Research article

Failure analysis of local settlement induced Q345R bottom plate cracking of crude oil storage tank

Zhang Shuxin\textsuperscript{a,b,*,} Kang Chun\textsuperscript{c}, Zhang Penggang\textsuperscript{c}, Luo Jinheng\textsuperscript{a}, Shao Yingjie\textsuperscript{d}, Wu Gang\textsuperscript{a}, Deng Banghui\textsuperscript{c}

\textsuperscript{a} Tubular Goods Research Institute, China National Petroleum Corporation & State Key Laboratory for Performance and Structure Safety of Petroleum Tubular Goods and Equipment Materials, Xi’an, Shaanxi 710065, China
\textsuperscript{b} School of Civil Aviation, Northwestern Polytechnical University, Xi’an 710072, China
\textsuperscript{c} Tarim Oilfield Company, PetroChina Company Limited, Korla 841000, China
\textsuperscript{d} Xi’an Petroleum University, Xi’an, Shaanxi 710065, China

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\textbf{ABSTRACT}

A 5000m\textsuperscript{3} single deck floating roof crude oil storage tank was found to have a cracked Q345R bottom plate during an open tank inspection. To analyze the cause of the failure, a series of experiments were carried out. The results showed that the chemical composition of the failed crude oil storage tank bottom plate material Q345R had a slight excess of S, V, and Ti which causes the material to form a bainite structure, resulting in a hard and brittle material with poor toughness. Q345R is susceptible to H\textsubscript{2}S stress corrosion cracking according to SCC test. Based on the working condition investigation, the cracked plate was subjected to the local settlement and H\textsubscript{2}S contained corrosive medium. With the stress concentration induced by local settlement, the bottom plate cracked. In order to avoid such incidents, Q345R material should be avoided in H\textsubscript{2}S containing environment, and online monitoring should be carried out regularly to assess the overall condition of the tanks.

1. Introduction

Atmospheric storage tanks are widely used in petroleum and petrochemical fields. In oilfield transfer stations and joint processing stations, storage tanks are usually used to temporarily store exploited crude oil and to separate the water from the medium. Since the oilfield exploited medium contains water, CO\textsubscript{2}, H\textsubscript{2}S and O\textsubscript{2}, the primary failure mode is bottom plate corrosion \cite{1, 2, 3, 4, 5}, including uniform and pitting corrosion. In the crude oil commercial depot, the storage tanks are used for peak tuning and storage. The storage medium is purified oil with low water content, and the corrosion risk is relatively small, the failure modes are lightning strike \cite{6}, settlement \cite{7}, mis-operation \cite{8}, accessories failure \cite{9}, seismic induced buckling failure \cite{10, 11}, etc.

F. Trebmisuna et al. \cite{12} investigated the roof collapse failure of the dome roof tank, and found that the quick discharging of the medium led to the pressure drop, and with the unqualified weld of the supporting steel bands, the roof collapsed. Mahmoud AboElkhier et al. \cite{13} studied an explosion failure of the toluene tank. The tank exploded during the charging process, and the roof separated from the top. Unqualified weld between the roof and the shell that contains the scales and impurities is the leading cause of the failure. Jae-Seong Kim et al. \cite{14} analyzed an oil storage tank’s T fillet joint cracking failure. The hardness of the weld heat affected zone is high, indicating that the weld parameter is not proper, the crack initiated at the root of the multi-pass weld. Rajmund Ignatowicz et al. \cite{15} researched a tank bottom plate external corrosion. The rainwater penetrated into the bottom of the tank due to the poor seal between the bottom and shell, the local settlement formed. The bottom plate leaked with the presence of the plastic strain induced by settlement and the corrosive environment. M. Mobin \cite{16} studied the pit corrosion of the aboveground storage tank, the pit corrosion formed due to the blistering failure of the coating and corrosive medium.

The storage tank’s failure cases reported focused on poor welding and corrosion. There is a scarcity of research about the bottom plate’s crack failure associated with a combination of stress corrosion crack and local settlement. Crack failure would lead to rupture and leaks of the oil, and the failure consequence is severe. Therefore, this failure case is of great value to research.

In this study, a 5000m\textsuperscript{3} single deck floating roof crude oil storage tank was found to have a cracked bottom plate during a tank inspection. The crude oil storage tank was put into operation in 2004. The capacity of the...
Figure 1. The macro view of the failed bottom plate (a) the cleanout door (b) the overall view of the two cracks (c) the crack at the left side, the red rectangle indicated the studied sample (d) the crack at the right side.

Figure 2. The failed bottom plate (a) the upper surface of the bottom plate (b) the lower surface of the bottom plate (c) the fracture.
tank is 50894m³, the highest design level is 18m, the diameter of the tank is 60m, the material of the tank shell is 16MnR (Q345R) with a thickness of 34mm. The material and thickness of the tank bottom plate are: the bottom plate Q235A with 10mm, the annular plate Q345R with 14mm, and the bottom plate near cleanout door is 16MnR with 20mm according to construction standard GB 6654-1996 \[17\]. (Designated Q345R in latest standard GB 713–2014 \[18\]). The tank was periodically maintained in 2009 and 2014, no cracks were found. In 2019, during the third tank maintaining process, two cracks were found on the bottom reinforcement plate at each side of the cleanout door with lengths of 1000mm and 1430mm, respectively, as shown in Figure 1 (a–d). The medium stored in the tank is crude oil with a certain amount of water. According to water quality analysis, the water contains chloride ions with a content of more than 100000ppm and hydrogen sulfide.

In order to analyze the root cause of the bottom cracking failure, one piece of the bottom plate was cut off to conduct a series of experiments.

2. Experiments and results

2.1. Visual inspection

Figure 2 shows the sample of the failed storage tank bottom plate cut for research. In order to observe the crack, the grey coatings were polished. The residual coating around the crack of the inner wall was intact without bulge or any defects, as shown in Figure 2a. The outer wall of the bottom plate was covered with red coatings with brown corrosion products, as shown in Figure 2b. The crack was flat, shows no plastic deformation characteristic from the side view. The fracture was flat and covered with thick corrosion products (Figure 2c).

Table 1. The chemical composition test result (wt.%).

| Element | Sample | Requirement of GB 6654-1996 | Requirement of GB 713-2014 |
|---------|--------|-----------------------------|---------------------------|
| C       | 0.15   | ≤0.20                       | ≤0.20                     |
| Si      | 0.31   | 0.2–0.55                    | 0.2–0.55                  |
| Mn      | 1.34   | 1.2–1.6                     | 1.2–1.7                   |
| P       | 0.010  | ≤0.035                      | ≤0.025                    |
| S       | 0.014  | ≤0.030                      | ≤0.030                    |
| Ni      | 0.0044 | ≤0.030                      | ≤0.030                    |
| Cr      | 0.0088 | ≤0.030                      | ≤0.030                    |

Table 2. Tensile test result.

| Sample | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
|--------|------------------------|----------------------|----------------|
| Bottom plate | 689  | 486                | 22.7           |
| Requirement of GB 6654-1996 | 490–620 | ≥325             | ≥21            |
| Requirement of GB 713-2014 | 500–630 | ≥325             | ≥21            |

Table 3. Charpy impact test result.

| Sample | Absorbed energy/°C 20 °C | Average result |
|--------|--------------------------|----------------|
| Bottom plate | 5.5, 5.1, 4.8 | 5.1 |
| Requirement of GB 6654-1996 | ≥31 at 0 °C |
| Requirement of GB 713-2014 | ≥41 at 0 °C |

Table 4. Brinell hardness test result.

| Sample | Brinell hardness (HBW5/750) |
|--------|-----------------------------|
| Bottom plate | 215, 215, 215 |

2.2. Material performance

2.2.1. Chemical composition

The chemical composition of the bottom plate was analyzed by ARL4460 direct reading spectrometer. The result was shown in Table 1. Because the storage tank was constructed in 2004, the design standard for storage tank bottom plate material 16MnR was GB 6654-1996. While according to the latest standard GB 713–2014, 16MnR steel was renamed as Q345R. Therefore, the chemical composition of the bottom plate material was compared with the standard GB 6654–1996 and GB 713–2014. The chemical composition meets the requirement of GB 6654-1996, while the content of S, V, Ti are slightly higher than the upper limit of the requirement of GB 713–2014 and Al is lower than the upper limit.

2.2.2. Mechanical property

The tensile test was carried out by UTM 5305 universal material machine according to GB 228 \[19\], the rod specimens with a diameter of 12.5 mm in gauge section was tested under room temperature. The result was shown in Table 2. The yield strength and elongation of the storage tank bottom plate meet the requirements of GB 6654–1996 and GB 713–2014, while the tensile strength exceeds the upper limit of the requirements of GB 6654–1996 and GB 713–2014.
Figure 4. Metallographic structure of fracture.

Figure 5. The micro morph of the fracture.
The Charpy impact test was conducted by PIT752D-2 according to GB 229 [20] under room temperature, the dimension of the Charpy V-notch test sample was 10 × 10 × 55 mm. Three parallel samples were used to ensure the reproducibility and accuracy. The result was shown in Table 3. The average value of the impact absorbed energy of the tank bottom plate is lower than the lower limit required by GB 6654–1996 and GB 713–2014 for Q345R. The low impact energy value indicates that the material is prone to brittle cracking.

Brinell hardness test was conducted by BH3000 tester, three test points were applied to ensure the reproducibility and accuracy. The result was shown in Table 4. Generally, the material used in H2S-containing environments should have a Rockwell hardness value less than 20HRC [21], which is equivalent to 226 HB. Therefore, the sample meets the requirement for material used in a H2S environment [21].

2.3. Metallographic analysis

The metallographic microscope was adopted to observe the microstructure of the bottom plate material, the microstructure is ferrite + pearlite + bainite, as shown in Figure 3. The nonmetal inclusion grade is A1.0 Cl.0 D1.0, grain size is 8.5 grade, and band structure is 1.0 grade.

2.4. Fracture analysis

The cross-sectional morphology of the crack was observed under metallographic microscope, as shown in Figure 4. There are secondary branch cracks around the fracture, which is the typical characteristic of SCC. There are microcracks existed inside the matrix near the fracture with a mixture of trans-crystalline and intergranular characteristic.

2.5. Corrosion product

The scanning electron microscope Hitachi S3400 was used to observe the fracture morphology. The accelerating voltage was 20kV. The fracture surface was covered with corrosion products, as shown in Figure 5. The composition of the corrosion products was analyzed by energy-dispersive spectroscopy, as shown in Figure 6, the analysis result was shown in Table 5. The fracture surface corrosion products mainly contained elements Fe and O with little amounts of Cl and S elements which is consistent with the presence of H2S and Cl ions in the medium.

The phase composition of the corrosion products was grinded to powder and analyzed by continuous scanning X-ray diffraction with the scanning voltage 40kV, scan speed 8 deg./min, scan range from 20 to 90°. The result was shown in Figure 7. The corrosion products mainly contain CaCO3, Fe3O4, SiO2, Fe2O3 and FeS. CaCO3 and SiO2 may come from soil pollution, and FeS and iron oxide indicates that the material was subjected to H2S and O2 corrosion.

3. Discussion

The above test results can be concluded as follows, the chemical composition meets the requirement of construction standard GB 6654–1996. The content of C, Si, Mn, P, Ni, Cr, Mo, Cu, Nb of the tank bottom plate meets the requirements of latest GB 713–2014 [18] for Q345R; the content of S, V, Ti are slightly higher than the upper limit of the standard and Al is lower than the requirement of the standard. The yield strength and hardness properties meet the standard requirements, but the Charpy impact properties are far below the standard requirements and the tensile strength is higher than the standard requirements, indicating

Table 5. The EDS result.

| Element | C    | O    | Si   | S    | Cl   | Mn   | Fe    |
|---------|------|------|------|------|------|------|-------|
| Weight percentage/% | 12.45 | 39.15 | 0.39 | 0.46 | 0.79 | 0.79 | 46.06 |
| Atom percentage/%    | 23.72 | 55.98 | 0.31 | 0.33 | 0.45 | 0.33 | 18.87 |
that the material is hard and brittle. The metallographic structure of the material is ferrite, pearlite and bainite, the presence of bainite has detrimental effect on the material performance. The fracture is covered with a layer of corrosion products. The EDS and XRD analysis results show that the corrosion products are mainly iron dioxide and FeS, which is consistent with the medium containing H2S. To analyze the root cause of the cracking of the bottom plate, a comprehensive analysis should be made from the analysis of working conditions, material selection, and structural analysis.

3.1. Working condition

The corrosive medium influences the failure of the bottom plate. According to the results of water quality analysis, the water contains Cl− with a content of more than 100000ppm and hydrogen sulfide. The medium has strong corrosion effect on carbon steel.

During the maintenance process, the annular plate was found to have an uneven foundation settlement, as shown in Figure 8. Under high liquid level, it will cause the upper side of the bottom plate to be subjected to tensile stress.

3.2. Material selection

Although the chemical composition of Q345R meets the construction standard GB 6654-1996, however, from the latest standard GB 713–2014, all three elements S, V, Ti exceeds the standard slightly and the Al element is low. Sulfur is a harmful element in steel which would cause thermal brittleness of steel, reduce ductility and toughness of steel, and form cracks during forging and rolling. According to Tan Qingyuan’s research [22], with the increase of Ti, V and other alloying elements, the hard and brittle non-metallic inclusions of TiN and VN nitrides tend to form microcracks in the center of the thick plate. The hardness of bainite is higher than that of matrix ferrite and pearlite. When deformed, micro-cracks are easy to form due to stress concentration. According to statistics, when the mass fraction of titanium is between 0.018% and 0.020%, the passing rate for internal crack detection by ultrasonic test is
close to 98%, while it is less than 90% when fraction of titanium is between 0.026% and 0.035%.

Therefore, a slight excess of S, V, and Ti causes the material to form a bainite structure, resulting in a hard and brittle material with poor toughness. This is consistent with the impact result.

According to the metallographic results, it is inferred that the failure mechanism is hydrogen sulfide stress corrosion cracking. However, Q345R is not a typical hydrogen sulfide stress corrosion sensitive material. At the same time, from the macroscopic analysis, both cracks pass through the welds on both sides of the cleanout door, it is inferred that the cracks are related to the welds. Therefore, we carried out the hydrogen sulfide stress corrosion cracking test of the Q345R weld to verify whether the material is susceptible to SCC.

Verification tests were performed under constant tensile load according to the NACE TM0177-2016 method. The test solution was a H$_2$S saturated saline solution consisting of 5% NaCl + 0.5% glacial acetic acid dissolved in deionized water. The loading stress was 247 MPa, and the test temperature was 24 °C. The result showed that the Q345R with bainite structure broke at the fine-grain zone under H$_2$S environment, as shown in Figure 9(a). The fracture presents intergranular fracture and step-like characteristics, as shown in Figure 9(b). Therefore, the material is not resistant to H$_2$S stress corrosion cracking.

3.3. Finite element analysis

Stress is required for stress corrosion cracking to occur, and we performed a finite element analysis near the cleanout door of the tank. According to the above-investigated results, there was local settlement at the edge of the storage tank. We established a model near the cleanout door of the storage tank according to the actual dimension, and reinforcing plates was provided on the inner and outer surfaces of the cleanout door. The load applied was gravity and medium pressure. The Von Mises stress distribution was shown in Figure 10, and the stress concentration point is at the corner between the cleanout door and the bottom plate.

According to Jerzy Ziolko’s research [23], local stress concentrations existed at the corner between the cleanout door and the bottom plate, and the value would even exceed the yield strength under the highest liquid level. In order to be able to reduce the stress concentration, the wall thickness of the bottom plate can be increased.

3.4. Comprehensive analysis

According to the above analysis, it can be concluded that the root cause of the storage tank bottom plate cracking is hydrogen sulfide stress corrosion crack, as shown in Figure 11. The medium in the storage tank contains H$_2$S and brine, which was proved by the monthly medium composition test. There is stress concentration, which was verified by the infinite element analysis. Based on the SCC test, the selected material Q345R is not resistant to H$_2$S stress corrosion cracking. In addition, dendritic secondary cracks can be seen in the metallographic test, which is a typical stress corrosion cracking feature. Because the actual working conditions are far more complicated than the experimental simulation, this is why the actual situation is that the cracking occurs after many years of service, while the sample cracks quickly under the NACE test.

Therefore, it can be concluded that the selected material Q345R is not resistant to H$_2$S stress corrosion cracking, with working conditions containing H$_2$S, and coupled with the existence of an uneven settlement of the storage tank, stress corrosion cracking occurred.
4. Conclusion

In this paper, a series of tests and simulations were conducted to study the cracking failure near the cleanup door of a crude oil storage tank, and the following conclusions can be obtained:

(1) The bottom plate of storage tank cracked at the corner between the cleanup door and the bottom plate. The annular plate of the tank had an uneven foundation settlement which caused local stress concentration according to the finite element analysis.

(2) The chemical composition of the failed crude oil storage tank bottom plate material Q345R meets the requirement of construction standard GB 6654-1996, while the content of S, V, Ti is slightly higher than the upper limit of the latest standard of GB 713–2014. A slight excess of S, V, and Ti causes the material to form a bainite structure, resulting in a hard and brittle material with poor toughness. Q345R is susceptible to H2S stress corrosion cracking according to SCC test.

(3) Stress corrosion cracking of the bottom plate occurred under working conditions containing H2S and coupled with the existence of an uneven settlement of the storage tank.

5. Recommendation

In order to avoid reoccurrence of such failures, the following measures should be taken:

(1) In H2S containing environment, Q345R material should be avoided.

(2) Online monitoring and inspection of storage tanks, such as acoustic emission online inspection, should be carried out regularly to assess the overall condition of the tanks.

(3) In the inspection process of offline inspection, the focus should be on tank stress concentration zone.

Declarations

Author contribution statement

Zhang Shuxin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kang Chun, Zhang Penggang, Deng Banghui: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Luo Jinheng, Shao Yingjie: Analyzed and interpreted the data, Wrote the paper.

Wu Gang: Performed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

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