Simple analysis on failure of high strength bolts in Chongqing Chaotianmen Bridge

Juan Wen[1,2], Zheng Li[1*] ,Tao Hu[1]and Lan Liu[2]

[1]Chongqing Cheng Tou Road and Bridge Administration Co.Ltd, Chongqing, 400060,P.R.China

[2]College of Material Science and Engineering, Chongqing University,Chongqing 400044,P.R. China

[*]Corresponding author's e-mail: 1043000111@qq.com

Abstract. From 2009 to 2012, 14 failure high strength bolts were found in Chaotianmen Bridge,and 11 bolts were collected on site, of which 8 bolts were pitted and rusted. The chemical composition, metallographic structure, hardness and other mechanical properties of these 11 bolts were analyzed and tested to explore the reasons for fracture failure of high strength bolts. The results show that six failure high strength bolts` HRC values are of 40, 40.5 and 43 (4 bolts), which does not meet the technical requirement of GB/T1231-2006, and the unqualified rate accounts for 54.5%. Tempered martensite, which belongs to brittle structure, was detected in metallographic structure in samples with unqualified hardness. The failure of high strength bolts is not only related to the unqualified metallographic structure, but also related to the construction processs, operating environment and other aspects. Especially the influence of environmental corrosion on the quality, micro-structure and mechanical properties of high strength bolts should be paid more attention by bridge managers. It is necessary to further explore and clarify the influence of environmental factors on the corrosion fracture of high strength bolts and its mechanism, so as to provide a basis for the measures taken to prevent the breakage of high strength bolts.

1. Introduction

Chongqing is the famous bridge capital and mountain city, surrounded by two rivers. Bridge project is an important part of the transportation system of Chongqing city, which plays a very important role in the city. As a new type of connecting material, high strength bolts are widely used in large buildings and structures such as railway bridges, aircraft hangers, gymnasiums, high-rise buildings and industrial workshops due to good mechanical properties, high connecting stiffness, easy connection quality and convenience for construction and installation. According to reports [1-2], about 1.5 million sets of high strength bolts are used for the Jiujiang Yangtze river bridge, and 860,000 sets of high strength bolts are used for the upper structure of the main bridge of Chongqing Chaotianmen Yangtze river bridge. However, due to the strength, corrosion resistance, force load and the influence of surrounding environmental media of their own materials, the phenomenon of falling off and breaking occurs frequently in the process of using high strength bolts, which brings major hidden dangers to the bridge. The annual breaking rate of stress corrosion fracture of high strength bolts used on steel Bridges along a railway in China is about 0.02%[3].The breakage rate of high strength bolts in the steel structure of Chongqing Chaotianmen Yangtze river bridge is about 0.0025%.

A lot of work has been carried out by domestic and foreign scholars on the fracture failure analysis of high strength bolts. Haifeng Zhang [4] analyzed bolt fracture and matrix by various analysis methods. Jian Mu [5] adopted the scale model of Chongqing Chaotianmen Bridge as the background to conduct experimental research on the mechanical properties and looseness of high strength bolt connection of rail longitudinal beam and crossbeam joints under dynamic load, and discussed the failure conditions of friction looseness of high strength bolt connection. In terms of materials, the fracture failure analysis of 20MnTiB, 35VB, 45 steel and 40B steel high strength bolts has been reported. Shutun Liu et al. [6] predicted the delay reliability of 40B steel M22 high strength bolt. Tianzai Wang et al. [7-8] analyzed and discussed the reliability of the delayed fracture of 10.9s M27 high strength bolts made of 35VB steel in humid air. Pengfei Zhang [9] compared the microstructure and properties of 45 steel and 20MnTiB steel after tempering, and studied the differences in mechanical, anti-corrosion and fatigue properties. Jie Hu et al. [10] examined and analyzed the fracture reason of the 10.9s M24 high strength bolt made of 20MnTiB steel after anti-rust treatment. Xiu Yang et al. [11] studied the variation of fatigue limit of 30CrMnSiA high strength bolts of military aircraft under simulated Marine atmosphere environment by using neutral salt fog test. Meng Zhang [12] took uncoated steel structure Q235B steel M20 high strength bolt connection specimens as the research object to conduct indoor accelerated corrosion by wet heating treatment, studied the friction connection properties of high strength bolt after corrosion, discussed the influence of rust degree on its anti-slip coefficient, sliding load and ultimate load, and established the quantitative relationship between corrosion degree and high strength bolt connection performance index. Ordinary 10.9s high strength bolts are not resistant to atmospheric corrosion. Surface spraying requires 3-5 years of anti-corrosion coating maintenance and re-anti-corrosion coating every 10-15 years. The process of coating causes some problems such as environmental pollution and high cost. Aiming at this problem, Zhijun Luo et al. [13] of Shougang disclosed in the patent a kind of high strength bolt steel with anti-corrosion in industrial atmosphere for painless bridge structure and manufacturing method. The steel can be used to produce 10.9s M16-M30 high strength bolts with excellent resistance to industrial atmospheric corrosion and low temperature.

In the study of high strength bolt reliability model prediction, Ridong[14] used GTN model to predict the fracture load of high strength bolts. Yamamoto et al. [15] proposed a quantitative model of relative sliding of bolts and nuts based on two-stage loosening theory. Xinglin Yang [16] established the mathematical model of the stress corrosion fracture of high strength bolts by using the theory and method of fracture mechanics, which described and speculated the real cause of fracture failure, and discussed the influence of the initial crack length and the stress on the extension life of the stress corrosion crack. Based on the theory of fracture mechanics and Gerberich-Chen formula, Huili Wang [17] established the corrosion fracture crack estimation model and fatigue life estimation model for high strength bolts. Taking the M24 high strength bolt joint of 20MnTiB steel as an example at the same time, he calculated and predicted the stress and stress of high strength bolt node, and quantitatively analyzed the crack depth and corrosion fatigue life of high strength bolt fracture in the corrosion environment. There are many researches on fracture failure analysis of high strength bolts based on fracture mechanics theory, but few researches are focused on quantitative analysis to predict the reliability of high strength bolts from the perspective of environmental corrosion.

2. Preliminary analysis on failure of high strength bolts in Chaotianmen Bridge

2.1. Spatial and temporal distribution characteristics of failure high strength bolts

The main truss of Chaotianmen Bridge is connected by 10.9s M30 high strength big hexagonal head bolts, and the connection system and deck system are connected by 10.9s M24 high strength big hexagonal head bolts. The corresponding materials of high strength bolts of M30 and M24 are 35VB steel and 20MnTiB steel respectively. According to the statistical data of failure high strength bolts of Chaotianmen Bridge from 2009 to now, as shown in Figure. 1, ninety five high strength bolts were found to be shedding and fracture in total, and of which fifty seven were in M24 specifications and thirty eight were in M30 specifications. Before 2012, two M24 and twelve M30 high strength bolts were found to be failure, and 11 of them were tested for failure analysis. Since 2013, the number of failure high strength bolts has been found to increase in a straight line, which is related to the service life of bolts and the improvement of bridge inspection and management level.

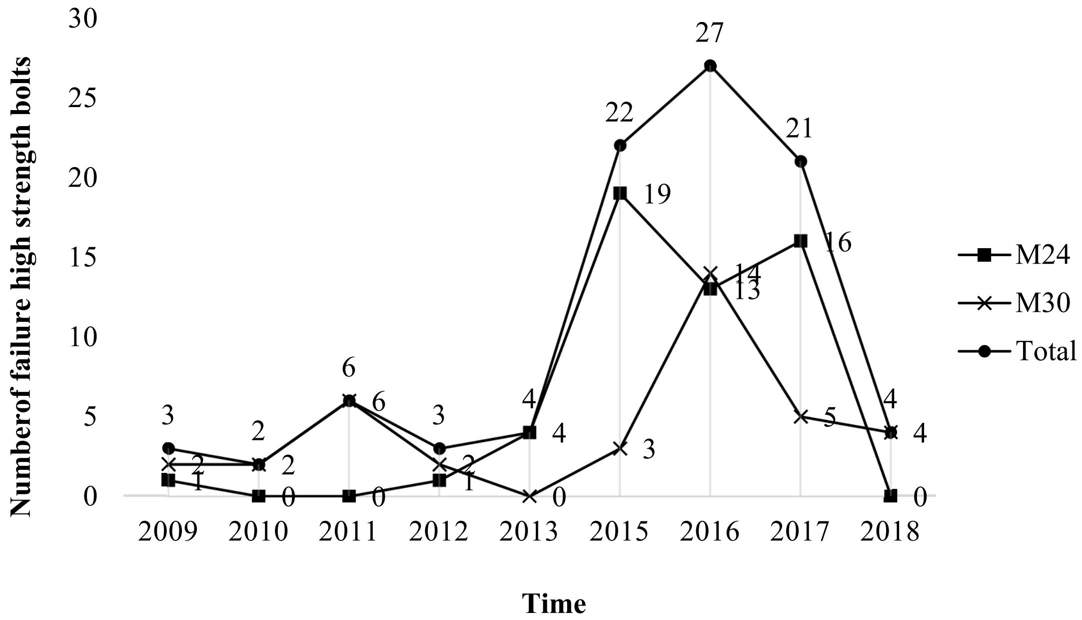

Figure 1. Temporal distribution of failure high strength bolts.

It has found that failure high strength bolts in the north and south side of Chaotianmen Bridge are basically symmetrical distribution, 46 in the North side, 40 in the South side, and the location of the rest is unknown. The statistical distribution of the number of failure high strength bolts in different structural systems and cross sections of the bridge is shown in figure.2 and figure.3.

From figure.2 it can be seen that the number of failure high strength bolts at Upper chord A of the main arch is the largest, followed by the lower chord E of the main arch, and the lower deck M is slightly higher than the upper deck C.

From figure.3 it can be seen that the number of failure high strength bolts has increased along with the development of the bridge head to the center of the bridge, and is mainly concentrated in the 30-36 section.

According to the statistical data of failure high strength bolts of Chaotianmen Bridge from 2009 to now, one M24 and two M30 high strength bolts failed respectively in 2009, 2015 and 2016, at the same place NA33, section 33 upstream of North upper chord A of the main arch. There are nine nodes where high strength bolts failed twice during 9 years, respectively, the upstream of North upper chord NA35, the upstream of South upper chord SA33, the middle of South upper chord SA32, the middle of South upper chord SA30, the middle of lower chord HE36, the middle of lower chord HE34, the upstream of South lower chord SE29, the downstream of South lower chord SE28 and the downstream of South lower chord SE15. There are seven nodes where high strength bolts failed more than three times during 9 years, respectively, 5 times in the North upper chord NA31 section and NA33 section, 6 times in the North upper chord NA34 section, 4 times in the South upper chord SA32 section and SA33 section, 4 times in the South lower chord SE28 section and SE36 section.

The statistical data indicates that most of the failure high strength bolts sites of Chaotianmen Bridge are concentrated in the top chord of the arch, where both the displacement of the structure and the stress variation are very large under the load.

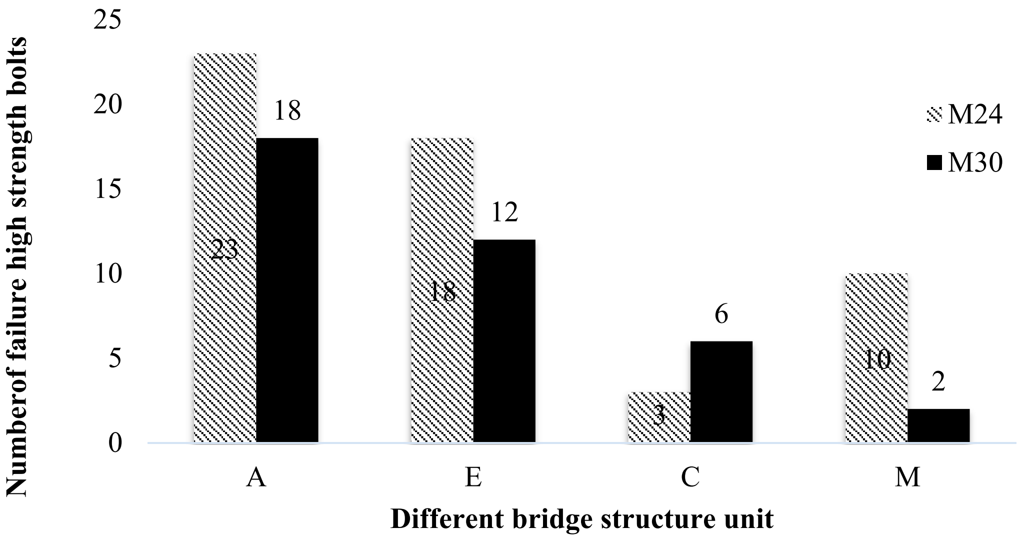

Figure 2. Spatial distribution of failure high strength bolts in different structure units.

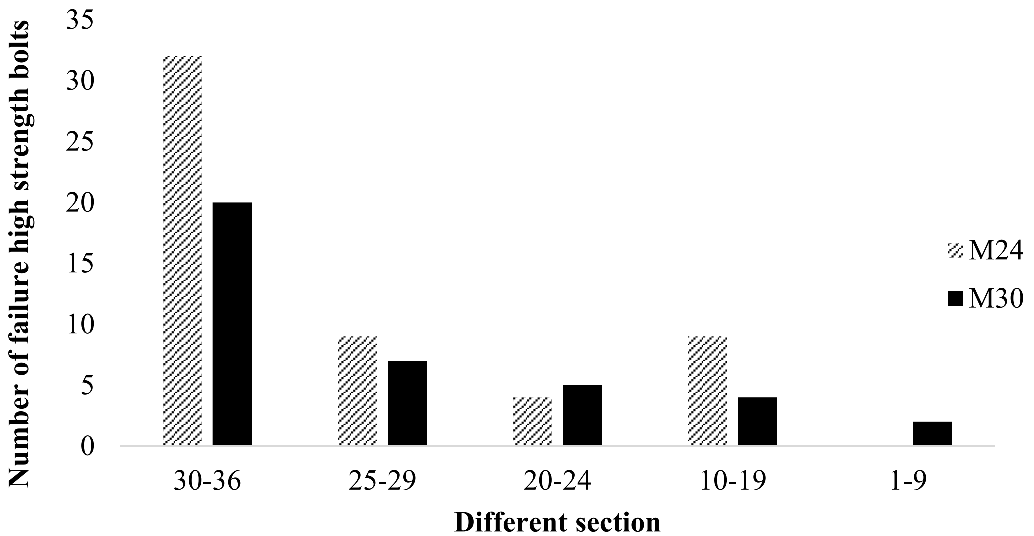

Figure 3. Spatial distribution of failure high strength bolts in different section.

2.2. Composition and micro-structure properties of failure high strength bolts

Among these 14 failure high strength bolts found from 2009 to 2012, 11 bolts were collected on site. 8 of the 11 bolts were pitted and rusted. 9 of the 11 bolts with the fracture surface were found at the root of the screw, and the rest 2 bolts with the fracture surface were found at the thread. The chemical composition, metallographic structure, hardness and other mechanical properties of the 11 bolts were analyzed and tested to explore the reasons for fracture failure of high strength bolts. The results of analysis are shown in table 1.

The chemical compositions standard of 20MnTiB and 35VB steels are stipulated in GB/T699-2015 and GB/T1231-2006 respectively, which are shown in table 2.

Table 1. Chemical composition and micro-structure properties of failure high strength bolts.

Model	Location	C	Si	Mn	P	S	V	B	HRC	Micro-structure
M30	NSA33	0.34	0.26	0.7	0.01	0.005	0.0849	0.0019	40.5	Tempered sorbite
M24	NSA35	0.19	0.22	1.37	0.02	0.006	0.002	0.0012	37	Tempered sorbite
M30	SSA28	0.33	0.26	0.7	0.01	0.005	0.086	0.002	43	Tempered martensite
M30	SSE29	0.35	0.26	0.64	0.016	0.003	0.08	0.0026	43	Tempered martensite
M30	SXE28	0.35	0.21	0.63	0.015	0.006	0.0731	0.0019	38	Tempered sorbite
M30	NSA30	0.33	0.24	0.64	0.016	0.003	0.08	0.0022	36.5	Tempered sorbite
M24	NHA34	0.19	0.23	1.47	0.02	0.011	0.0003	0.002	39	Tempered martensite
M24	NXC28	0.21	0.22	1.47	0.018	0.015	0.0003	0.003	40	Tempered martensite +Tempered sorbite
M30	SSE3	0.35	0.27	0.69	0.011	0.006	0.08	0.002	43	Tempered martensite
M30	NXA34	0.34	0.29	0.69	0.009	0.004	0.09	0.002	43	Tempered martensite+ Tempered sorbite
M24	NXA33	0.18	0.23	1.45	0.018	0.011	0.003	0.002	39	Tempered martensite

N-North, S（1）-South, S（2)-upstream, X-downstream, H-middle,
A-Upper chord, E-lower chord, C-bridge upper deck, M-bridge lower deck..

Table 2. Chemical composition standard of 20MnTiB and 35VB.

Specifications	C	Mn	Si	P	S	V	B	Cu	Ti
35VB	0.31-0.37	0.50-0.90	0.17-0.37	≦0.04	≦0.04	0.05-0.12	0.001-0.004	≦0.25	
20MnTiB	0.17-0.24	0.17-0.37	1.3-1.6	≦0.04	≦0.04	-	0.0008-0.0035	-	0.04-0.10

Compared with table 1 and table 2, it can be concluded that the chemical compositions of the steel meet the requirements of the national standard in the 11 sets of high strength bolts.

According to GB/T1231-2006 "Technical Specifications for High Strength Hexagon Head Bolts, Hexagon Head Nuts and Gaskets for Steel Structures", the Rockwell Hardness of 10.9s high strength bolts is 33HRC~39HRC. However, from table 1 it can be seen that six failure high strength bolts` HRC values are of 40, 40.5 and 43 (4 bolts), which do not meet the above technical conditions, and the unqualified rate accounts for 54.5%. Tempered martensite is detected in metallographic structure in samples with unqualified hardness. Tempered sorbite has good comprehensive mechanical properties because of good toughness, plasticity and high strength. While tempered martensite has high hardness (HRC58-64) and high wear resistance, strength, and toughness. It belongs to brittle structure. Because of the precipitation phase and uneven distribution of carbide, it is easy to corrode and delay fracture in natural environment. According to the analysis results, the metallographic structure and mechanical properties of the high strength bolts failed to meet the technical requirements of GB/T1231-2006, which is one of the important reasons leading to the fracture of the high strength bolts.

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2.3. Other reasons

From the above analysis, it can be seen that half of the high strength bolts whose material and metallographic structure meet the requirements of the standards, but still have fractured. Therefore, it can be inferred that the failure of high strength bolts is not only related to the unqualified metallographic structure, but also related to the construction processs, operating environment and other aspects.

1) 8 of the 11 failure bolts found at the scene are pitted and rusty. There are two possible reasons for this phenomenon. One is that the bolt has been rusted before installation due to improper sealing measures. The other is that the gasket is not tightly attached to the nut (cap) or the steel plate ,resulting in the corrosion of moisture entering the bolt hole.

2) Super-tighten of high strength bolts during construction.

3) The holes of the joint plate and the steel truss are manufactured in the factory. If the error is too large in the construction process, the high strength bolt after installation may be broken by shearing force.

4) During the operation stage of the bridge, the anti-corrosion coating of high strength bolts is destroyed, thus the high strength bolts are exposed in humid air and rainwater for a long time. Then for a certain length of time the stress corrosion and delayed fraction of high strength bolts occurred.

5) Temperature stress. The temperature changes caused by sunshine or cold current are different in different structure units, resulting different temperature stress in different locations. And the high strength bolts that with large force changes are easy to break.

3. Conclusion

The failure rate of high strength bolts in the steel structure of Chaotianmen Bridge is about 0.0025%. Most of the failure high strength bolts sites of Chaotianmen Bridge are concentrated in the top chord of the arch, where both the displacement of the structure and the stress variation are very large under the load. Among these 14 failure high strength bolts found from 2009 to 2012, 11 bolts were found on site, of which 8 bolts were pitted and rusted, and 9 bolts with fracture surface at the root of the screw and 2 bolts with fracture surface at the thread were found. The chemical composition, metallographic structure, hardness and other mechanical properties of the 11 bolts have been analyzed and tested to explore the reasons for fracture failure of high strength bolts. The results show that the chemical compositions of the steel meet the requirements of the national standard in the 11 sets of high strength bolts. However, six failure high strength bolts` HRC values are of 40, 40.5 and 43 (4 bolts), which do not meet the technical requirements of GB/T1231-2006, and the unqualified rate accounts for 54.5%. Tempered martensite, which belongs to brittle structure, is detected in metallographic structure in samples with unqualified hardness.

The failure of high strength bolts is not only related to the unqualified metallographic structure, but also related to the construction processs, operating environment and other aspects. Especially the influence of environmental corrosion on the quality, micro-structure and mechanical properties of high strength bolts should be paid more attention by bridge managers. However, by far, there have been many researches on fracture failure analysis of high strength bolts based on fracture mechanics theory, but few researches are focused on quantitative analysis to predict the reliability of high strength bolts from the perspective of environmental corrosion. To provide a basis for the measures taken to prevent the breakage of high strength bolts, it is necessary to explore further and clarify the influence of environmental factors on the corrosion fracture of high strength bolts and its mechanism.

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References

[1] Li, Y.C. (1993) Introduction to design of steel girders for main bridge of Jiujiang Yangtze river bridge. Bridge Construction, 1:77-81.
[2] Shi, S.Y. (2008) The accuracy control of drill hole for Chaotianmen Bridge. Steel Structure, 23:67-69.
[3] Jiang, Z. L., Wang, T.Z. (1982) Fracture mechanics analysis of stress corrosion cracking of high strength bolts. Industrial Construction, 7:42-48.
[4] Zhang, H.F., Wang, C.F. (2007) Analysis of failure reason of high strength bolt. Hot Working Technology, 36:85-87.
[5] Mu, J. (2010) Experimental research on fatigue failure of connecting nodes with high strength bolts. Thesis for Master degree of Chongqing jiaotong University, Chongqing.
[6] Liu, S.T., Cui, K. (1982) Reliability analysis of delay fracture of high strength bolts in steel structure. Industrial Construction, 9:30-37.
[7] Wang, T.Z., Li, S.F., Peng, S.L. (1987) Test and study on delayed fracture resistance of 35VB steel. Ordnance Material Science and Engineering,12:1-5.
[8] Li, M.L., Pu, C.H., Li, S. (2017) Fracture Failure Analysis on 35VB Steel High Strength Bolt. Hot Working Technology, 46:259-263.
[9] Zhang, P.F. (2017) Effect of different surface treatment processes on microstructure and properties of high strength bolt steel. Thesis for Master degree of Southwest Jiaotong University, Chengdu.
[10] Hu, J., Zou, D.Q., Yang, Q.Q. (2017) Fracture failure analysis of 20MnTiB steel high strength bolt used for rail. Heat Treatment of Metals,42:185-188.
[11] Yang, Y., Zhao, J.J., Yang, X.K. (2017) Effects of salt-fog environment on fatigue limit of high strength for military airplane. Equipment Environmental Engineering, 14:57-60.
[12] Zhang, M. (2011) Corrosion of high strength steel bolt friction type connection test of performance degradation. Thesis for Master degree of Xi 'an university of architecture and technology ,Xi 'an.
[13] Luo, Z.J., Wang, X.C., Sun, Q.S. (2017) Industrial atmospheric corrosion resistant high strength bolts steel for bridge structure without coating and its manufacturing method. http://www.soopat.com/Patent/201710375670.
[14] Liao, R.D., Sun, Y.J., Liu, J.X. (2011) Applicability of damage models for failure analysis of threaded bolts. Engineering Fracture Mechanics,78:514-524.
[15] Yamamoto, A. (1977) Investigations on the self-loosening of threaded fasteners under transverse vibration. Journal of the Japan Society of Precision Engineering,43:470-475.
[16] Yang, X.L., Zhang, J.M., Chen, Y.G. (2009) Modeling and simulating of stress corrosion Cracking in high stress bolt. Journal of Nanjing University of Aeronautics & Astronautics,41:130-133.
[17] Wang, H.L., Xia, J.G., Qin, S.F. (2014) High strength bolt corrosion fatigue life estimate mode and its application. Journal of Dalian Maritime University,40:113-116.