Study on Fatigue Life Enhancement Mechanism of Riveted Structures Based on Load Control

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Abstract： The fatigue life analysis of riveted structures is influenced by multiple factors and involves complex mechanisms. To investigate the characteristics of fatigue behavior and dominant factors, a typical riveted structure was selected as the study object. Systematic strength tests and fatigue tests were conducted, combined with finite element strength calculations and fatigue life assessment based on the BS7608 standard. This approach revealed the staged evolution law of the riveted structure's fatigue behavior. The failure modes and surface characteristics of the specimens were analyzed in detail during the tests. The location of initial fatigue crack initiation under different loads exhibited a certain regularity, which significantly affected the fatigue life of the riveted structure. By comparing the finite element analysis with the test data, the dominant factors at each stage were identified. The results quantified the behavioral characteristics of different stages and proposed a critical load control method to effectively improve the fatigue life. This study provides a theoretical basis for the design optimization and life assessment of riveted structures.

Keywords: Fatigue; fretting wear ; riveted joint; slip

1 Introduction

Riveted structures are widely used in many fields because of their unique advantages, but their fatigue problems are complex and important. Riveted structures are characterized by simple process, earthquake and impact resistance, easy maintenance and disassembly, and wide range of application, and are widely used in aerospace, automobile manufacturing, construction engineering and other fields are widely used, but its fatigue life problem has been a difficult point in engineering practice. Fatigue failure is often caused by cyclic loading, especially in the micro-motion environment, the fatigue strength of riveted components is significantly reduced, and even lead to early fracture, resulting in serious safety hazards. However, the fatigue problem of riveted structures involves a variety of factors, including stress levels, material properties, load types, environmental effects, and so on. The role of fretting wear and bending moments are also added, making the study more difficult[1,2]. Fretting wear is a surface damage phenomenon caused by cyclic loading, which is detrimental to fatigue life and tends to occur in the joints[3]. Bending moments are a by-product of applied loads, which are usually asymmetric in location and are introduced by the application of external loads[4]. The combination of many factors makes the fatigue problem of riveted structures extremely complex. Then, which factors play a dominant role in this, and what specific effects they produce, this is undoubtedly a question worthy of our in-depth investigation.

The fatigue of riveted structures is not a new topic, and its research history dates back to the last century. Among them, the research results of Homan and Jongebreur are quite representative, and a life prediction method is proposed for riveted lap joints of thin plate materials under constant amplitude loading. The method aims to establish a set of S-N curves to evaluate the fatigue life of riveted structures, and deeply considers multiple factors such as load transfer of rivets, bypass load of rivet rows, and additional bending moments, etc., but, unfortunately, the it does not take into account the important influence of fretting wear[5]. With the deepening of research, the serious impact of fretting wear on the fatigue life of riveted structures has gradually attracted attention. Relevant scholars have established a mechanical model for in-depth analysis, and combined with experimental research, comprehensively analyzed the evolution of fretting wear from crack generation to expansion and surface morphology. The study not only profoundly elaborated the principle of fretting wear, but also clearly pointed out that fretting wear is an important cause of fatigue damage of riveted structures[6-8]. In order to reveal the fretting wear phenomenon of riveted structures more intuitively, some researchers have used finite element simulation methods to simulate and analyze the fretting simulation[9]. However, the factors affecting the fatigue life of riveted structures are much more than that. In order to obtain a more effective method for assessing the fretting wear of riveted structures, other researchers have carried out in-depth studies from various perspectives, such as normal force, displacement amplitude, lubricant applied on the contact surface of the connecting plate, and specific wear rate[10,11]. In recent years, the fatigue life prediction research of riveted structures based on the damage tolerance method has also gradually emerged[12]. However, due to its complex change process, there has never been a unified standard to complete the fatigue failure assessment of riveted structures. However, people usually pursue the unification of event results without thinking about the continuous unification after event decomposition. The failure location of riveted structures can be different under different loads. In order to investigate the reason behind this phenomenon, the article takes the lap riveted joint form specimen as an example, and identifies and segments the fatigue dominant factors of the riveted joint structure through the statistical analysis of the strength and fatigue test results, combined with the finite element method. Based on the test phenomena, the fatigue life of the structure was calculated using the material fatigue calculation method, and a comparative analysis of the fatigue multi-segmentation of the riveted structure was carried out. The study shows that different failure dominant factors determine the fatigue life at different stages, therefore, the multi-stage nature of the fatigue life of riveted structures is evaluated, which is of great significance for the anti-fatigue design in engineering applications.

2 Fatigue test of riveted specimens

The form of riveted joints is more flexible, covering various types such as lap joints, single lap plate joints, and symmetrical butt joints. Among them, lap joints have dominated the engineering field due to their convenience and practicality[13]. Studies on multi-rivet structures have revealed an important phenomenon that under external loads, damage tends to occur first at the outermost rivets. It was further observed that in structures with multiple rows of rivets, the concentration of fatigue damage tends to be even more on the most marginal side of the rivets[14]. In view of these findings, a single rivet lap joint was selected as the focus of the study, and the corresponding riveted test piece was carefully prepared. Riveted specimen as shown in Figure 1.

Figure 1. Riveted specimen

In the manufacture of riveted specimens, the connecting plate is made of Q450NQR1 weathering steel, with a width of 50mm and a thickness of 10mm, while the rivets, which are closely connected to it, are made of high-strength steel with a strength class of 8.8. LMY type round head rivets were used, with a diameter of 16mm and a drilled hole diameter of 17mm.

A hydraulic servo material testing machine was selected for the test. The test consists of two parts: strength and fatigue test. For the strength test, the loading form of load grading is adopted, with each grade increasing by 20kN until the specimen is destroyed. The LMS SCADAS system was selected for data acquisition, with the sampling frequency set to 256 Hz and the data resolution up to 24 bits.The fatigue test load was loaded in the form of a sinusoidal waveform. The maximum load was set between 30kN and 90kN, divided into 7 levels, the minimum load was 10% of the maximum load, and the loading frequency was 25Hz.The strength test of riveted joints as shown in Figure 2.

Figure 2. The strength test of riveted joints

3 Results and discussion

The study of the riveted structure is based on strength tests to collect strain data and measure slip loads at critical points of the structure. In order to understand the mechanical behavior of the riveted structure, a finite element model was established and the model was calibrated based on the strain measurement data to clarify the strain-stress situation of the riveted structure. In addition, fatigue tests were conducted and the results were statistically analyzed.

3.1 Riveted structure strength test results

Before performing the tensile strength test of the riveted structure, it is necessary to affix strain gauges at the critical locations on the surface of the test piece. Specifically, strain gauges S1-S6 are arranged on the rivet head side of the test piece, while strain gauges S7-S12 are arranged at the same positions on the back side. wherein strain gauges S1 and S2 are symmetrically arranged about the longitudinal axis of the test piece, and strain gauges S3 are arranged on the longitudinal axis of the test piece. The strain gauges S1 and S2 are arranged symmetrically about the longitudinal axis of the specimen, and the strain gauges S3 are arranged on the longitudinal axis of the specimen. The arrangement of strain gauges as shown in Figure 3. The damage form of riveted structure strength test as shown in Figure 4.

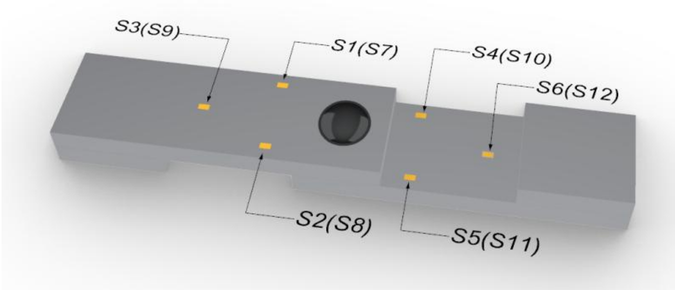

Figure 3. The arrangement of strain gauges

Figure 4. The damage form of riveted structure strength test

When the test was loaded to 140.6kN, the riveted structure specimen was damaged. The specific form of damage manifested itself in the fracture failure of the rivets, obvious bending deformation of the connection plate at the rivets, and enlargement of the rivet holes along the tensile direction.

3.2 Measured results of slip loads on riveted structures

The loads for the strength tests were loaded in graded cycles at 20kN intervals. During the second stage of loading, i.e., the cycle from 0kN to 40kN, the connecting plate overcame the friction under the tensile load and produced a relative slip. This phenomenon is manifested in the time-domain curve of strain gauge S1 as an obvious strain surge. The time domain curve of strain gauge S1 as shown in Figure 5.

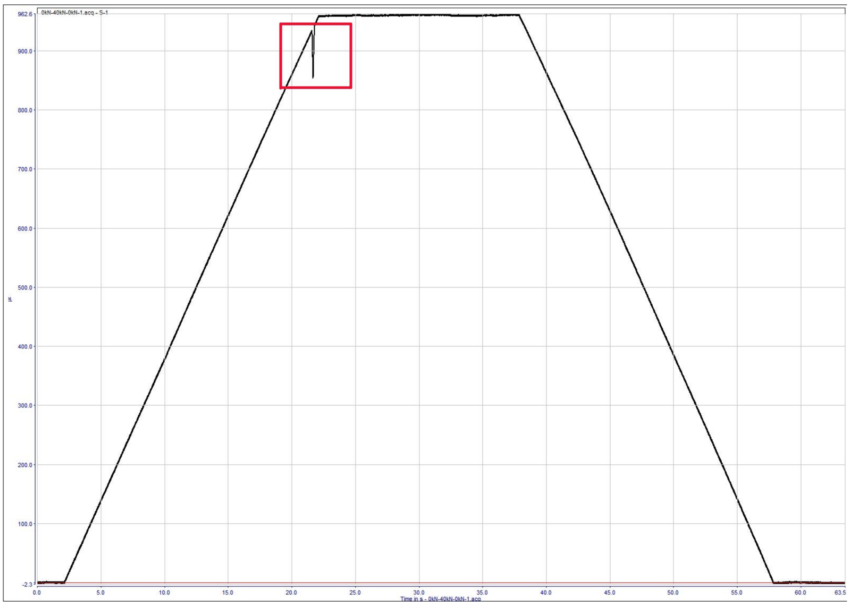

Figure 5. The time domain curve of strain gauge S1

This cyclic test was performed with a target value of 40kN load and a tensile load was applied at a uniform speed. By observing the moment of abrupt change in the curve of strain gauge S1, the load value at the moment of slip was calculated to be about 39kN.

3.3 Comparison of finite element calculations and test results for riveted structures

Since the joint surface of the riveted structure at the joint plate cannot be measured directly, in order to understand the stress distribution here, the riveted structure was modeled using finite element software. At the same time, the finite element model was corrected by combining the strain data measured in the strength test. The comparison table between the test measurements and the finite element calculation results as shown in Table 1. The stress distribution at the contact surface of the connecting plate of the riveted structure was obtained by applying tensile load. The stress distribution at the contact surface of the connecting plate as shown in Figure 6.

Table 1. The comparison table between the test measurements and the finite element calculation results

Strain gauge	Tensile load 20kN			Tensile load 40kN		
	Test measurement results (με)	Simulation Calculated Values (με)	Contrast bias (%)	Test measurement results (με)	Simulation Calculated Values (με)	Contrast bias (%)
S1	129.4	124.3	4.0	254.5	254.4	0.0
S2	124.5	124.2	0.2	244.9	253.9	3.7
S3	100.3	105	4.7	197.9	203.2	2.7
S4	-52.5	-48.4	7.9	-102.4	-96.6	5.7
S5	-52.1	-48.6	6.8	-102.2	-97.3	4.8
S6	-27.6	-25	9.3	-53.9	-50.4	6.4
S7	-50.2	-47.6	5.2	-95.8	-95.8	0.0
S8	-51.5	-47.9	7.0	-98.1	-96.2	1.9
S9	-24.0	-25	4.2	-44.8	-45.7	2.0
S10	130.1	125.1	3.9	259.5	259.9	0.1
S11	133.3	125.2	6.1	266.0	260.3	2.2
S12	104.2	105	0.8	207.8	206.1	0.8

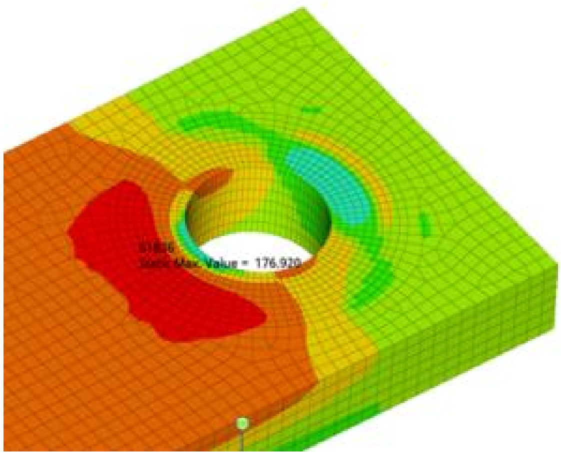

Figure 6. The stress distribution at the contact surface of the connecting plate

As can be seen in Table 1, the strain measurements from the strength tests were compared with the finite element calculations under tensile loads of 20 kN and 40 kN. The results show that the maximum deviation of the comparison of the strains is 9.3% and this deviation occurs at S6. This comparison deviation satisfies the requirements of the strength analysis of the finite element model. From the calculated results in Fig. 6, it can be observed that at the contact surface of the connecting plate of the riveted structure, the maximum value of the stress is mainly distributed around the holes and is kept at a certain distance from the edge of the holes.

3.4 Fatigue test results of riveted structures

In the fatigue test of riveted structures, the same batch of specimens is divided into two groups and tested under the same test conditions with graded test loads, and the number of specimen destruction or 10^7 cycles is set as the test termination condition. The statistical table of fatigue test results for riveted structures as shown in Table 2. In order to evaluate the stress levels of the fatigue tests, the stress levels at each level of the test were calculated and obtained based on the maximum load at each level of the test as well as the cross-sectional area of the specimen at strain gauge S3. Based on these data, a curve fitting was carried out in logarithmic coordinates to plot the S-N curve of the riveted structure. The S-N curve of the riveted structure as shown in Figure 7.

Table 2. The statistical table of fatigue test results for riveted structures

Specimen name		Load（kN）		Number of cycles N
		Minimum value	Maximum values	
Group 1	Specimen 1	9	90	9.74×10^4
	Specimen 2	8	80	1.22×10^5

	Specimen 3	7	70	1.97×10^5
	Specimen 4	6	60	4.40×10^5
	Specimen 5	5	50	8.04×10^5
	Specimen 6	4	40	1.64×10^6
	Specimen 7	3	30	$>1.00\times10^7$
Group 2	Specimen 8	9	90	9.40×10^4
	Specimen 9	8	80	1.42×10^5
	Specimen 10	7	70	2.09×10^5
	Specimen 11	6	60	3.66×10^5
	Specimen 12	5	50	8.75×10^5
	Specimen 13	4	40	1.69×10^6
	Specimen 14	3	30	$>1.00\times10^7$

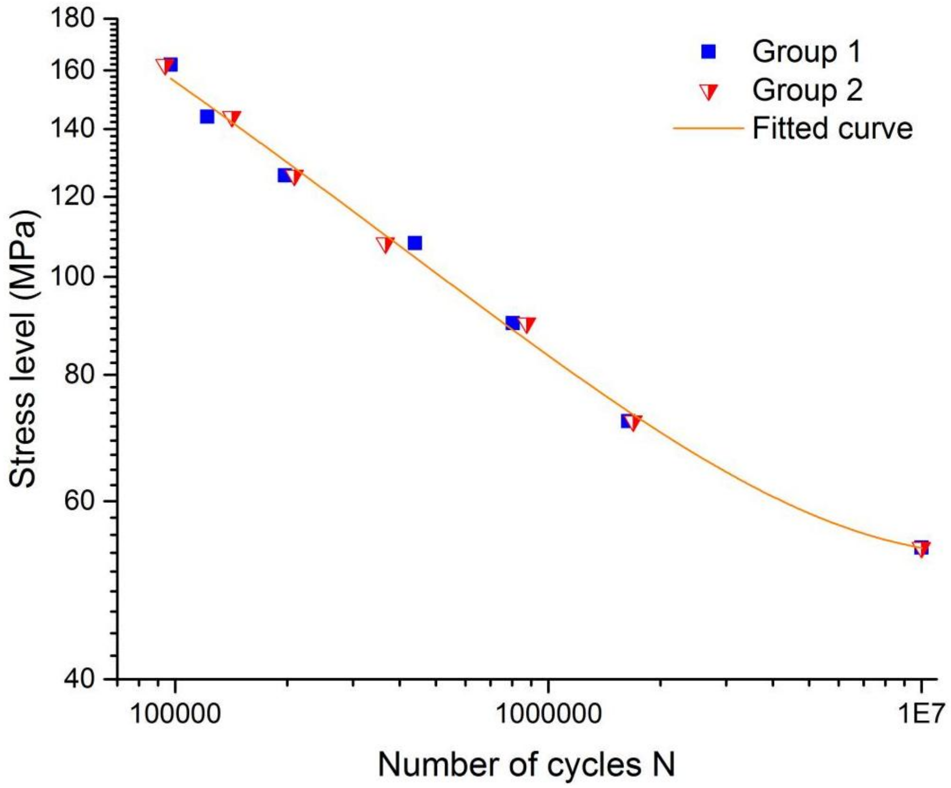

Figure 7. The S-N curve of the riveted structure

As can be seen from the data in Table 2, when comparing the results of the two sets of fatigue tests, it can be observed that the number of cycles of fatigue failure at all levels shows a gradual increase with the increase of the test load. At the same time, the number of fatigue cycles is similar under the same level of load, which indicates that the tests have better repeatability and consistency. As can be seen from Fig. 7, in logarithmic coordinates, when the maximum load of the test is in the range of 40kN to 90kN, the curves show a regular form of change, indicating that in this load range, the fatigue performance of the structure is relatively stable. However, at 30kN load, the curves show a significant turn and flatten out, which may mean that the fatigue performance of the structure has changed significantly at this load.

3.5 Failure mode analysis and discussion of riveted structures

Statistics for the failed specimens show that the form of damage in some of the specimens is mainly characterized by fracture of the connecting plate around the rivet holes. Specifically, the cracks in Specimens 1-5, 8-12 did not originate in the rivet holes, but rather in the location outside the holes, with the cracks expanding from the center to both sides of the face. A large number of fine cracks and metal powders were present near the crack source, which is typical of fretting wear. Accordingly, it is judged that the failure of these riveted specimens is due to fatigue damage induced by micromotional wear. The fatigue damage caused by fretting wear as shown in Figure 8.

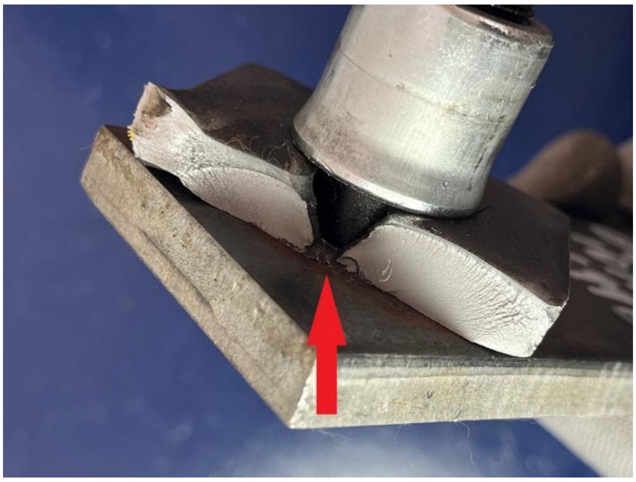

Figure 8. The fatigue damage caused by fretting wear

Specimen 6 and Specimen 13 exhibited two main forms of failure at a maximum test load of 40 kN. One form of failure, characterized by fretting wear, occurred around the rivet holes and was similar to the previous form of failure under high load conditions. The other type of fracture occurs at the location of the connecting plate where the stress is higher in the finite element strength calculation, and this form of fracture can be interpreted as a fatigue failure of the connecting plate that occurs under external load, i.e., a fatigue failure of the parent material. The fatigue failure of the connection plate as shown in Figure 9.

Figure 9. The fatigue failure of the connection plate

The methods for assessing fatigue failure of parent materials are described in the BS7608:2014+A1 standard. Under conventional loading, for each class of joint, there is a relationship between the range of stresses S_r applied and the number of cycles N to reach fatigue.

$$S_r^m N = C_d \tag{1}$$

Considering practical engineering problems, the value of d is usually taken as 2 (representing the number of standard deviations below the mean value). In this way, the fatigue life N can be calculated for a given range of nominal stress changes S_r.

$$\lg N = \lg C_d - d\overline{\sigma} - m \lg S_r \tag{2}$$

Based on the geometry of the assessed joint and the direction of action of the externally applied fatigue loads, the joint was determined to be a parent material, with a class B rating. The values of the relevant parameters were obtained according to the BS7608:2014+A1:2015 standard[15]. After calculation, the fatigue life of the joint plate for Specimen 6 and Specimen 13 under the maximum test load of 40 kN is about 2.47×10^6 cycles.

During the fatigue test, Specimen 7 and Specimen 14 were terminated due to the number of cycles reaching 10^7, and all other specimens underwent destructive failure. After calculation, the fatigue life of the connecting plate of Specimen 7 and Specimen 14 under the maximum test load of 30 kN was about 7.81×10^7 cycles.

In order to have a comprehensive understanding of the fatigue behavior of riveted structures, the results of strength tests, slip loads, finite element calculations, fatigue tests, and calculations of the life of the parent material were comprehensively analyzed. During the strength and fatigue tests, a total of four test termination conditions were triggered, specifically, rivet breakage, breakage at the peripheral location of the rivet hole, breakage of the connecting plate, and a cycle number of 10^7 times The number of cycles reached 10^7. It is worth noting that no rivet breakage occurred during the fatigue test, which indicates that the weak link of the structure is not the rivet under this fatigue test condition. The results of the fatigue test clearly showed three stages as the applied load was reduced step by step.

In the first stage, when the maximum load of the test was in the range of 50kN to 90kN, the fatigue crack sources of the specimens all originated near the rivet holes and were accompanied by the generation of fine cracks and metal powders. This kind of fatigue failure is mainly caused by the fretting wear between the connecting structures, which illustrates that the fatigue failure of riveted structures is mainly caused by the fretting wear under larger load conditions.

In the second stage, when the maximum load is set to 40kN, it can be observed by analyzing Fig.7 that the number of cycles still shows a regular trend in logarithmic coordinates. However, with further reference to the data in Figure 5, it can be found that the slip phenomenon occurs in the connection structure under the load of about 39 kN. Under this level of fatigue test loading, discrete forms of specimen failure occur, including failure near the rivet holes due to fretting wear and fracture in the region of maximum stress in the parent material of the connection plate. The number of cycles for the two failure forms were 1.64×10^6 and 1.69×10^6, respectively, which were similar to the theoretical calculation of BS7608 of 2.47×10^6. It shows that the main influence of fatigue of riveted structures gradually shifts from fretting wear to stress influence in the vicinity of slip load, and this can be regarded as a critical point.

In the third stage, when the maximum load of the test is 30kN, it can be observed through the analysis of Figure 7 that, within the logarithmic coordinates, the statistics of the number of cycles turns, the curve area tends to flatten out, and the number of cycles reaches 10^7 when it is terminated, and the specimen is not fractured. Compared with the previous level of test results 1.64×10^6, the number of cycles increased significantly. This indicates that the fatigue life of riveted structures has gone through a turning point, and is gradually stepping into the small stress range of the high life region. In order to understand this change more deeply, according to the BS7608 standard on the fatigue life of the connecting plate parent material for theoretical calculations, the results show that the number of cycles up to 7.81×10^7.

The combination of the above experimental and computational results can be clearly seen. At the slip critical load of the riveted structure, its fatigue life appears to be obvious. When the load acting on the riveted structure is less than the slip critical load, there is no obvious micro-motion wear phenomenon in the riveted joint, and the fatigue of the structure is in a long-life state. When the load acting on the riveted structure is greater than the slip critical load, there are obvious micro-motion wear phenomena at the riveted joints, and there are obvious crack sources, which largely reduce the fatigue life of the structure. This indicates that the application condition that exceeds the slip load of the riveted structure can seriously affect the fatigue life of the riveted structure. Fatigue behavior that does not exceed the slip load of the riveted structure will keep it in a long-life condition.

4 Conclusions

Through an in-depth study of the fatigue behavior of riveted structures, the dominant factors of fatigue life under different levels of loading were obtained. It is found that the dominant factors of different fatigue failure forms of riveted joint structures are different. This study further verified the key role of micromotional wear in the fatigue damage of riveted structures through experimental analysis, and this finding is highly consistent with the findings in the literature, which further supports the basis of micromotional wear as the main mechanism of riveted structure failure[8]. Based on these dominant factors, the fatigue life of riveted joints can be analyzed in segments, which can be divided into the fretting wear dominant stage, the stress dominant stage and the small load long life stage. In the fretting wear stage, the fatigue assessment can be carried out by using the micro-motion wear failure assessment method; while in the stress-dominated stage and the small load long-life stage, the material fatigue assessment method can be applied for fatigue assessment. The dividing line of the stages can be determined with reference to the slip critical load. In the context of low carbon and environmental protection, the reliability design of riveted structures, as an efficient and environmentally friendly connection method, is particularly important. This study provides a valuable reference for the fatigue-resistant design of riveted structures. In the future, the study will further explore the effects of different rivet diameters, painting of the contact area of the connection plate, and different preload forces on the fatigue behavior of riveted structures, with a view to carrying out more in-depth research on anti-fatigue behavior.

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