

The Fatigue Failure Analysis of Steel Structure and Review of Collapse Accidents

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Abstract— Bolt-ball grid structure is a high order statically indeterminate spatial grid structure that made up of multiple root bars and the bolt-ball nodes according to a certain grid form, It has the advantages of good appearance ,simple and applicable for large span, lighter weight, stress reasonable and it used in industrial and civil architecture widely. It is important to note that many bolt-ball grid structure engineering collapse has happened in recent years though the bolt net structure has developed more mature. It is necessary for us to analysis this kind of bolt-ball serious engineering accident carefully to find out the cause of the accident, summarize experience and lessons, promote the healthy and secure development of the bolt net structure .

In this paper, exemplified by a certain factory building of Shanxi bolt-ball rack collapse as the research background, we will study the area of collapse network frame through the methods of field observation, deformation measurement, fracture analysis and sampling test, and analyze the failure process of the network frame, find out the accident reason finally. Main job:

- (1) Find out the key clues of the accident through the field observation and measurement, including the measurement of component size, the inspection of construction quality, the analysis of fracture macroscopic and the photos, etc. and retain the component samples from the collapse area.
- (2) Conduct the material test of the component, including mechanical properties test and chemical composition test, find out the changes in composition and property after 13 years, then determine the bolt fracture type of the high strength bolt.

Keywords— Bolted spherical joints, Stress concentration; Fatigue failure; space structure; Accident.

I. INTRODUCTION

Because special function and other reasons, more and more buildings in modern society require the structure to have a large span. In china, since the 2008 Beijing Olympic Games and 2010 Shanghai World Expo, the spatial structure has developed to a higher level, and the requirements for the space structure will be higher and higher, it is such a good opportunity to great promote the space structure of the country. With the progress and development of China, there are more and more high-standard large-span space structure in various regions, and various new forms and technologies are constantly applied. The technical level of china's space structure has also been continuously improved [1].

Among the many structure forms of space structure and steel structure, the grid structure is one of the most important traditional structure forms. It's a spatial structure composed of several members connected by nodes

according to certain grid form, which has the characteristics of high order statically indeterminate. The United States was the first to use the grid structure, which was only used in military buildings and facilities at the beginning, and gradually applied to various civil and industrial buildings after a period of time. The appearance of grid structure is simple and beautiful, and it has many advantages of steel structure, and the stress of each member is reasonable, so it is very suitable for the application of large-span structure. Since the late 1980s, China began to introduce relevant technologies and component processing technologies of grid structure, and widely used in practical projects. The cumulative projection area of grid structure in China has increased at a rate of about 900000m² every year, and its development and application in China can be described as fierce and rapid [2] [3].

In terms of the technical level and application scale of the grid structure, China has surpassed the United States, the birthplace of the grid structure, and has become the largest country in the grid structure. Now in our country, the grid structure can be seen everywhere, from canteen, storage room, stadium, large auditorium, conference hall, industrial workshop, etc., the application of grid structure is very wide. The first use of grid structure in China is the roof of a building in Shanghai Normal University. The building was built in 1964. The plane size of the grid is $40.5\text{ m} \times 31.5\text{ m}$, the members are made of angle steel, and the joint form is welded plate joint. The installation and construction of the grid structure marks the beginning of the application and development of China's space structure, and symbolizes the expansion of China's space structure technology Righteousness. After the introduction of the grid structure form, a lot of domestic research resources have been spent on the research and innovation of this structure form, and a new type of grid structure, welded hollow spherical joint grid, has been explored. Up to now, the bolt ball node grid structure and welded hollow ball node grid structure have become the two most important structural forms of the grid structure, and gradually become the two centers of the development of the grid structure. In terms of the use scale or technical level, the bolt ball grid has surpassed the latter and won the first place [4].

Bolt sphere grid is a kind of grid structure which uses welded steel pipe or seamless steel pipe as member, bolt sphere as node and high-strength bolt as connection. The bolt ball joint design is composed of a variety of components, including solid steel ball, hexagon socket, fastening screw, high-strength bolt, sealing plate or cone head, which can effectively connect the steel pipe members, not only ensure the strength, but also make the construction more convenient. The structure of bolt ball joint is shown in "Fig.1-1".



Fig. 1-1: The bolt-ball node joint

With the rapid development of bolt ball grid structure there are also some problems. The collapse accidents of bolt ball grid structure still occur frequently which needs to be paid more attention. The bolt ball grid structure is often used in stadiums, auditoriums, conference halls and other buildings where a large number of people gather, workshops such as warehouses and workshops where a large number of valuable instruments and equipment are stored, The allowable error rate is lower, the risk factor is higher, and there is no effective prediction method at present. Once the bolt ball grid collapses, it will not only cause heavy casualties, but also cause huge economic losses, which will pose a major threat to national property and people's life safety, the consequences are unimaginable, and the social impact is extremely bad [5]. Because of such a position, it is particularly important to conduct a more in-depth analysis and research on the bolt ball grid structure accident. Through scientific research to explore the root mechanism of the bolt ball grid structure accident starting from the design, construction, use. etc., comprehensively and objectively understand and analyze the problems existing in each link [6][7], and learn lessons from the lessons of experience, and then carry out more reasonable bolt ball grid frame design, formulate more complete specification, regulations and more effectively reduce the occurrence of bolt ball grid accidents.

II. RIVEW OF COLLAPSE ACCIDENT

Most of the failures with steel structures investigated are with key clues of the accident through the field observation and measurement, including the measurement of component size, the inspection of construction quality, the analysis of fracture macroscopic and the photos, etc.

Fatigue accidents and fatigue problems occur frequently at China and The world, many fatigue accidents occur in the flight, this has attracted the shock and high attention of all countries in the world, especially the aviation industry[8]. Some fatigue problems cannot be detected in time due to the appearance only, but in the long-term of flight and combat, there is fatigue of instruments and aircraft, it leads to sudden failure of functions in aviation operations, Causing major flight accidents [9]. For example, in 1985, jal-123 aircraft, in the rear of the aircraft pressure diaphragm metal fatigue failure, resulting in the fall.

Fatigue failure not only exists in aviation industry, but also poses potential threat to civil engineering, mechanical engineering, etc. For example, in March 1991, metal fatigue failure occurred in the steam tube of MEIHONG atomic power station in Japan [10]. September 1992, bolt

ball grid structure collapse due the large number of high-strength were broken in Shenzhen International Exhibition Center China [11]. November 1994, warehouse of Tianjin Carpet import and export company collapse of bolt ball grid structure in China [12]; In 1994 SHENGSHUI bridge, the central section collapse accident in South Korea [13]. In June 1998, the wheel metal fatigue of German high-speed train caused derailment [14]. On November 7, 2001, NANMEN bridge, known as "the first arch in Asia", located in YIBIN City, Sichuan Province, suffered fatigue fracture of its suspension cable and bridge deck [14]. On May 23, 2004, the collapse accident of 2E terminal in Paris Charles de Gaulle airport was due to the initial crack at the joint between the ceiling of the terminal and the circular steel structure pillar. Due to the long-term effect of the repeated load, the initial crack continued to expand, and the joint finally reached the critical size, resulting in sudden fatigue fracture [14]. July, 2005, the grid collapsed suddenly due to the fatigue failure in Inner Mongolia XIFENG Thermal Power Co., Ltd. China [15].

Fatigue problem was first put forward in 1829 by W.A.ALBERT, a German mining engineer, in the repeated loading test of welding chain for mine hoisting [16].

In 1839, French PONCELET first used the term fatigue.

In 1843, RANKINE, a Scottish physicist, encountered the first fatigue strength problem in railway transportation engineering, that is, the number of cycles of failure of Locomotive Axles under static failure load and repeated bending beam load is quite different, and the failure cycle times of crystal failure load can be as long as 4 years without failure, However, the number of failure cycles of the beams subjected to repeated bending 1000 time.

In 1961, Stuart et al. First introduced probability distribution into material fatigue limit in mechanical design.

At present, the American Society for testing and materials (ASTM) defines fatigue as follows: when a point or some points are subjected to torsional stress, and cracks or complete fracture are formed after enough cyclic action, the development process of local permanent structural change in materials is called "fatigue" [17].

The main mechanism of fatigue failure is as follows: there are various kinds of small defects in the process of steel production, processing and transportation. When the alternating load is applied on the component or structure, the stress distribution on the defective section is uneven, resulting in stress concentration. With the development of cracks, when the section is gradually weakened to resist the failure, the component will be destroyed [18][19].

III. ANALYSIS OF A TYPICAL STRUCTURE

The most serious of the collapse cases under service in terms of the consequences in the classification analysis of steel structure accident, personal losses and great economical losses. etc..

In this paper, exemplified by a certain factory building of SHANXI bolt-ball rack collapse as the research background, we will study the area of collapse network frame through the methods of field observation, deformation measurement, fracture analysis, sampling test, and analyze the failure process of the network frame to find out the accident reason finally. Main job:

(1) Find out the key clues of the accident through the field observation and measurement, including the measurement of component size, the inspection of construction quality the analysis of fracture macroscopic and the photos, etc. and retain the component samples from the collapse area.

(2) Conduct the material test of the component, including mechanical properties test and chemical composition test, find out the changes in composition and property after 13 years, then determine the bolt fracture type of the high strength bolt.

3.1 PROJECT OVERVIEW

A workshop was built in 2002. The main structure of the workshop building is reinforced concrete frame. The roof was adopts orthogonal square pyramid type bolt sphere grid with grid size of 3M×3M, the grid frame height of 3.0M, and a grid frame size of 62.8M×29.6M. The building project area is about 1859M², the building height is about 27M and two-way slope rise is 4%. The grid steel is Q235B high-frequency welded or seamless steel pipe with long axis direction around Each three bolt ball on the top chord of the edge are provided with a support. See "Fig.3-1 " for grid structure.

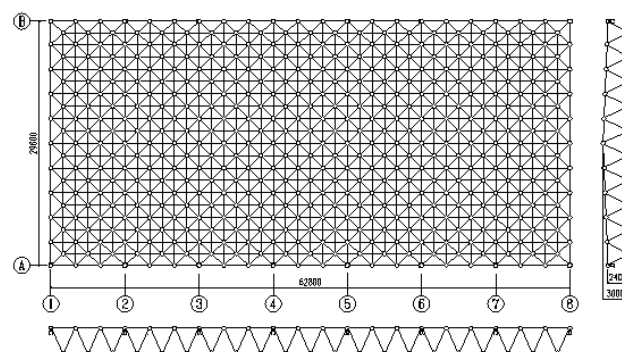


Fig. 3-1: Network frame structure diagram

3.2 THE ACCIDENT CONSEQUENCE ANALYSIS

On May 17, 2015, local collapse occurred in the southwest corner of the bolt ball grid roof of the plant, and the lower chord of some grid frames was bent greatly, See "Fig.3-2 "-"Fig.3-3 ". At night of May 20, the whole collapse occurred in three sections of a span on the west side of the bolt ball grid. See "Fig.3-4 "~"Fig.3-7 ". Some large equipment was damaged and no casualties were caused due to unmanned operation at night.



Fig. 3-2: Partial collapse.



Fig. 3-3: Lower chord bending

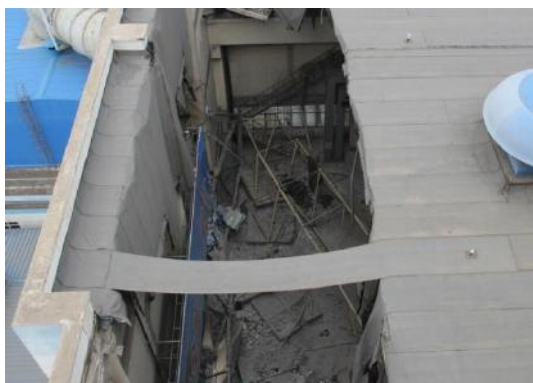


Fig. 3-4: The overall collapse



Fig. 3-5: The collapse of the scene



Fig. 3-6: The collapse of the scene

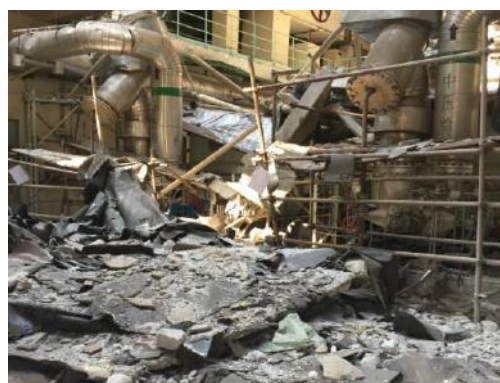


Fig. 3-7: The collapse of the scene

3.3 THE SITE INVESTIGATION

The on-the-spot investigation of the accident site is one of the important means to initially determine the cause of the accident, to understand the actual situation of the accident site and to find the key clues of the accident. After the collapse of the grid structure, we immediately informed the workshop to isolate the site of the accident for protection, and rushed to the accident site for a general survey. Through observation, we found that there are many problems with the bolt ball grid structure[20].

3.3.1 PRODUCTION PROBLEM

Through the observation of the bolt sphere grid structure in the area without collapse, it is found that some high-strength bolts connecting the web members are missing sleeve pins, but the outer skin is complete, as shown in Figure "Fig.3-8 ". It can be seen from the field photos that the pin is missing before painting. If the pin is missing before installation and the sleeve does not have the snap action of the pin, the high-strength bolt will not rotate and tighten with the sleeve during installation, it is likely that the high-strength bolt will not screw into the bolt ball or the screw in length is not enough, but it cannot be checked from the appearance, resulting in huge safety All hidden dangers. See "Fig.3-8"



Fig. 3-8: Bolt sleeve pin is missing

3.3.2 INSTALLATION PROBLEM

The M42 high-strength bolt connected to the diagonal web rod at the southwest corner of the grid frame has two rounds of ball thread. See "Fig.3-9 " the high-strength bolt out of the thread. This is caused by the slippage of the M42 high-strength bolt and the lower chord ball. The bolt ball grid has the problem of false bolts during the installation and construction, and the construction quality is not high, and the bolt ball grid is used by thousands of high-strength bolts. It is not excluded that other bolts also have the same problem, and the hidden danger is huge.



Fig. 3-9 M42 high-strength bolt out of the thread

3.3.3 DUST PROBLEM

The ash on the side of the bar and bolt ball is 1-3MM, with an average thickness of about 2MM. See "Fig.3-10" - "Fig.3-11" . This shows that the maintenance problem of the bolt ball grid in the daily use process has not attracted the attention of the user, and there is a management problem of long-term maintenance and troubleshooting, which makes the bolt ball grid unable to meet the durability of its original design, and it cannot be timely in case of structural problems It is found that there is a large potential safety hazard.



Fig. 3-10: Bar of formation



Fig. 3-11: Bolt ball formation

3.3.4 FATIGUE FAILURE

Through the observation of the accident site, it is found that the fracture surface of M33 high-strength bolt connecting the upper chord at the long axis of the southwest corner support of the grid structure shows a clear fatigue fracture morphology. See "Fig.3-12" - "Fig.3-13" which indicates that the bolt ball grid structure has fatigue problems, and the fatigue fracture belongs to brittle fracture, which can be the failure source of the grid structure collapse, so it needs to be paid attention to



Fig. 3-12: The bearing



Fig. 3-13: M33 high strength bolts fracture

IV. INDOOR TEST

4.1 CHEMICAL COMPOSITION TEST OF STEEL

The chemical composition has a great influence on the performance of steel. Now, on-site sampling is carried out for the collapsed grid structure of the workshop, and the chemical composition test is carried out for the steel pipe and bolt of the grid structure.

4.1.1. TEST CONTENT

a) The chemical composition of the steel pipe with a diameter of $\phi 60 \times 3.25$, $\phi 75.5 \times 3.5$, $\phi 114 \times 4$, $\phi 140 \times 4$, $\phi 159 \times 6$, and $\phi 159 \times 8$ was detected.

b) High strength bolt M20, M24, M27, M33, M36, M39, M48, M56, a total of eight specifications of chemical composition detection.

4.1.2. TEST CONCLUSION

In the original design drawing, the steel pipe material is Q235B, and the high-strength bolt material is 40Cr. The test results of carbon structural steel (GB / T700-1988), alloy structural steel (GB / T3077-1999), material certificate and accessories.

Through the comparative analysis of test result, the following conclusions are drawn.

a) The carbon content of the steel pipe with a diameter of 159×8 is 0.21%, which does not meet the requirement of 0.20%.

b) The carbon content of M20 high strength bolt is 0.46%, which does not meet the limit of 0.44% [20].

4.2 MECHANICAL PERFORMANCE TEST OF STEEL

At the same time of testing the chemical composition of steel, in order to further determine whether the material is qualified, we carried out mechanical performance tests on the steel pipe and high-strength bolts of the mesh frame.

4.2.1 TEST CONTENT

a) The chemical composition of the steel pipe with a diameter of $\phi 60 \times 3.25$, $\phi 75.5 \times 3.5$, $\phi 114 \times 4$, $\phi 140 \times 4$, $\phi 159 \times 6$, and $\phi 159 \times 8$ was detected.

b) High strength bolt M20, M24, M27, M33, M36, M39, M48, M56, a total of eight specifications of chemical composition detection.

4.2.2 TEST CONCLUSION

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Through the comparative analysis of test result, the following conclusions are drawn.

a) The tensile strength of steel pipe with four specifications, namely, $\phi 60 \times 3.25$, $\phi 77.5 \times 3.5$, $\phi 114 \times 4$ and $\phi 140 \times 4$, does not meet the requirements of the specification.

b) The yield strength of M48 high strength bolt does not meet the requirements of the specification.

4.3 OTHER PERFORMANCE TEST OF HE HIGH-STRENGTH BOLT

The high-strength bolts of the grid are produced by Shijiazhuang city Standard Parts II Plant, and the material is 40Cr. On the basis of testing the chemical composition and mechanical performance testing of high-strength bolts, in order to further determine whether the high-strength bolts are qualified, the other performance of the high-strength bolts of the grid is further tested. The test results are show : All indicators are qualified.[20]

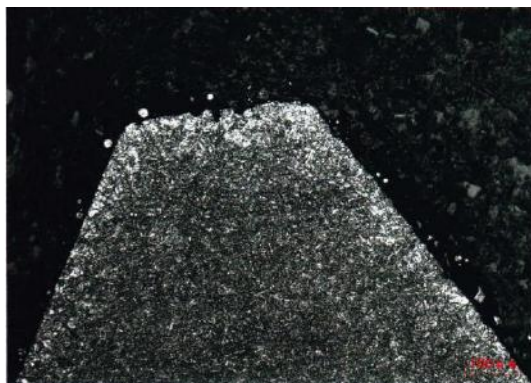


Fig. 4-1 Thread 1



Fig. 4-2 Thread 2

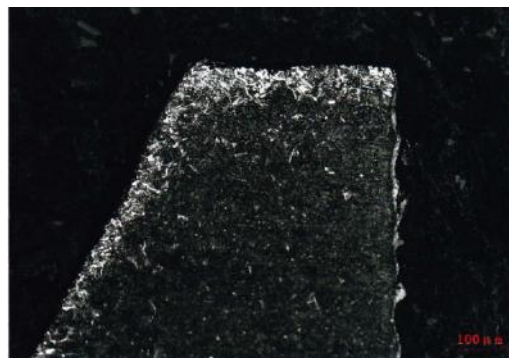


Fig. 4-3 Thread 3

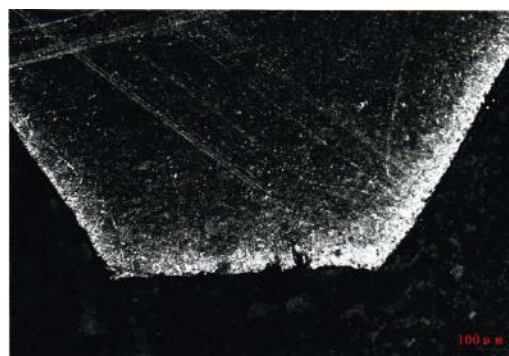


Fig. 4-4 Thread 4



Fig. 4-5 Thread 5



Fig. 4-6 Thread 6



Fig. 4-7 Thread 7

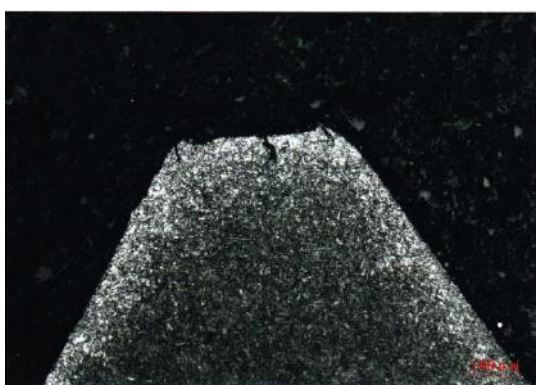


Fig. 4-8 Thread 8

4.4 FRACTURE ANALYSIS OF HIGH-STRENGTH BOLT

Fracture analysis is an important technical means to judge whether fatigue failure or not. Fracture analysis can be divided into macro analysis and micro analysis. Macro analysis of fracture can be used to determine the nature of fracture, such as ductile fracture and fatigue fracture. However, if we want to get more information, we must use the micro analysis method of fracture to observe, and we can see the details of fracture that cannot be seen in macro view under the micro level, which is very helpful to explore the formation and propagation mechanism of cracks [5]. According to the references and data, the fatigue fracture of high-strength bolt shows three different characteristics in the micro view, which are fatigue source area, expansion area and brittle fracture area.

4.4.1 FATIGUE SOURCE AREA

The fatigue source is most likely to occur in the place where the stress concentration is the most serious. For high strength bolt, the most serious place of stress concentration is the outermost thread where the high-strength bolt contacts with the bolt ball. The first thread near the head of the bolt and the intersection of the bolt rod

and the bolt head are also places where the stress concentration is more serious. In general, cracks begin to appear from the outside. If the fatigue fracture surface is observed by microscope, it can be found that the area of fatigue source area is far smaller than that of propagation area and brittle fracture area. There are a lot of shellfish lines in the area, and there are many black spots or patches. If there are such black spots in many areas, it means that there are more than one fatigue source area of the fracture. When the shell pattern of fatigue fracture is not obvious enough to be observed, we can find the position of fatigue source by observing radiation and fatigue fringe.

4.4.2 EXPANSION AREA

If the high-strength bolt is fatigue fracture, then the fracture surface of the bolt is bound to show a crack growth area. The fatigue source region is smoother, while the extended region is rough. The shellfish and fatigue stripes in the region are more obvious, so it is easier to observe. The shell line will extend from the fatigue source as the starting point, and its density can reflect the crack growth rate, and it is also an important judgment basis for the load form and stress concentration degree. When there are multiple fatigue sources, the cracks propagate in different curvature centers. When they meet in two different planes, steps or long tear edges are formed by shear or tearing. When the fatigue failure of high-strength bolt is variable amplitude fatigue failure, the characteristics of the fracture surface such as shell lines will show greater irregularity, in contrast, the fracture surface of the bolt with constant amplitude fatigue failure is more regular.

4.4.3 BRITTLE FRACTURE ZONE

When the crack size reaches a certain limit, the area of the propagation zone exceeds a certain limit, and the effective bearing section of the high-strength bolt is not enough to resist the external tensile force, the instantaneous brittle fracture of the high-strength bolt will occur. The instantaneous fracture zone often appears in the position opposite to the fatigue source area. Its roughness is the largest in the three regions, and the irregularity of its shape is the largest among the three regions. The appearance of brittle fracture zone is very similar to that of bolt fracture in static failure test. There are obvious radial or herringbone pattern in the middle plane strain area and shear lip in the edge plane stress area. The M33 high-strength bolt connecting the top chord of the grid angle support is taken for microscopic analysis of the fracture. After cleaning, rinsing and drying the fracture surface of M33 high strength bolt for inspection, it is placed in the scanning electron microscope for microscopic fracture

observation and micro analysis of fracture surface. See "Fig.4-9 " ~ "Fig.4-12 " for details.

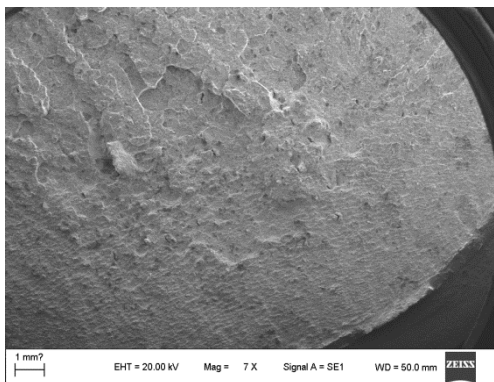


Fig. 4-9 The fracture morphology (7 times)

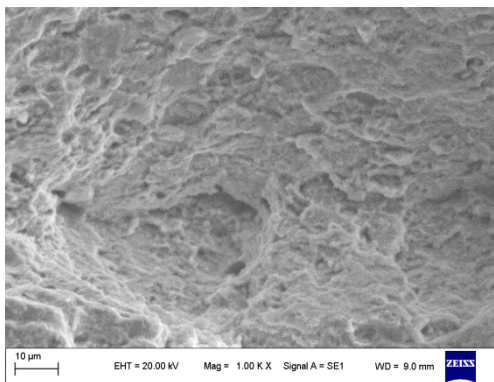


Fig. 4-10 Fatigue striations (1000 times)

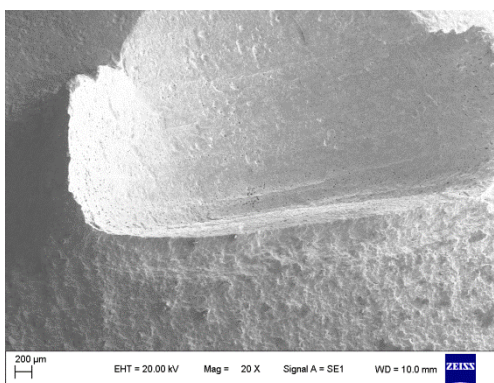


Fig. 4-11 Pin hole crack source (20 times)

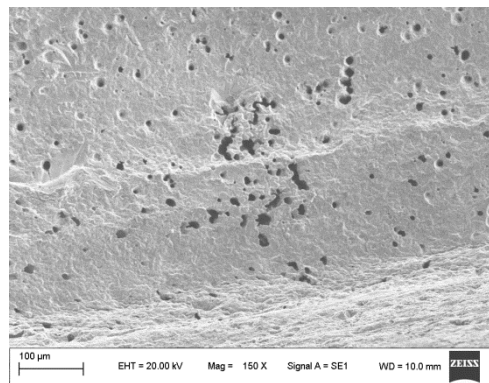


Fig.4-12 Pin hole inner surface pitting corrosion pit (150 times)

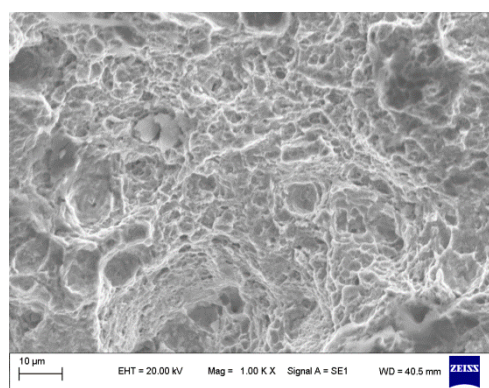


Fig. 4-13 Extension area morphology (1000 times)

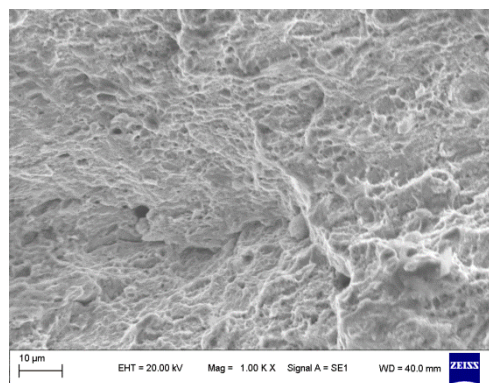


Fig.4-14 Transient breaking area morphology (1000 times)

The results show that the fracture morphology presents typical characteristics of fatigue source region, propagation region and instantaneous fracture zone. There are two fatigue source regions in the fracture. One is that the crack starts at the root of the thread, showing fracture dimple morphology and radiation striation morphology; the other is that the crack starts at the pin hole, and there are many corrosion pits on the inner surface of the pin hole;

there are secondary cracks in the propagation area of the fracture; the instantaneous fracture area of the fracture is a mixed fracture morphology. The fracture morphology is low cycle fatigue.

V. CONCLUSION

It is of great significance to study the causes of the accidents. In this paper, taking the collapse accident of a bolt sphere joint grid workshop as the research background, the causes of the accident are analyzed and explored through scientific and effective technical means such as field survey and software simulation. The conclusions are as follows:

(1) In the bolt sphere grid structure, the fatigue phenomenon of high-strength bolt often occurs on the bolt sphere grid with the suspension crane, while the bolt sphere grid without the suspension crane rarely has fatigue problem. Through this accident analysis and appraisal, it can be seen that when the suspension crane is not set under the bolt sphere grid, the fatigue failure of high-strength bolt may also occur, such as the wind load. Some factors will lead to bolt fatigue failure, which needs our attention [21-23].

(2) Through the analysis and research, it is found that the direct cause of the collapse accident of the bolt sphere joint grid workshop is: the accidental overload causes the low cycle fatigue fracture of the high-strength bolt. The indirect reason is that there is a problem of false tightening in the construction of high strength bolts. [20]

(3) Through the fatigue researcher it's found that the bolt in bolt grid structure need more researcher and more studies.

ACKNOWLEDGEMENTS

In this paper, a large number of technical means are used to identify the collapse accident of bolt sphere grid structure in a factory building. On the basis of sufficient data and in an objective, responsible and prudent manner, the failure source of the collapse accident of grid structure is finally determined, and the collapse process of grid structure is simulated by using the finite element analysis software. In the whole process of technical appraisal, the author found that the collapse accident of the bolt sphere grid is caused by multiple factors, and there are some problems in the design, construction and use process. Today, the application of bolt sphere space truss is more and more extensive. In order to make a contribution to the health and safety development of the industry, combined with the actual problems existing in the project, I would

like to put forward some suggestions with my own shallow views [24-25].

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