Welded joint permissible defects influence on the resource of a vertical steel tank under low-cycle loading

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Abstract. This paper is devoted to the VST determining the residual life issues by the shell welds low-cycle fatigue criterion with permissible defects, taking into account a typical stress concentrator, which has not been fully studied. The fatigue tests results analysis for materials made of low-alloy steel, taking into account welded joints, is given. The Ansys software package has built a model and calculated the stress-strain a vertical steel tank lower belt state for storing oil and oil products VST 20000 with a branch pipe. It is shown that the VST design most dangerous point is in the branch pipe upper part. The maximum stresses and stress amplitudes were obtained in the stub pipe zone and the wornom seam. The cycles to failure performed calculations number showed that the lower VST belt without welded joints wall area withstands 2.4 times more loading cycles than the area with a welded seam and 9.3 times more than the dangerous point in the nozzle stub area.

1. Introduction

Metal tanks are among the structures that work in severe operating conditions. The rigid welded joints presence in tanks and a decrease in the plastic properties of the metal at negative temperatures cause significant internal stresses and creates conditions that exclude their redistribution possibility. These and some other reasons reduce the reservoir reliability, sometimes lead to its destruction.

The emergencies' analysis on vertical steel tanks indicates that the destruction begins in the stress concentration zones and, as a rule, is of a fatigue nature. Most often, cracks appear in the tank wall junction with the bottom and in the wall mounting vertical junction if there is a wall shape deviation from the design one in this zone. Also, in the tanks lower belt there are structural elements - the technological pipes and hatches insertion points, their welded seams, which are external stress concentrators, and require additional control.

During the vertical tanks' operation, various defects arise due to both design errors and external loads and impact on objects during operation. Among the operational factors, the main role belongs to low-cycle loading associated with filling and emptying tanks, as well as corrosive effects on the vertical steel tank (VST) metal structures unprotected parts. The fatigue damage accumulation most active processes take place in defect zones that are potentially stress concentrators.

2. Low-cycle loads

Low-cycle loads are understood as a sequence of load changes with the cycles number not exceeding 5·10^4, which ends in the initial state, and then repeats. At oil pumping stations in tanks, an example of
such loads is the tanks constant filling and emptying. During the VST operation in the static loading mode, the tank filling level is in the range from 46 to 70% of the maximum allowable filling, while the filling - emptying cycles average number is around 100 cycles. When operating in a cyclic loading mode, the filling level is from 85 to 90% of the maximum allowable filling, and the filling - emptying cycles’ average number is 200 - 350 per year [1].

Under the high cyclic loads’ influence, there are an assembly and factory defects intensive development. The statistics analysis on tank failures shows that the failure cause in almost all cases was fatigue cracks in the chime weld and the lower edge chords [2, 3].

Metal structures long-term operation in an aggressive environment leads to the metal deformation ageing, i.e. to reduce the resistance to brittle fracture [3]. The ageing coefficient for the investigated steel 09G2S after 25 years of operation is 1.09-1.34. At the same time, the strength characteristics have slight deviations from the standard values established by GOSTs, but a significant decrease in the plasticity characteristics is observed.

3. Steel 09G2S welded joints low-cycle fatigue
Tanks reliable and durable operation depends on the loading cycle and tension amplitude. Investigating these factors influence, we have carried out an experimental data approximation from the article by K.B. Kuskov and I.M. Kovensky. [4], and the relationship between the cycles number before the failure of the sample N and the stress amplitude $A_\sigma$ were obtained. Three-parameter exponential regression formulas are obtained in MahtCad:

- type A

\[
N_{330}(A_\sigma) = 1.14 \cdot 10^6 \cdot \exp(-0.13 A_\sigma) + 1500 \\
N_{250}(A_\sigma) = 2.34 \cdot 10^6 \cdot \exp(-0.13 A_\sigma) + 29900
\]

- type B

\[
N_{330}(A_\sigma) = 1.91 \cdot 10^6 \cdot \exp(-0.012 A_\sigma) - 1.04 \cdot 10^6.
\]

For the welded joints material with permissible defects in the VST-20000 calculation, the closest fit is the dependence $N_{250}(A_\sigma)$, which, for an amplitude of 40 MPa, gives the cycles number to failure three times less than for steel without seams. The corresponding graphical results are shown in figure 1.

![Figure 1. Dependence of the cycles number before the sample failure on the change in stress amplitude $A_\sigma$. Type A - with visually distinguishable permissible defects of the weld, type B - without a weld.](image-url)
This steel fatigue test results analysis [5] indicates that the even a high-quality welded seam presence reduces the metal's resistance to fatigue failure duration by 1.4-2.4 times. The cycles number to failure decreases at stress values close to the yield point and with an increase in the stress change amplitude. It can also be seen from the experimental data analysis that the ultimate strength for steel 09G2S with welded seams is 1.44 times less than for the same steel without welded seams. Also, from figure 2 it can be seen that the ultimate strength of samples with visually distinguishable permissible weld defects does not depend on the stress amplitude.

Figure 2. Steel 09G2S low-cycle fatigue curve. 1 - without a welded seam; 2 - with visually distinguishable permissible defects of a welded seam at a stress amplitude of 36 MPa; 3 - the same for an amplitude of 45 MPa according to extrapolation results.

4. The VST stress-strain state calculation using FEM

In this work, the study object is the VST - 20,000 for oil and oil products with a diameter of 45.6 m, which shell consists of 6 belts with a height of 2 m each. The thickness of 1 belt is 13 mm, the thickness of 2-6 belts is 12 mm. The VST material: steel 09G2; for this steel Poisson's ratio $\mu = 0.3$; Young's modulus $E = 2.1 \cdot 10^5$ MPa; density of steel $\rho = 7850$ kg/m$^3$; yield strength $\sigma_t = 345$ MPa.

The reservoir stress-strain state was calculated using the finite element method in the Ansys software package under the static loading condition. The geometric model consists of six belts and a bottom. The roof was not modelled because it practically does not experience cyclic loads when draining and filling the tank.

For calculations, the model finite element grid dimension variation method was chosen by increasing the elements' number in the stress concentration zone. The constructed finite element model contains 403 thousand nodes (figure 3). The elements size on the edges lower belts is 0.1x0.1 m, on the upper ones - 2 times larger.

When calculating the VST structure model, the structure deadweight (including the roof mass) and the pressure gradient from the liquid weight were taken into account. The calculation results analysis shows that the most stressed zone is the zone between the bottom and the vertical steel structure first belt. The stress at the tank maximum loading is 233 MPa (figure 4). The wall nodes maximum displacement is 18 mm.

Separately, the tank lower belt with an embedded nozzle with a diameter of 400 mm was modelled. The loading was carried out by static pressure on the wall in a size equivalent to the hydrostatic pressure from a liquid column of 10.83 m (maximum filling). The calculation results are shown in figure 5. It is shown that the VST design most dangerous point is in the branch pipe upper part. The maximum stresses were obtained in the stub-in zone of the branch pipe 340 MPa (98% of the yield point), and in the chime weld 148 MPa, while the stress amplitude in the tank wall without the branch pipe is 140 MPa, with the branch pipe - 307.3 MPa.
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Figure 3. The elements increase in the stress concentration zone when creating a finite element model.

Figure 4. The Mises stress of the reservoir at the maximum inflow.

Figure 5. Stresses in the area of the lower belt nozzle at the maximum inflow.

5. The VST residual resource calculation under low-cycle loading

When diagnosing reservoirs, it is necessary to calculate the residual resource under low-cycle loading. This calculation was performed under the methodology recommended in CD 153-112-017-97. Instructions for vertical steel tanks residual resource diagnostics and assessment.

The tank wall residual resource is determined as the cyclic destruction cycles for two stages sum:

\[ N_c = N_0 + N_P, \]

where \( N_0 \) is the cycles number before the macro cracks' formation; \( N_P \) - the cycles number before an avalanche-like crack formation. The cycles’ number that affects the macro cracks' formation in the VST wall is determined by the formula:

\[ N_0 = \min\{N_{01}; N_{02}\} \]
\[ N_{o1} = \frac{1}{4} \left[ \frac{1.28 \cdot E \cdot \ln \frac{1}{1-\psi}}{1.28 \cdot n_{\sigma} \cdot \sigma_{a} \cdot \frac{1}{\phi_{c}} - \sigma_{1}} - 1 \right]^{2} \]

\[ N_{o2} = \frac{1}{4 \cdot n_{N}} \left[ \frac{1.28 \cdot E \cdot \ln \frac{1}{1-\psi}}{1.28 \cdot \sigma_{a} \cdot \frac{1}{\phi_{c}} - \sigma_{1}} - 1 \right]^{2} \]

where \( E \) is the elasticity modulus, MPa; \( \psi \) - relative narrowing; \( n_{\sigma} \) - stress safety factor; \( \sigma_{a} \) - the conditional stresses amplitude at the design point of the VST wall, MPa; \( \sigma_{1} \) - endurance limit for wall material, MPa; \( \phi_{c} \) - coefficient taking into account the decrease in performance as a result of welding; \( n_{N} \) is a safety factor for durability. When performing the calculations, the following values of these quantities were taken for the VST material: \( E = 2*10^{5} \) MPa; \( \psi = 0.3 \); \( n_{\sigma} = 2 \); \( \sigma_{1} = 240 \) MPa; \( \phi_{c} = 0.8 \) for manual welding and \( \phi_{c} = 0.9 \) for automatic welding; \( n_{N} = 10 \).

The conditional stresses amplitude at the tank wall design point is determined by the formula

\[ \sigma_{a} = K_{s} \cdot \sigma_{n} \]

where \( K_{s} \) is the stress concentration coefficient in the elastoplastic zone; \( \sigma_{n} \) - maximum stress in the tank wall, MPa.

The complete cycles’ number:

\[ N_{0} = \frac{5207(\text{cycles})}{5073(\text{cycles})} \]

We select the obtained results smallest and adjust it for corrosion conditions. The resource taking into account corrosion is determined by the formula:

\[ T = \frac{N_{0} \cdot (1 - \beta_{nc})}{n} \]

where \( \beta_{nc} = \lambda \cdot \text{lg}N_{0}; n \) - the loading cycles number per year; \( \lambda = 0.1 \) in the measures’ absence to reduce the corrosion impact.

It was found that with the filling-emptying cycles’ number equal to 100 per year, the tank wall residual resource before the macrocracks formation is 31.93 years.

6. The strength calculation under low-cycle loads

Under GOST 34233.6-2017, the low-cycle strength condition will be met if the stresses’ amplitude arising during the VST operation does not exceed the permissible stress amplitude for a cycles’ given number.

The permissible stress amplitude is determined by the formula:

\[ [\sigma_{a}] = C_{t} \cdot \frac{A}{\sqrt{n_{N}} \cdot N} + B \]

where \( A, B \) - characteristics depending on the material; \( C_{t} \) - temperature coefficient, \( n_{N} \) - safety factor for the number of cycles; \( n_{\sigma} \) - stress safety factor. The values of these values for the VST material: \( n_{N} = 10, n_{\sigma} = 2 \); \( A = 0.45*10^{5}; B = 0.4R_{m}/t \); \( R_{m} \) - material ultimate tensile strength at the design temperature.

The permissible stress amplitude for the cycles number corresponding to operation in the cyclic loading mode of 200 cycles per year for 30 years for the VST wall sheet based on the ultimate strength of 490 MPa is 280 MPa, and for the section with a welded seam with permissible defects based on the value obtained in part 3 the tensile strength of 340 MPa is slightly less, and is equal to 250 MPa.

At a given stress amplitude, the low-cycle strength condition will be met if the cycles operating number does not exceed the cycles permissible number \([N]\) equal to
The loading cycles permissible number for the VST wall sheet was obtained, equal to 19130, and for the section with a welded seam with permissible defects, 11420. Thus, the low-cycle strength condition is fulfilled both for the wall main web and for sections with welded seams, but the amplitude condition is not met for the pipe weld area.

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