# Full-Permeability Analysis of Normal Amplitude and Variable Amplitude Fracture of M24 High Strength Bolts

**Rong Xing, Junjie Zhang, and Honggang Lei**

**Abstract** Fatigue problem on high strength bolts have already become more and more important in morden times and it is essential that we do research on bolt fatigue mechanism by the fatigue fracture analysis of the failed bolt because of fatigue. Through detailed analysis of constant amplitude stress and variable amplitude stress on M24 high strength large hexagonal head bolts, it is concluded that there are three common failure mode among all bolts' fatigue failure. Fatigue failure characteristics and fracture developing status of source region, transient broken zone and extension zone were obtained, and it provides a important basis for the study on fatigue performance and life estimation of high strength bolt connection, and meanwhile it also expands the application range of bolt joint of prefabricated steel structure.

**Keyword** Prefabricated steel structure · High strength bolt · Fatigue failure · Fatigue fracture · Constant amplitude · Variable amplitude

## 1 Introduction

Steel structure is a kind of popular structure type in modern times, which is applicable in various types of buildings. It has light weight, and it also has high bearing capacity, as makes many designers achieve a variety of spectacular steel structure buildings. Different buildings can make use of different linking ways to make their components form an integral whole, so the connection mode is relatively crucial, and it is especially obvious that the security of our residential buildings which are lived daily is deeply rooted in the heart of the people. With the frequent occurrence of natural disasters, the citizens are concerned about safety question mostly. The

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problem of high-strength bolts used in steel structure dwellings is becoming more and more prominent, and among all questions especially vital one is the fatigue problem of high-strength bolts under the cyclic action of long-term load. The urgent solution of fatigue problem caters to the aspirations of lots of people.

Fatigue problem was put forward on the basis of repeated loading test of the chain by the German engineer W A J Albert in 1829 early [1]. The essence of fatigue problem is fatigue failure, which occurs under the local place of high stress and high strain, and then it causes fatigue crack or complete fracture due to fatigue. Because of high strength bolt fatigue many engineering accidents occurred, it is well known that on June 4th, 1979 the hung bolt broke in Kemper Stadium, which led to the part collapse of the center of the roof [2]. Therefore, the fatigue of high-strength bolt is always a important and difficult point in the engineering and academic circles.

High-strength bolt fatigue is a fatigue problem of metal structure. Fatigue problem has its complexity, and it need to be solved by the way of fatigue test study [3, 4]. Fatigue failure occurs accompanying with cracking formation, and then cracking expands at the concentration of stress, eventually leading to fracture. Domestic and foreign scholars have paid a lot of attention to stress concentration [5–9]. Insides these, scholars from various countries have also done a lot of research on the fatigue damage mechanism [10–12] and fatigue life estimation. So it is essential that we do research on bolt fatigue mechanism by the fatigue fracture analysis of the bolt that failed because of fatigue [13–17]. It is an important method to describe fatigue crack's extension process and to reveal the mechanism of fatigue failure.

Many domestic and foreign scholars have made experimental study and theoretical analysis on the fatigue performance and fatigue life of high strength bolt connection, thus drawing important conclusions. Lei [13, 18–20] from Taiyuan University of Technology had had metallographic analysis on the fatigue fracture of the M20 high strength bolt used in the bolt-ball-mesh frame, revealing the mechanism of fatigue failure; the main application is that on the basis of the analysis of fatigue damage mechanism and cumulative damage process; he had the experimental study on the fatigue performance of fifteen Grade 8.8 M24 high strength bolts. Bolt's fatigue failure originated at the root of the thread, which is gradually formed from multiple point sources to line sources firstly, and then gradually expanding along annular and radial respect, and the annular expanding rate is higher than the radial expanding rate. These results are all closely related to the fatigue fracture of high strength blots.

## 2 Experiment Analysis

### *2.1 Experiment Purpose*

Based on the experiment study of the tension fatigue performance about M24 high strength hexagonal headed bolt, this paper analyzes the fatigue fracture of shear bolt and establishes the fatigue design method in detail, which lays a solid theoretical foundation for the extended application of the prefabricated steel structure buildings.

## 2.2 Materials and Method

The fatigue failure of the high strength bolt in this experiment was mainly caused by the fatigue break which occurred at the thread root between the bolt rod and the nut, which is the same as this damage mode of most high strength bolts in the experiment; secondly, the fatigue fracture occurs at the thread root that doesn't occlude with the nut, which is the same as only one among high strength bolts, therefore this damage mode is more special; finally, the high strength bolt is not completely broken, you can see the fatigue cracking that makes the bolt connection fail, which is the same as only three bolts' damage mode in the experiment, and especially occurs at the multi-bolt connection nodes. This paper mainly analyzes the fatigue fracture of the first two high-strength bolts with fatigue break. The number of bolts that are studied under constant amplitude stress is ten, which are named M24-1, M24-2, M24-3, M24-4, M24-5, M24-6, M24-7, M24-8, M24-9 and M24-10. Among them analyzed object is the typical samples such as M24-1 and M24-5; the special samples includes M24-5 and M24-10. The number of bolts that are studied under variable amplitude stress is four, which are named M24-B1, M24-B2, M24-B3 and M24-B4 successively. Among them M24-B2 and M24-B3 are selected for analyzed object.

This content is completed by the combination way of micro and macro analysis, and macroscopic fracture analysis mainly makes use of naked eye, magnifier and camera etc., while microscopic fracture needs use the scanning electron microscope. The experiment used Phenom XL desktop scanning electron microscope. Each equipment and research object are shown in Figs. 1 and 2. The macro and micro analysis methods of the fracture have advantages because of the observable range and observation level, which cannot be replaced each other in practical use. The combination of macro and micro analysis, mutual evidence and common application effect is better.

The ten constant fatigue fractures were classified, and by the way of the macro and micro analysis this experiment have studied not only the typical and special morphology fatigue features of constant amplitude, but also fatigue source's failure of variable amplitude, and it can reveal the fatigue cracks' extending process and fatigue failure mechanism commonly applied in the fatigue failure.

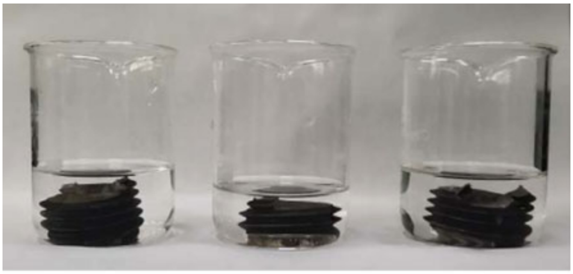
**Fig. 1** Experiment equipment


(a) Ultrasonic cleaner

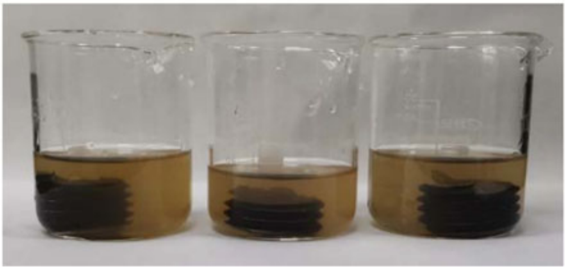
(b) anhydrous ethanol

(c) SEM

**Fig. 2** Research objects



(a) Bolts section before cleaning



(b) Bolts section after cleaning

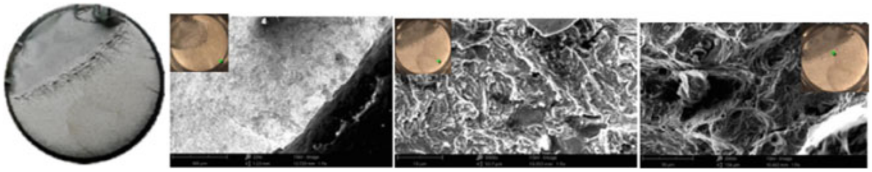


**Fig. 3** M24-2 macro and micro fractures ($\Delta\sigma = 190$ MPa, $N = 230.234 \times 10^4$)

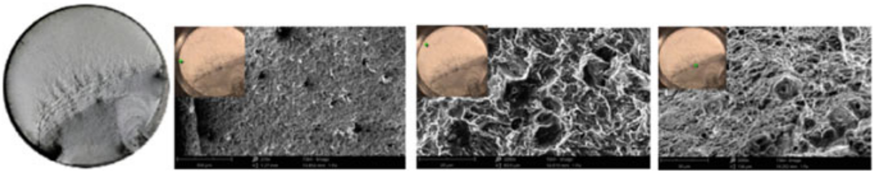


**Fig. 4** M24-5 macro and micro fractures ($\Delta\sigma = 206$ MPa, $N = 48.9235 \times 10^4$)

## *2.3 Discussion*

### Typical Fatigue Fractures of Constant Amplitude

Firstly, the typical fatigue macro breaks and micro breaks of M24-2, M24-5 under different stress amplitude and cycles shown in Figs. 3 and 4, emphasizing the fatigue failure characteristics of their fatigue source zone, fatigue extension zone and transient zone.

In Figs. 3 and 4 above there are macroscopic fracture,200× source, 3000× extension and 2000× instantaneous zone from left to right respectively. It can be seen that they have some common characteristics:

(1) Macroscopic fracture: The three fractures all have the smooth fatigue source area which is flatter, fatigue extension zone accounting for about two-thirds of the fracture area, and the instantaneous area which shows plastic deformation and tension breaking, which is a typical fatigue fracture.
(2) Microscopic fracture: Similarities are that fatigue source originates from the side of the fracture; initial defects are the main cause of early caused fatigue crackings. The characteristics of 3000× extension zone mainly shows the fatigue striation morphology; the distribution of the fatigue striation is not regular, and the spacing of the adjacent fatigue strips is quite different, which fully indicates that the bolt's force is complex. The characteristics of 2000× instantaneous area is observed that there is a large number of toughness nests, and there are obvious signs before fracture, it belongs to the failure type of plastic deformation.

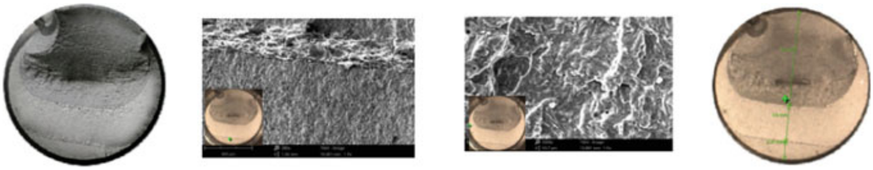


**Fig. 5** M24-1 macro and micro fractures ($\Delta\sigma = 210$ MPa, $N = 55.8769 \times 10^4$)

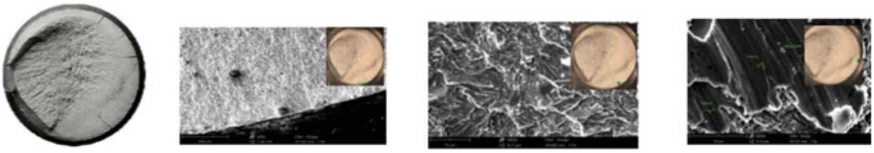


**Fig. 6** M24-10 macro and micro fractures ($\Delta\sigma = 195$ MPa, $N = 76.8906 \times 10^4$)

### Special Fatigue Fractures of Constant Amplitude

Among them, the fracture morphology of M24-1 and M24-10 under different stress amplitude and cycles are more special fatigue fractures, analyzing the macro and micro fractures combining with loading process.

Figure 5 is the macroscopic break, the junction of the 200× expansion area, 5000 × the expansion area and the three-section length (Fig. 6).

The above figures are macroscopic fracture, 200× source area, 3000× extension area 5000× extension area. Their similarities and differences is shown in the following:

(1) Macroscopic fracture of M24-1: The above fatigue fracture is divided into three areas, among which the expansion is divided into two parts;
(2) Microscopic fracture of M24-1: In fatigue source, there are the visible junctions of extension zone. In extension zone there is the obvious fatigue strips, and at the junction of the two extension areas, there are toughness nests.
(3) Macroscopic fracture of M24-10: The fatigue source occurs on the lower right side of the fracture, and the transient zone is located on the upper left side of the fracture.
(4) Microscopic fracture of M24-10: In fatigue source, the spacing of adjacent striation extends from one direction, such as 856 nm, 916 nm, and 1220 nm respectively.

### Fatigue Fractures of Various Amplitude

The constant amplitude fatigue fracture analysis cannot fully reflect the fatigue failure characteristics of the M24 high strength large hexagonal head bolt, then making the detailed analysis of the macro and micro parts of M24-B2, and M24-B3 under various amplitude stress, which is shown in Figs. 7 and 8; Tables 1 and 2.

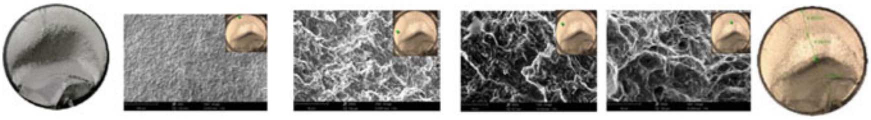


**Fig. 7** M24-B2 macro and micro fracture

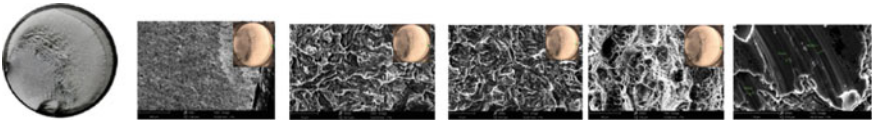


**Fig. 8** M24-B3 macro and micro fracture

**Table 1** Fracture analysis of M24-B2

| | | |
|---|---|---|
| Loading process | | (1) $\Delta\sigma = 200$ MPa, $N = 49.0045 \times 10^4$; (2) $\Delta\sigma =$ 220 MPa, $N = 40.0765 \times 10^4$ |
| Macroscopic | | It is divided three failure zone |
| Microscopic | 200× source | The fatigue source originates from the upper part of the fracture, and the length along the diameter is 4.86 mm; |
| | 2000× extension zone | Through the regional boundary, the angle between the fatigue cracking extension direction and the cross section can change. The failure characteristics of the boundary zone is plastic tearing<br>The length along the diameter is 4.56 mm; |
| | 5000× extension zone | Significant fatigue striation appears, it is more easier to observe the direction of cracking extension<br>The length along the diameter is 9.6 mm |

## 3 Conclusion

With the help of magnifying glass, camera and advanced SEM, this paper makes macro and micro analysis of ten constant amplitude fatigue fractures and four variable amplitude fatigue fractures, so as to obtain the fatigue failure characteristics of torsion-shear high strength bolts, and it further studies the fatigue failure mechanism combining with loading process.

Firstly, analyzing the macro and micro fracture of constant fatigue. It is known that fatigue source usually occurs at the part with the initial defects; the spacing between the fatigue strips of the cracking extension area can roughly reflect the loading level of the stress amplitude. There are a lot of toughness nests that can reflect plastic fracture characteristics.

In the case of the single fatigue source, the fatigue source area and the transient break area are always in the opposite part of the fracture diameter direction, and the instantaneous break area is in proportional to the loading stress. In the case of

**Table 2** Fracture analysis of M24-B3

| | | |
|---|---|---|
| Loading process | | (1) Δσ = 220 MPa, N = 36.8906 × 104; (2) Δσ = 210 MPa, N = 3.1516 × 104 |
| Macroscopic | | The right area of the fracture has the obvious boundary, and the fracture is obviously divided into three regions |
| Microscopic | 200× source | The fatigue source originates from the upper right of fracture |
| | 5000× extension zone | Showing the characteristics of plastic fracture, the boundary of the fracture should be the trace loaded twice by variable amplitude fatigue, and the toughness nests and morphology are diverse and irregular In addition, showing the irregular distribution of the fatigue striation; |
| | 2000× instantaneous break zone | The transient fracture zone is located on the lower left side of the fracture, and the fatigue cracking extends from the upper right side to the lower left side |

multiple fatigue source, the fatigue step generally forms on the fracture, judging the order that the fatigue source comes to being according to the distance of the fatigue source from the fatigue step.

Secondly, the variable fatigue fracture is analyzed and it is discovered that the fracture morphology is more complicated. After the loading-stopping-reloading process, the bolts will generally leave a significant boundary in the fracture expansion area, and the boundary area presents the plastic fracture characteristics. Through the dividing line, the fatigue cracking extends again.

These conclusion can provide more information for the study on fatigue performance and life estimation of high strength bolt connections, avoiding or debasing the probability of fatigue failure on high strength bolt connections. And meanwhile it also expands the application range of bolt joint of prefabricated steel structure.

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