnSiA, and the test piece form is divided into two types: 8 static test pieces, including 4 pieces of heat treatment and non-heat treatment, 5 pieces of fatigue test pieces, all heat treatment, the specific parameters are shown in Tables 1 and 2.

The relationship between the three empirical formulas of Goodman, Gerber, and Soderberg can be represented by Fig. 1. Because the Goodman linear formula is generally conservative, the Goodman linear formula is often used to correct the S-N curve after the test when the engineering material is 30CrMnSiA (heat treatment).

This test includes static test and fatigue test, static test using DDL-300 electronic universal testing machine, fatigue test using MTS Teststar  $\pm 100$  kN for loading, as shown in Fig. 2.

**Table 1.** Actual measurement size of static test piece.

Number	Width (mm)	Thickness (mm)
J1-1(Thermal)	10.1	10.6
J1-2(Thermal)	10.0	10.3
J1-3(Thermal)	10.1	10.5
J1-4(Thermal)	10.1	10.5
J2-1(No Thermal)	10.1	10.7
J2-2(No Thermal)	10.5	10.1
J2-3(No Thermal)	10.0	10.5
J2-4(No Thermal)	9.8	10.5

**Table 2.** Actual measurement size of the fatigue test piece.

Number	Width (mm)	Thickness (mm)
P2-1(Thermal)	15.2	6.08
P2-2(Thermal)	15.3	6.1
P2-3(Thermal)	15.5	6.08
P2-4(Thermal)	15.26	6.10
P2-5(Thermal)	15.20	6.14

**Fig. 2.** Test equipment.

### 4.3 Test Data Processing for S-N Curves

The test results of the static performance parameters of the material are relatively concentrated, and only the average of all test results needs to be taken. Fatigue test, due to the large dispersion of fatigue life, for the acquisition of any point in the S-N curve, there is a minimum number of specimens, according to the theory of t distribution, according to a certain degree of confidence and error requirements, according to the test data to

give the minimum number of specimens, to achieve the purpose of saving test time and improving test efficiency (Tables 3 and 4).

**Table 3.** Static test piece test results.

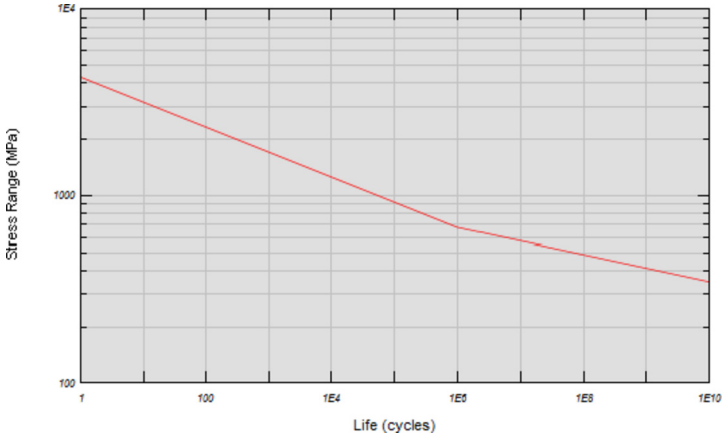
Number	Tensile strength $\sigma_b$ (MPa)	$\sigma_{0.2}$ (MPa)	Young's modulus $E$ (MPa)
J1-1(Thermal)	975	890	198562
J1-2(Thermal)	1010	935	212038
J1-3(Thermal)	890	785	214165
J1-4(Thermal)	915	830	215846
Average value	947.5	860	210152.8
J2-1(No Thermal)	620	350	207481
J2-2(No Thermal)	630	335	193711
J2-3(No Thermal)	645	345	181431
J2-4(No Thermal)	650	355	158991
Average value	636.25	346.25	185403.5

**Table 4.** Fatigue test piece (heat treatment) test results

Number	Load	Cycle life	Logarithmic cycle life
P2-1	$S_{max} = 710$ MPa $S_{min} = 71$ MPa	130463	5.115
P2-2		100205	5.001
P2-3		88044	4.945
P2-4		87988	4.944
P2-5		60373	4.781
Average value	4.957		
Standard deviation	0.1081		
Coefficient of variation	0.0218		
Number of samples	4		

#### 4.4 S-N Curve Fitting of Water Brake Device Material

Design life software can preliminarily fit the S-N curve of stress ratio  $R = -1$  and  $Kt = 1$  according to the type of material and the ultimate strength of the material, because the material used in this study object is heat treated, so the ultimate strength is taken from 947.5MPa in the table, and the preliminary fitted S-N curve is shown in Fig. 3.



**Fig. 3.** Preliminary fitting of the S-N curve ( $R = -1$ ).

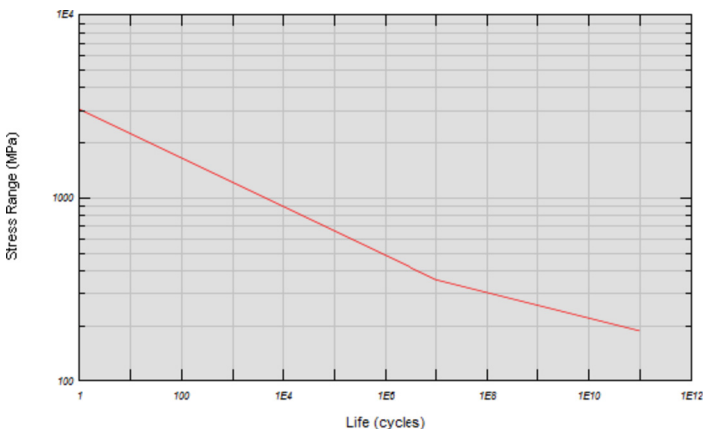
The formulas for the two paragraphs in the figure are:

$$0.133lgN + lgS = 3.6$$

$$0.07lgN + lgS = 2.7$$

where  $S$  refers to the difference between peak-to-valley values.

The change trend of the S-N curve of the same material is basically the same, because the fatigue test has obtained the data of a point on the S-N curve, so only the preliminary S-N curve can be translated to obtain the S-N curve of the weld material, as shown in Fig. 4.



**Fig. 4.** S-N curve of weld material ( $R = 0.1$ ).

The formulas for the two paragraphs in the figure are:

$$0.133lgN + lgS = 3.5$$

$$0.07lgN + lgS = 2.57$$

where *S* refers to the difference between the peak-to-valley values.

### 5 Calculation of Fatigue Life of Water Brake Device

The fatigue life simulation analysis first requires the finite element analysis results of the geometry, relying on the finite element software to calculate the working stress and working strain at each point on the structure. Then, according to the S-N curve of the material obtained by the experiment, a fatigue analysis method is selected, and the life calculation results can be obtained after post-processing.

For the load part, the corresponding load spectrum is extracted according to the working condition of the actual structure for input. The specific analysis process is shown in Fig. 5.

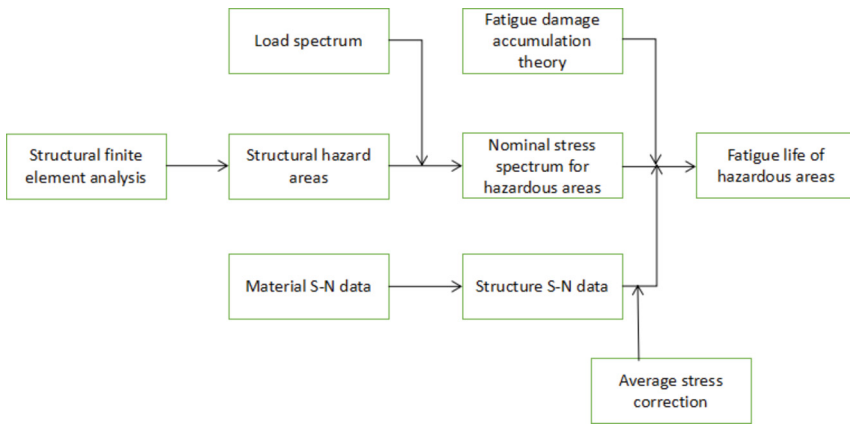


Fig. 5. Fatigue simulation analysis process.

#### 5.1 Determination of Fatigue Danger Points

Fatigue analysis focuses on hazardous areas during finite element simulation, i.e., areas with high stress levels. During the finite element analysis, four regions of the bucket structure were found to have high stress levels, including the front end of the side plate (as shown in Fig. 6, the connection area between the side plate and the front plate), the rear end of the side plate (as shown in Fig. 7, the connection area between the side plate and the back plate), the upper lip area (as shown in Fig. 8), and the side plate weld area (as shown in Fig. 9).



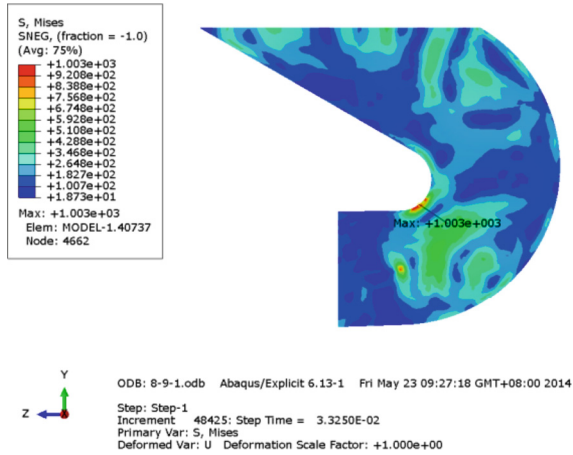


Fig. 6. Indication of danger points at the front of the side panels.

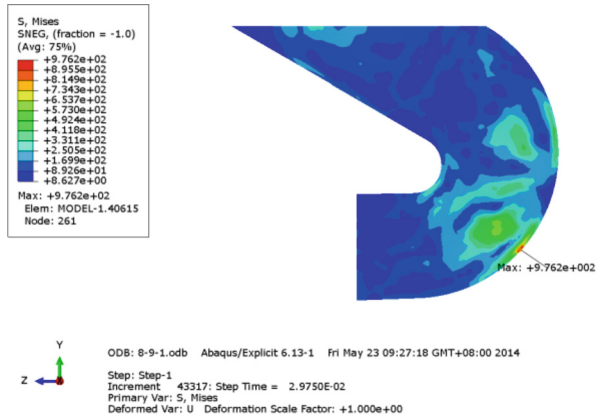


Fig. 7. Indication of danger points at the rear end of the side panels.

## 5.2 Determination of Fatigue Load Spectra

In the finite element motion simulation part, the working state of the entire structure is simulated, and a working stroke is defined as: the first impact of the water flow on the step, the water flow enters a stable flow state after the impact is completed, and then the impact of the second step, in this way, until the water gradually decelerates to a standstill after the fifth step.

Since the motion simulation part only simulates a short distance before and after the water flow hits the step, most of the distance of the stable flow of water between the two impact steps is not simulated, according to the numerical simulation results, the stress of this part is in a small range of fluctuation state, take the two stress points after each water flow impact step as the wave stress, and then give the number of fluctuations according to the analysis distance (time) proportional relationship, so as to obtain a complete working

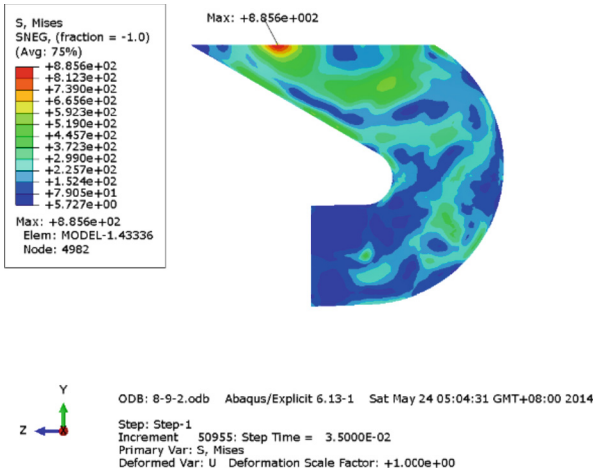


Fig. 8. Indication of the danger point on the upper lip.

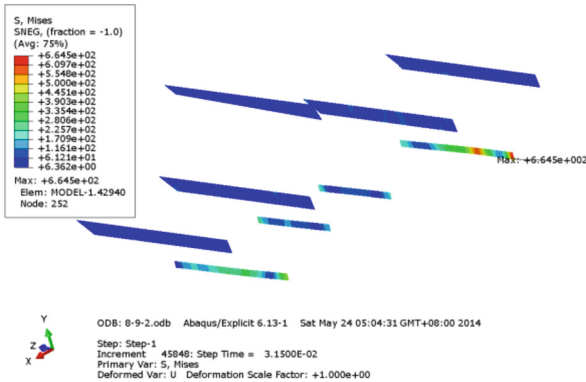


Fig. 9. Illustration of weld hazard points.

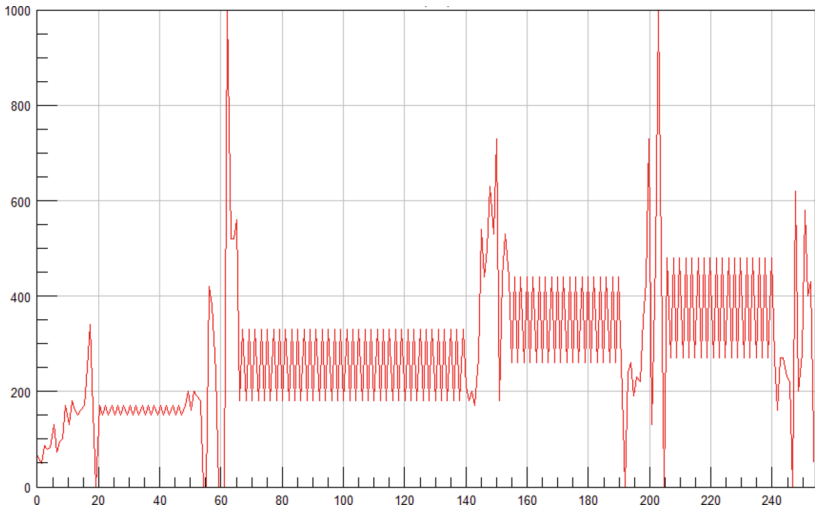
stroke of the stress data, and then according to the spectroscopic principle of rainflow treatment, the final load spectrum is obtained. The corresponding load spectra for the four locations are as follows (Figs. 10, 11, 12 and 13):

### 5.3 Calculation Results for Each Hazard Location

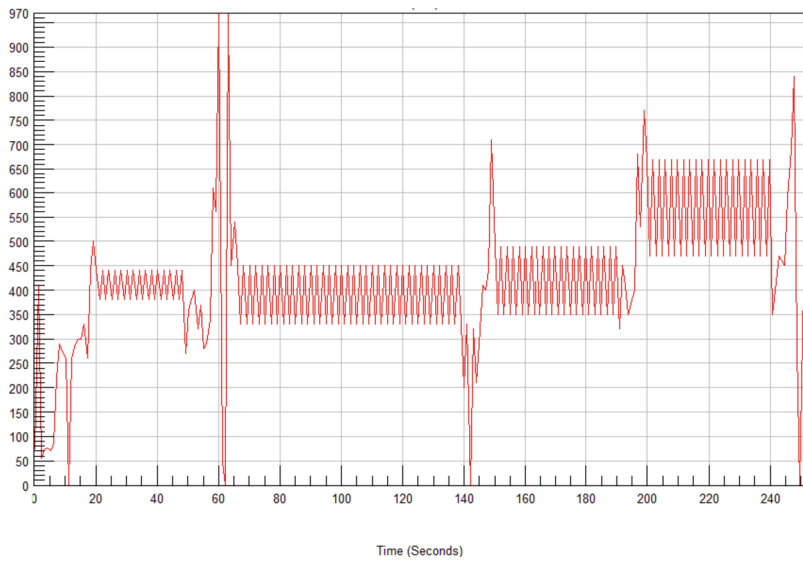
Fatigue life analysis of water brakes was performed using Designlife’s S-N fatigue analysis module (Figs. 14, 15, 16 and 17).

The fatigue life of each hazardous part is shown in Table 5.

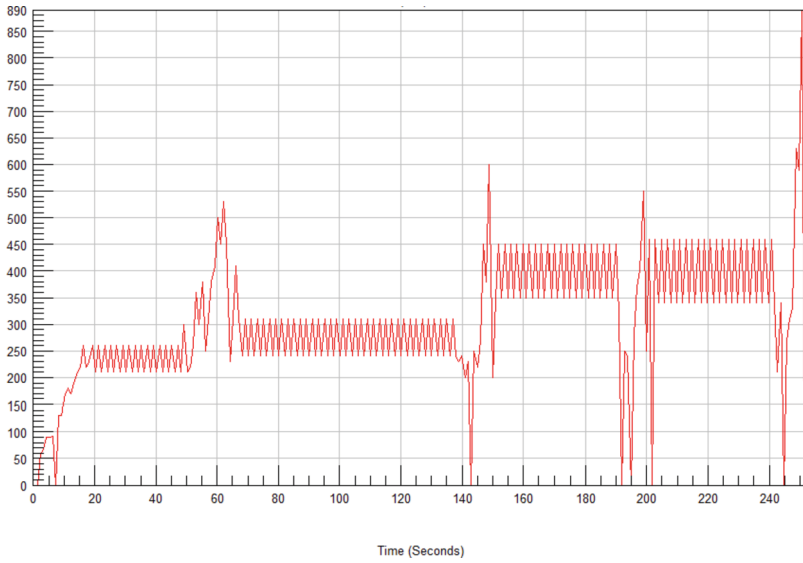
Comprehensive analysis of the fatigue life of each dangerous part of the water brake, the fatigue life of the front end of the side plate of the water brake device is the shortest, which can be effectively used 8102 times, and the fatigue life of other dangerous parts is higher than here. Therefore, the fatigue life of the water brake device is 8102 times.



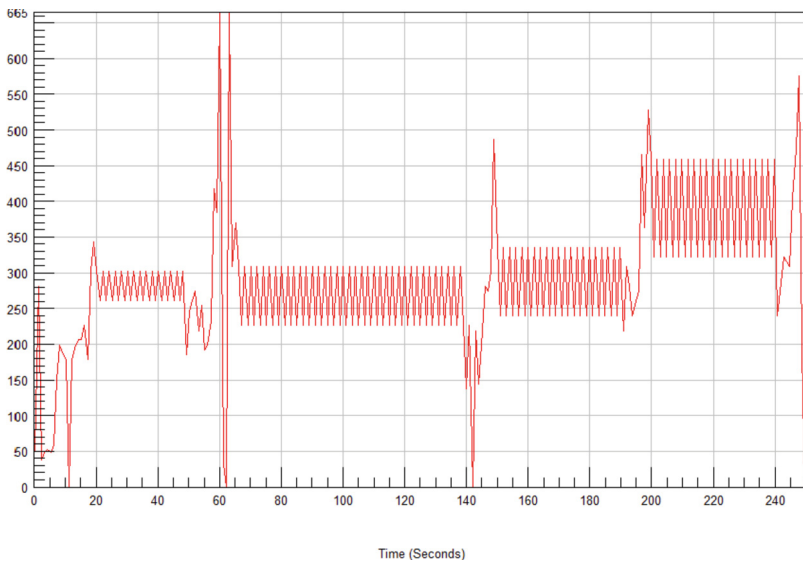
**Fig. 10.** Hazard element stress load spectrum at the front end of the side plate.



**Fig. 11.** Hazard element stress load spectrum at the rear end of the side plate.



**Fig. 12.** Upper lip hazard element stress load spectrum.



**Fig. 13.** Stress load spectrum of weld hazard elements.

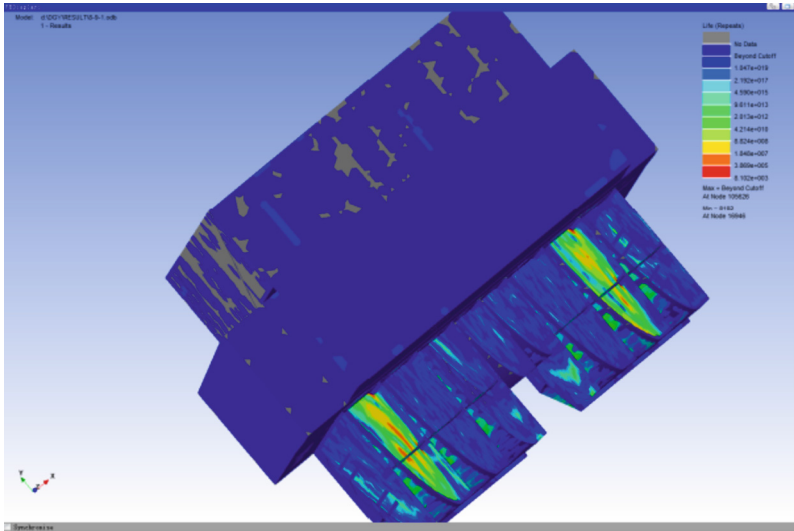


Fig. 14. Side plate front end life cloud.

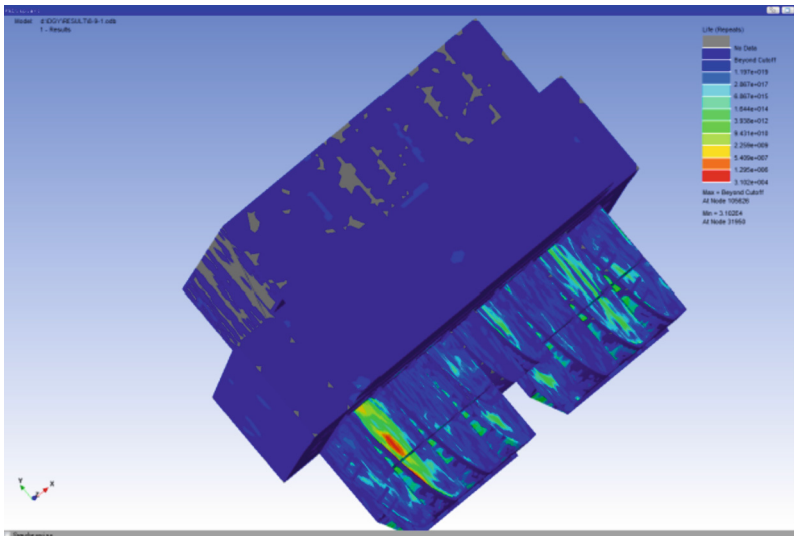


Fig. 15. Side plate rear end life cloud.

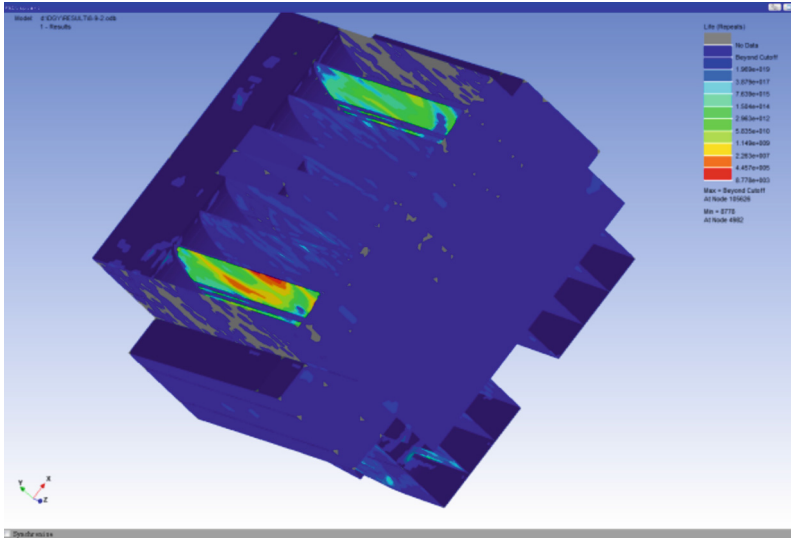


Fig. 16. Upper lip mouth life cloud.

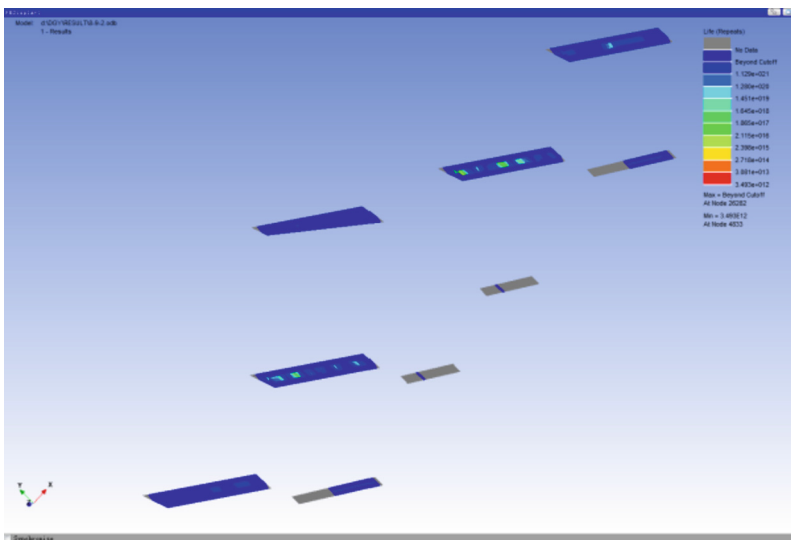


Fig. 17. Weld life cloud.

**Table 5.** Hazardous part life.

Dangerous parts	Front end of side panel	Rear end of side panel	Labial opening	Welding seam
Simulation lifespan	8102	31020	8788	$3.49 \times 10^{12}$

## 6 Conclusion

In this paper, the Finite Element Analysis Model of Multi-pipeline Water Brake Device is established, and the S-N curve of the water brake device material is fitted by empirical equation and experimental method based on the nominal stress method. The danger point of the water brake device is obtained through simulation analysis, and the fatigue life of the danger point is analyzed by fatigue analysis software, which shows that 8102 load spectrum strokes can be safely used in the water brake device without considering the safety factor, and 4051 load spectrum strokes can be safely used by the water brake device when considering the 2 times safety factor.

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