SUBSTANTIATION OF «LEAK-BEFORE-BREAK» CRITERION FOR VERTICAL CYLINDRICAL TANKS FOR OIL STORAGE

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The paper gives the results of experimental studies of cyclic crack resistance of samples of butt-welded joints on 06GB-390 steel in the case of oil storage tanks at stable development of a through-thickness fatigue crack, initiating from the notch surface along the fusion line, from the moment of its initiation up to reaching the length of about 30 mm. Large-scale samples of welded joints of 650 × 160 × 20 mm dimensions were tested at harmonic alternating zero-to-tension stress cycle with $\sigma_{max} = 2/3\sigma_y$. It is shown that application of rolled sheets of the above-mentioned steel for design rings of tank wall allows, at application of «leak-before-break» criterion, eliminating extended fractures in the wall welded joints.

Keywords: *fatigue crack, development of through-thickness fatigue crack, «leak-before-break» criterion, cyclic loading*

Over the recent decades, because of instability of oil price in the world oil market, many countries are building tanks of 50,000–100,000 m^3 and greater capacity to create the required stock of this product. Requirements to ecological safety of such constructions are becoming more stringent with every year, accordingly. Normative requirements as to steel mechanical properties, in particular in Z-direction, for rolled sheets of tank walls and their welded joints have grown significantly. However, in view of various peculiarities, defects in the wall welded joints cannot be eliminated completely, which at wall operation under cyclic loading conditions can become the source of initiation and development of tough fatigue fractures. Under such conditions, the problem of establishing the fatigue life of the stage of stable subcritical propagation of through-thickness fatigue crack in design rings of tank wall is becoming particularly urgent. Appearance of a dark spot on the white wall from seeping oil from the formed through-thickness crack, can be a reliable criterion of crack detection in those cases when the time of its growing up to critical size will allow guaranteed detection of the crack under the conditions of technical examination of tanks according to the applied procedures. Such a criterion of crack detection in pressure vessels was called «leak-before-break» [1].

The purpose of the proposed work was experimental substantiation of the possibility of application of «leak-before-break» criterion to vertical tanks for oil storage, in which the lower rings are made of a new class of high-quality steel 06GB-390.

Application of new generation niobium-containing steels 06GB-390, 06G2B-440 [2] with impact toughness values $KCV_{-40} \geq 120$ J/cm^2 8 to 40 mm thick (furtheron strength classes will be omitted in the work) and with fine-grained isotropic structure for design lower rings of the walls essentially improved their crack resistance. In this respect study [3] is of interest, which shows that stabilization of critical crack opening displacement within $\delta_{cr} = 0.18$–0.20 mm is observed for a number of tested steels with $KCV_{-20} \geq 80$ J/cm^2. In view of that, it is logical to expect that at application of 06GB steel for lower rings of tank wall and possible formation of a fatigue crack in it, its growth rate will give enough time for detection of the above crack at subcritical stage of its development.

As was noted above, at application of «leak-before-break» criterion under the conditions of tank operation, it is important that the duration of the stage of stable crack growth in the linear (second) section of fatigue fracture diagram [4], expressed by the number of tank filling–emptying cycles, allowed enough time to enable detection of a through-thickness crack after oil outflowing from it, and taking the required safety measures. In this work flat samples with a transverse butt weld were tested to substantiate the criterion «leak-before-break» for a wall of oil storage tank (Figure 1). In samples made from rolled sheets of 06GB steel, cross-section with removed weld reinforcement was equal to 160 × 19.5 mm, and length was 650 mm. Maximum stress of harmonic loading cycle was taken, allowing for maximum

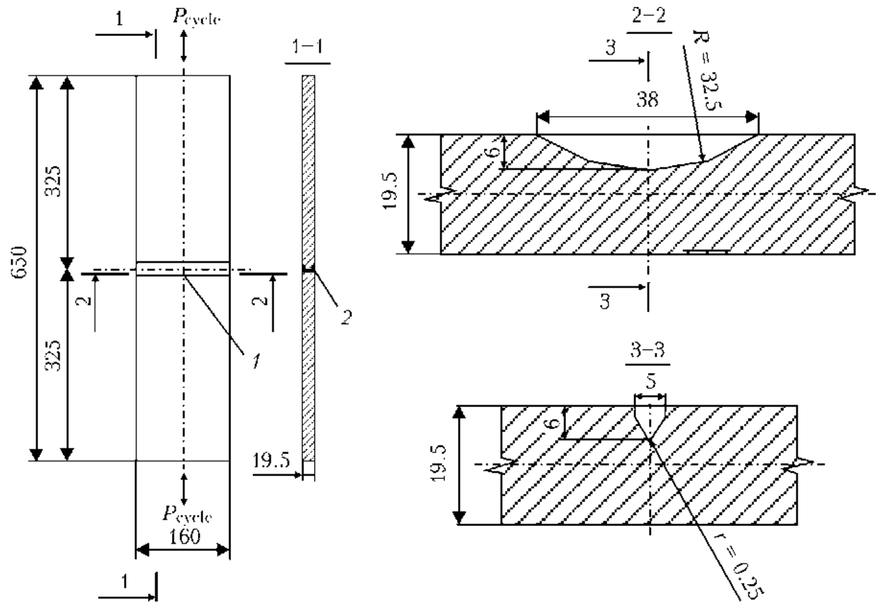

Figure 1. Schematic and dimensions of samples for testing welded joints of 06GB steel for cyclic crack resistance: *1* — notch in the fusion zone; *2* — weld reinforcement was removed from two sides

value of calculated hoop stresses in the tank wall [5] found from the following condition:

$$\sigma_h \le R_y \gamma_w / \gamma_n,$$

where R_y = 350 MPa is the calculated resistance; γ_w = 0.8 is the coefficient of operating conditions of wall rings; γ_n = 1.1 is the fitness-for-purpose factor.

In view of the above, maximum stress of alternating loading cycle was taken as σ_{max} = = 260 MPa. Such a level of hoop stresses allows for tolerances [5] for deviation of the geometrical shape of new tank wall from the design value. Considering that the tank wall is a thin-walled shell of up to 60 m diameter and up to 20 m height, after 15–20 years of service the norms [6] allow exceeding the initial geometrical deviations (foundation sagging under the wall, appearance of dents, etc.) 2 times. It is natural that under these conditions, in individual regions of the wall hoop stresses will be significantly higher than the initial values, that was allowed for by coefficient γ_w = 0.8, but these stresses should not exceed the calculated values for this steel considering the periods of technical examination of tanks. Growing of the initial surface notch in the sample at the first stage up to formation of a through-thickness crack, and then growth of this crack leads to reduction of sample net section area and increase of stresses in the sample that to a certain extent simulates the noted local increase of hoop stresses in the actual tank wall.

Initial crack-like surface notch was made in sample center at a distance from the weld fusion line with specially ground cutter. Length of semielliptical notch $2a$ was 38 mm, and its depth was 6 mm at notch rounding-off radius of 25 mm. All the samples were tested in hydro-pulsator TsDM 200pu at uniaxial zero-to-tension alternating stretching with 5 Hz frequency. Duration of the stage of surface crack initiation from the notch and its growing through sample thickness up to appearance of through-thickness crack is given in [7].

Fatigue testing of samples was conducted at room temperature; however, considering that rolled sheets of 06GB steel of 8–50 mm thickness maintain their high plastic properties in the temperature range T = +20 – –40 °C [2], it can be assumed that the obtained test results are correct up to temperature T = –40 °C. During testing the initial length of the formed through-thickness crack was measured on sample side opposite to the notch and number of cycles, at which it formed, was measured. Furtheron cycle number was recorded at its elongation by each 3–6 mm. At crack length $2a \approx 40$ mm its tip developed plastic contractions and testing was stopped. Results of fatigue testing of the samples are given in the Table. Figure 2 gives the dependence of fatigue crack length on number of alternating loading cycles.

Table data show that at crack length $2a \le$ ≤ 30 mm in sample net section stresses did not exceed the calculated resistance of 06GB steel (R_y = 350 MPa). After the crack has grown to the length of $2a > 40$ mm in sample net section, maximum stresses reached values close to steel yield point, i.e. appearance of observed plastic contractions at such a crack length is not related

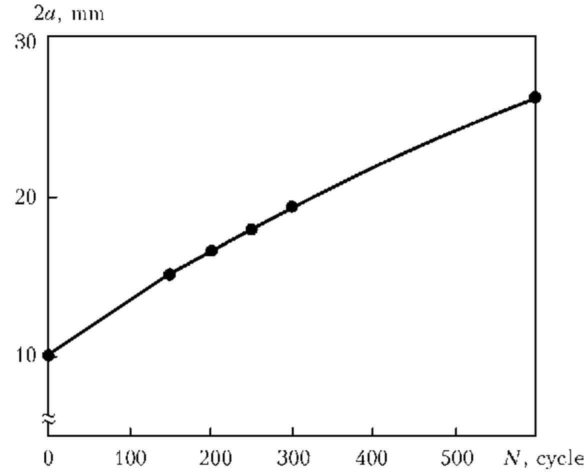

Figure 2. Dependence of length $2a$ of through-thickness crack in the fusion zone on the number of loading cycles N of samples of butt welded joints of 06GB steel (value of crack length $2a$ in each point is given as an average from testing 6 samples)

to limit state of cyclic crack resistance, but is due to limited dimensions of the sample. Such high stresses will not develop in the rings of actual tank wall at specified crack length, because of many times smaller weakening of the wall by the considered defect.

Application of empirical dependence between K_{1C} and KCV specified in the norms allows determination of critical crack length $2a_{cr}$ for the given welded joint at minimum temperature of tank service $T = -40$ °C. In keeping with [8] $K_{1C} = 0.1\sqrt{0.1 \frac{E}{1-\mu^2} KCV_{-40}}$, MPa·$\sqrt{\text{m}}$. At $KCV_{-40} = 246$ J/cm^2 we get $K_{1C} = 236$ MPa·$\sqrt{\text{m}}$ for the weld. At possible increased hoop stresses in the wall $\sigma_h = R_y = 350$ MPa, proceeding from the known relationship for through-thickness crack of critical length $2a_{cr}$, $K_{1C} = \sigma_h\sqrt{\pi a_{cr}}$, we get value $a_{cr} = 145$ mm for the given σ_h and $2a_{cr} = 290$ mm, respectively. For new tanks of 50,000 m^3 capacity in keeping with the norms [5], hoop stresses in the wall are taken to be equal to 260 MPa. At such stresses the calculated value of critical crack length reaches $2a_{cr} = 520$ mm.

Considering that KCV_{-40} values for base metal and weld are actually the same, obtained values of critical crack length can be extended also to the wall base metal.

Conservative value of critical length of through-thickness crack of about 30 mm taken at fatigue testing of welded joint samples, which allows reliably fixing the dark oil spot on the wall surface, gives a ten-fold margin for actual critical length of the tank crack of approximately 300 mm.

From Figure 2 it is seen that at steady stable development of a through-thickness fatigue crack in the samples, dependence of its length on the number of loading cycles is close to the linear one. Its stable propagation up to the length of 20 mm is observed during the first 300 loading cycles. At subsequent 300 cycles crack length increases by just 6 mm. Crack length, corresponding to 300 loading cycles, is of important practical value, as this number of loading cycles (oil discharge–filling) corresponds to one year of tank service in some oil tank farms [9]. In regular oil tank farms this value is not higher than 100–120 per year.

For tanks in service results obtained at sample testing should be corrected by the safety factor by the number of loading cycles. This correction is required to allow for the scale factor as to the possible presence of unrevealed defects in real tanks. In [10] proceeding from generalization of investigation results of a broad experimental program of full-scale fatigue testing of pressure vessels, it is proposed to take the safety factor by cycle number equal to 20. In our case it means that in reality the time for detection of outflowing oil spot on the tank wall equal to fulfillment of fifteen (330:20) cycles of oil discharge–filling

Growth of through-thickness crack length $2a$ on the surface opposite to the notch and stresses in the sample net section depending on the number of loading cycles N

#	Number of loading cycles N	Length of through-thickness crack* $2a$, mm	Sample weakening area, cm^2	Net sample area, cm^2	Maximum stresses across net section**, MPa
1	0	10.1	6.2	25.0	332.0
2	150	15.2	6.7	24.5	338.8
3	200	16.7	6.9	24.3	341.5
4	250	18.0	7.0	24.2	343.0
5	300	19.4	7.2	24.0	345.0
6	600	26.2	8.0	23.4	354.2
7	1400	40.0	9.5	21.7	373.0

*Crack length, cross-sectional area and stresses are given as average value by the results of testing 6 samples. **Maximum cycling force of 8300 kg; through-thickness crack of $2a$ length is located along the fusion line of butt welded joint of 06GB steel.

will be guaranteed. For oil tank farms with regular operation mode this is equal to one month, and at more intensive mode — to not less than two weeks of service. In case of compulsory everyday visual examination of tank wall surfaces in keeping with the rules of tank operation, this time is quite sufficient for guaranteed detection of the formed defect by «leak-before-break» criterion, and for taking measures to repair it. Period of stable crack growth at subsequent loading cycles from 300 up to 600 can be regarded as a guarantee of safe crack detection under force-major circumstances.

Guaranteed detection of fatigue cracks at the stage of their stable development prevents the possibility of fracture of tank design rings either in base metal or in welded joints. Therefore, in tank design it is necessary to first of all provide the conditions for elimination of local fractures of the main wall, bottom, r-bars and branchpipe assemblies. Ensuring the static strength of the main tank wall becomes the main objective for its design. Elimination of extended fracture formation on its surface will be ensured by application of the criterion of «leak-before-break», provided steels with Z 35 group of lamellar fracture resistance and impact toughness $KCV \geq$ ≥ 80 J/cm^2 at minimum service temperature of the tanks are used for the wall. Such requirements are met, in particular, by 06GB steel. In the presence of the main wall with application of this steel, the protective wall will just contain the possible oil spill within its limits, while taking the static load.

The proposed approach eliminates the need for construction on the main wall of additional structural elements in the form of bands or other solutions, as a tool for arresting extended fractures, or construction of special stiffener rings on the protective tank wall for preservation of the wall geometrical shape.

Prevention of extended fractures on the tank wall by application of rolled sheets of the new steels with the above mechanical properties and substantiated application of «leak-before-break» criterion does not eliminate the requirements of the high quality of rolled sheets and their welded joints. Producing welded joints on the new steels with mechanical properties not inferior to those of base metal and elimination of cold crack formation in them, requires application of special welding technologies and increased scope of their quality testing compared to the norms for tanks [11].

Results of experimental investigations, given in this publication and in work [12], have been successfully implemented at design and construction of two tanks with the protective wall, each of 50,000 m^3 capacity at oil-pumping station «Mozyr» (Belarus Republic). Erection and welding operations at construction of these tanks were performed with field supervision of PWI specialists.

CONCLUSIONS

1. It is shown that the fatigue life of the stage of stable subcritical development of the formed through-thickness fatigue crack exceeds 300 loading cycles. Considering the safety factor by cycle number equal to 20, which is taken for pressure vessels, the above fatigue life provides minimum two weeks of safe operation of oil storage tank. At performance of compulsory daily visual inspection of the tank wall surface in keeping with tank service rules, this time is sufficient for guaranteed detection of the formed defect by «leak-before-break» criterion and taking measures for its repair.

2. Making design rings of tank wall of 06GB steel up to 30 mm thick using the criterion of «leak-before-break» allows eliminating extended fractures in the wall welded joints and preventing the possibility of appearance of oil outflow with a high kinetic energy. In this connection there is no need to envisage additional structural elements in the form of bands on the tank main wall, or special reinforcing rings for preservation of the wall geometrical shape.

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