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The research on delayed fracture behavior of high-strength bolts in steel structure

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Abstract. High-strength bolts have been widely used in power plants. However, the high-strength bolts which being employed in pumping station, steel structure and pipeline anti-whip structure have been found delayed fracture for many times in a power plant, this will affect the reliability of steel fracture and bring blow risk caused by falling objects. The high-strength bolt with delayed fracture was carried out fracture analysis, metallurgical analysis, chemical analysis, mechanical analysis, as well as bolts installation analysis, it can be comprehensively confirmed that the direct cause of high-strength bolts delayed fracture is the stress corrosion, and the root cause of high-strength bolts delayed fracture should be the improper installation at the initial and the imperfect routine anti-corrosion maintenance.

1. Introduction
High strength bolts are widely used in main steel structure and secondary steel structure of power plants. Compared with the welding connection, high strength bolts have many advantages, such as simple structure, reliable connection, quick construction etc.
A number of 10.9 high-strength bolts have been found broken in steel structure of power plant, in addition, broken number of high-strength bolts have more than 10 in pumping station plant steel structure and pipe anti-whip structure. Preliminary inspection found that all of the bolts were delayed failure, the shortest failure time was 3 years, the longest time was 20 years. The original design of steel structure demand that the use life of high strength bolts should be equal to the life of steel structure, if large-scale high strength bolts fracture, will affect the reliability of steel structure, high strength bolts fall from the steel structure, there is a blow risk, so it is necessary to study the reason of delayed fracture of high strength bolts.
In this paper, The high strength bolts being analyzed were manufactured by Shen Guang Shanghai high strength bolt factory, the bolts has been used more than 15 years, bolt material is 20MnTiB, bolts surface has phosphating treatment, bolts size are M20, The failure bolt break at the screw near the nut, as shown in Figure 1.
Before leave factory, manufacturer had sampled each batch of bolts, the sampling results meet the requirements of the national standard of GB/T 1228~1231 91. The appearance of the bolts, accuracy of thread, form and location tolerance or other dimensions conform to the requirements of GB5779.1~3 - 86, GB/T1228~1231 - 91, GB/T3631~3633 - 95. The chemical composition, mechanical properties test (tensile strength, yield strength, elongation, shrinkage, impact toughness), wedge load test, friction coefficient also meet the relevant standards.
In this paper, the delayed fracture behavior of high strength bolts is studied by means of fracture analysis, metallographic examination, chemical composition analysis and hardness test. And the high strength bolts are randomly selected from the steel structure, and will be carried out comparative analysis to find out the reasons for the delayed fracture of bolt.

2. Experimental methods and results

2.1. Experimental object
A broken high strength bolt, as well as the same type, no broken high-strength bolts.

2.2. Fracture examination
Base on the analysis of macroscopic examination and microscopic examination, the failure characteristics and failure type of bolt are determined.

The failure bolt broke at the position of the screw and nut, the fracture is no plastic deformation, vertical with the screw. The fracture surface has been found trace of corrosion, the divergent lines starting at the corrosion location. It is shown that the corrosion location is source of crack, and the macroscopic examination is shown in Figure 2.

Cleaning fracture of failure bolt, the microscopic characteristics of fracture surface is observed. The source area of the crack is located at the bottom of screw thread, as shown in figure 3-a, the phosphating coating on the bottom surface of thread has been destroyed, corrosion products exist in the source region, the fracture shows intergranular fracture characteristics. The middle part of fracture is crack propagation zone, as shown in figure 3-b, there are intergranular feature and a few dimples in the fracture, the fracture extension area existe tear morphology and hydrogen embrittlement behavior. The opposite side of the crack source is the fracture zone, as shown in figure 3-c, the final fracture zone is dimple morphology, which is the ductile tearing area of failure bolt.

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**Figure 1.** High-strength bolts fracture location.

**Figure 2.** Macroscopic examination of failure bolt.

**Figure 3.** Microscopic examination of failure bolt: (a) The source region of crack, (b) The growth Area of Crack, (c) The final fracture area.
2.3. Metallographic analysis
The metallographic analysis shows that there are many intergranular cracks near the crack source, as shown in figure 4-a. There are corrosion pits on the adjacent surface of the section (the bottom of the thread adjacent to the fracture location), see figure 4-b, it can be seen that the intergranular crack originated from the corrosion pits, the crack length is about 0.14mm, and has not penetrated through the center of the bolt. According to the above crystal crack, the main crack has the same pattern, that is, the main crack comes from the corrosion pit; In addition, there are many secondary cracks near the main crack, when the main crack expands, bifurcation phenomenon occurs, therefore, comprehensive judgment the crack is caused by stress corrosion.

![Figure 4. The intergranular cracks of failure bolt: (a) Fracture surface, (b) neighboring regions.](image)

The metallographic structure of fracture bolt and sampling bolt is tempered sorbite, The metallographic structure is normal, as shown in figure 5-a, there is a strip distributed along the axial direction in each bolt, See figure 5-b, the size and quantity of inclusions meet the national standards.

![Figure 5. The Metallurgical of failure bolt: a microstructure b inclusions.](image)

2.4. Chemical composition analysis
The results of chemical composition analysis of the failed bolt and the broken bolt are shown in table 1, each bolt material is 20MnTiB, chemical composition meets the requirements of GB/T 3077-1999 standard [1], Sulfur content less than 0.035, Phosphorus content less than 0.035.

2.5. Hydrogen content analysis
Samples of hydrogen content were obtained from the surface and center of the failed bolt and sampling bolt, measurement results are shown in table 2. The analysis shows that the hydrogen content of broken bolt is higher than sampling bolt, the hydrogen content in the middle part of the bolt is higher than the surface. In the expansion area of bolt fracture, there are traces of hydrogen embrittlement characteristics, this is consistent with the hydrogen content test.

Hydrogen embrittlement can be judged for the generalized stress corrosion in the core of failure bolt, the reason is follow. Hydrogen embrittlement characteristic is not found in the source of crack initiation site, and the hydrogen content of crack source is low, the crack propagation region has hydrogen embrittlement characteristic and high content of hydrogen, therefore, the hydrogen embrittlement caused by the application environment, which should be caused by stress corrosion cathodic process.

The hydrogen embrittlement mechanism in crack propagation: the cathodic process of stress corrosion is releasing hydrogen process, the hydrogen is diffused to the core of bolt, and the hydrogen
content in the heart of bolt is higher than the surface, the crack propagation process has characteristics of hydrogen embrittlement, therefore, the hydrogen embrittlement can also be defined as generalized stress corrosion, but on the whole, the main reason of failure should be stress corrosion.

Table 1. Bolts chemical composition (wt/%)

| No.   | C    | Mn  | Si   | B    | Ti  | S    | P    |
|-------|------|-----|------|------|-----|------|------|
| Failure bolt | 0.21 | 1.46 | 0.31 | 0.0026 | 0.07 | 0.023 | <0.02 |
| sample1 | 0.20 | 1.38 | 0.26 | 0.0023 | 0.06 | 0.020 | <0.02 |
| sample2 | 0.21 | 1.46 | 0.31 | 0.0026 | 0.07 | 0.024 | <0.02 |
| sample3 | 0.20 | 1.52 | 0.32 | 0.0026 | 0.08 | 0.026 | <0.02 |
| sample4 | 0.21 | 1.50 | 0.28 | 0.0031 | 0.05 | 0.008 | <0.02 |
| sample5 | 0.24 | 1.47 | 0.30 | 0.0026 | 0.07 | 0.024 | <0.02 |
| GB/T 3077-1999 | 0.17~1.30~ | 0.17~0.37 | 0.0005~0.04~ | <0.02 | <0.02 |

Table 2. Bolts hydrogen content (mg/kg)

| No.   | position | testing 1 | testing 2 | testing 3 |
|-------|----------|-----------|-----------|-----------|
| Failure bolt | Near surface | 0.9 | 0.8 | / |
|          | core     | 3 | 2 | / |
| sample1 | Near surface | 0.2 | 0.3 | 0.3 |
|          | core     | 0.4 | 0.3 | / |
| sample2 | Near surface | 0.5 | 0.4 | 0.6 |
|          | core     | 0.3 | 0.5 | / |
| sample3 | Near surface | 0.2 | 0.2 | 0.5 |
|          | core     | 0.3 | 0.4 | / |
| sample4 | Near surface | 0.5 | 0.3 | 0.4 |
|          | core     | 0.5 | / | / |

2.6. Mechanical properties analysis
The hardness, tensile properties and impact properties of high strength bolts are measured by hardness tester, mechanical testing machine and impact testing machine.

The results are as follows:
The hardness of the broken bolt and sampling bolt are 33~39HRC; the tensile strength of the bolt (σb) sampling are 1085Mpa ~ 1152Mpa; The yield strength (σ0.2) are 1036Mpa ~ 1083Mpa; Elongation (δ5) are 14.7% ~ 15.9%; Section shrinkage (ψ) are 66.3% ~ 70.3%; The impact energy of the sampling bolt (Ak) are more than 47J, and the impact toughness value (ak) are more than 58.75J/cm². The mechanical properties of the broken bolt and non-broken bolts are all in accordance with the requirements of GB/T 1231-2006 standards [3].

3. Analysis and discussion
The above analyses show that the fracture of high strength bolt in steel structure is caused by stress corrosion. The material and mechanical properties of broken bolt meet the relevant national standards.
There is corrosion product in the source region of broken bolt, and the fracture is intergranular, there are many small cracks along the grain boundaries in the source region. The corrosion pits are found at the bottom of the thread adjacent to the fracture surface, and the intergranular cracks are initiated from the corrosion pits, therefore, comprehensive judgment stress corrosion is the direct cause of bolt broken.

The broken bolt is subject to stress corrosion, according to forming mechanism and influencing factor of stress corrosion, as well as the installation and environment of broken bolt, it is speculated that bolt failure is related to the corrosion and abnormal tensile stress.

3.1. Bolt corrosion
The steel structure of the power plant is installed outside the reactor building, the operating environment is marine atmospheric environment, there are Cl, S and other corrosive media in the air, so there is corrosion medium in the environment in which the bolt is located.

After the Broken bolt is tightened, sealed with putty in nuts, nut and two with mounting surface clearance, and painted anti-corrosion treatment to prevent wet air and rainwater into the bolt hole. Prolonged exposure to air and rain, paint and putty layer aging and cracking, the bolt is not tight seal. Once the corrosion medium reached the high stress position of the bolt, in the long term interaction between corrosion medium and stress, the phosphating layer of the high stress position of bolt is consumed gradually, the bolt matrix is directly exposed to the corrosive medium, and the bolt matrix was corroded.

Poor maintenance of bolt’s paint leads to corrosion medium contact with bolt. The initial design of the steel structure didn’t consider the subsequent anticorrosion work, maintenance personnel cannot reach some steel structure position, therefore, the power plant maintenance department cannot maintain the position which cannot reach in the steel structure.

It is observed that there are different degrees of corrosion in most sampling bolts, the phosphating coating of sampling bolts have been destroyed, and the protective effect of the paint layer has disappeared, bolts are easily corroded by atmosphere and rain.

3.2. Too much force on the bolt
According to bolt construction record, steel structure high strength bolt serious over screw, at least over 12%, the pre tension and the torque coefficient of high strength bolts are not satisfied with the national standard. According to the domestic standard, the pre tension of the 10.9 class M20 friction type high-strength bolt is 170KN[^3], the steel structure high-strength bolt pretension is 190.4KN, the reason for the pre tension higher is that the reference installation file is not appropriate. The torque coefficient of the installation of high strength bolt is the factory test value (0.146), not checked again in installation environment, the torque coefficient of the bolt is not adjusted by experience, which leads to the fact that the construction torque coefficient is larger than the actual torque coefficient.

![Figure 6. Finite element analysis: (a) normal tightening torque, (b) tightening torque exceeds.](image)

The finite element analysis shows that the normal average equivalent stress is 727Mpa, the average equivalent stress after super twist reaches 884MPa, and the stress value increases by 21.6%, as shown
in figure 6. The equivalent stress (884 MPa) and the yield strength (940 MPa) of the bolt after the super twist is about 0.94, according to the experience of the bridge industry, the status of the bolts must be replaced. After super twist, bolt force will increase, so that bolts are in a state of insecurity.

When the bolt is subjected to stress corrosion, the super twist will promote the development of corrosion, therefore, super twist is an important factor of bolt stress corrosion damage.

4. Analysis conclusions and solutions
In this paper, the manufacture, installation and operation of fracture bolt are studied, the reason for the delayed fracture of the bolt is found out.

According to the above analysis, the direct reason for the delayed fracture of steel bolt is the stress corrosion, this isn’t consistent with some of the conclusions given in the literature\[4-7\]. The root cause of delayed fracture is poor maintenance and improper installation of bolt, this result in the stress corrosion of bolt.

Preventive measures which based on the root cause of delayed fracture can prevent the high strength bolt from breaking, such as:
- Replace all too tightened bolts, construction process needs to strictly comply with national standards. Before the construction of high strength bolts, check on the torque coefficient, and select the correct construction pre tension, to ensure that the construction torque is suitable. High precision torque wrench should be used in the construction of high strength bolts, after the completion of construction of high strength bolts, spot checks should be performed, Timely tightening of the less screwed bolts, super twist should be replaced.
- Improve the anti-corrosion measures of high-strength bolts. Daily inspection found high strength bolt screw thread damage or rust, it should be immediately replaced
- Selection better corrosion resistance bolts. The replacement of high strength bolts should be based on the structural characteristics of steel, in severely corrosive and hard to reach places, should use the better corrosion resistance of Dacromet high strength bolt, increase the corrosion resistance of high strength bolts.

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