Methods for determining endurance limits for welded joints of marine stationary platforms

I V Starokon

Russian state university of oil and gas named after I.M. Gubkin, 65, Leninskiy pr., Moscow, 119991, Russia

E-mail: aps@gubkin.ru

Abstract. Today, oil, gas and other useful resources are being actively extracted at offshore fields using fixed offshore platforms. According to Federal Law No. 116 On Industrial Safety of Hazardous Production Facilities, offshore platforms are classified as hazardous production facilities, accidents at which are accompanied by significant damage. To prevent accidents at these facilities, an industrial safety examination is carried out, during which their resource is determined. The key parameter for determining the resource is the value of the endurance limit (or fatigue limit). Various theories are currently being applied to determine the fatigue limit. However, calculations on these theories give different results. The purpose of this article is to study various methods for determining endurance limits using welded joints of fixed offshore platforms as an example and choosing a method that allows you to obtain the most accurate value of this limit.

1. Introduction

It is well known that there are potentially recoverable hydrocarbon reserves on the territory of the oceans (covering an area of seventy-five million square kilometers). Offshore development has a long history and tradition. For example, in the area of the Japanese city of Izumosaki, an artificial island was built on which drilling rigs and other equipment necessary for oil and gas production were located. This construction dates back to 1870. Around 1900, the first deviated wells were drilled off the coast of California. The development of offshore fields was actively conducted after the end of the Second World War. So, for example, since 1947, deposits have been actively developed in the Gulf of Mexico. At that time, the first drilling platforms on a pile foundation were built there. Gradually, with the development of technology, the oil and gas production infrastructure was increasingly moving away from the coast. At the beginning of the year 2000, confirmed offshore gas reserves rose to fifty-three billion cubic meters and accounted for 33% of the world's gas reserves. The potential resources of Russian offshore oil and gas fields can be compared with the potential reserves of the largest offshore fields in the world. If we recalculate these reserves for fuel equivalent, it turns out that Russia possesses more than one hundred billion tons of fuel equivalent. Of this amount, 70% of oil and gas resources are located at depths of less than 100 meters, which greatly facilitates their production.

As it was mentioned before, nowadays, the world is actively producing oil, gas and other useful resources in offshore fields. During the development and operation of oil and gas fields on the shelf, various structures are used. These structures include floating drilling rigs, self-elevating drilling rigs, offshore stationary platforms and many types of other special structures. Of particular interest are
fixed offshore platforms (FOPs). Offshore fixed platforms have a very long history of use. One of the first in the history of FOPs was the so-called Guy Manson forts shown in fig. 1, which were built in 1942 at the mouth of the Thames to protect against German aviation and are still in operation for a variety of purposes.

Figure 1. Guy Manson Forts

In the USSR, fixed offshore platforms also have a long history of application. Back in 1949, the development of the Oil Stones field began, which are located on the Caspian Sea at a distance about 40 km east of the Absheron Peninsula. For the extraction of hydrocarbon resources, steel flyovers were built on which all the necessary equipment was located. Nowadays, FOPs are very often used for the extraction of hydrocarbon resources, metals, minerals and other minerals in offshore fields by both domestic and foreign companies. In Russia, fixed offshore platforms are located in various regions. So, for example, in the Sakhalin region, PJSC Gazprom operates the platforms: Molikpak, Piltun-Astokhskaya-B, and Lunskaya-A. FOPs “Berkut” and “Orlan” are operated by Rosneft. In the Caspian Sea, PAO Lukoil operates LSP-2 and the D-6 platform. The FGUP RK Chernomorneftegaz company operates about 30 offshore stationary platforms on the Black Sea shelf. Offshore stationary platforms are used for production at the largest offshore fields around the world. An example would be the Khyberia platform, located in the Atlantic Ocean near Canada. In the Gulf of Mexico in operation are more than four thousand of these structures. Those. it can be confidently noted that FOPs are used in the practice of world oil and gas production (both by domestic and foreign companies) and have a long history of application.

In accordance with Federal Law No. 116 On Industrial Safety of Hazardous Production Facilities, fixed offshore platforms are classified as hazardous production facilities (HPF). According to this law, HEP is characterized by the fact that for such facilities there is a high risk of an emergency, which can be accompanied by significant economic damage and lead to massive loss of life. For example, during the accident of the Alexandr Kinnell platform, more than 120 people died.

Nowadays there are many platforms (both in Russia and abroad) with a long service life. FOPs are operated in difficult offshore conditions. In these conditions, the platform is exposed to a variety of loads. Examples of such loads can serve as wave, wind, ice, from naval vessels, seismic, from the movements and others as a result of the impact of these loads arise variable stress, which are known from the classical theory of mechanics of destruction lead to the accumulation of fatigue damage in welded elements and connections of the platforms, which can provoke an emergency situation. Of particular importance the problem of the accumulation of fatigue damage comes out for assessing the life of repaired welded joints of an offshore platform.

Currently, the repair of these compounds is based on different technologies which include the installation of reinforcing pads, terminologically or special metal inserts. The resource of welded joints is based on the diagrams of fatigue, but to date the diagrams of fatigue for the repaired welds are
missing. For such diagrams the key value is the fatigue limit (also called in the literature the endurance limit). In the normative-technical documentation describes various methods of finding the limits of fatigue, which give completely different results. Therefore, the aim of this paper is to study the accuracy of different methods for the determination of endurance limits with regard to its definition for welded joints of offshore fixed platforms, which will continue to determine the endurance limit for each of the known technology of repair welds.

Nowadays, a regulatory and technical framework has been developed which contains fatigue diagrams for new welded joints of offshore stationary platforms. This documentation includes the foreign regulatory framework [1, 2] and the Russian one [3]. According to the regulatory documents [1–3], the endurance limit of welded joints of offshore platforms is in the range from 20 MPa to 35 MPa, if we operate in terms of the range of stress and a diagram is constructed accordingly. And from 10 MPa to 18MPa, if the diagram is built for the amplitudes of alternating stresss. Therefore, we will consider its value that will be close to the amplitudes of alternating stresses of 10-35 MPa as a target indicator for methods of calculating endurance limits. We also note that the basic endurance limit of a welded joint without taking into account the residual stresses, roughness and other factors described below is determined depending on the temporary tensile strength and is assumed to be 234 MPa. It should be noted that oil and gas production is carried out under difficult conditions [4, 5], and factors such as anticorrosion coatings [6–9], kinetics of austenite [10] and other factors described in works [10-15].

2. Results
It is generally accepted that endurance (or fatigue) is determined on the basis of laboratory tests. Moreover, the results obtained in the laboratory must be correlated with the actual welded joint, taking into account the scale factor, the surface roughness of the platform welded joint, stress concentration, residual stresses in the welded joint, and other factors. The objective of this article is to choose a comparison method, which in the technical literature is also called scaling or transfer, the laboratory value of the endurance limit on real welded joints of the offshore platform.

Let us analyze how various methods of calculating the endurance limit allow us to obtain a result close in value to 10-35 MPa. As an example, in a we consider the results of experiments performed by the author and presented in the table 1. The objective of the experiment was to determine the fatigue life of tubular welded joints of an offshore stationary platform. As a result of the study of the project, it was found that during the construction of offshore platforms for welding elements made of steel 09G2S (D), electrodes E50A of the UONI-13/55 grade in accordance with SAUS 9467-75 were used. The tensile strength of such a weld should be 490 MPa.

Table 1. Test results of welded joints

| Stress amplitude $O_{sa}$ [MPa] | Sample №1 | Sample №2 | Sample №3 | Sample №4 | Sample №5 | Sample №6 | Number of cycles, $N$ |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------------|
| 115                             | 4332      | 3975      | 4672      | 4348      | 4301      | 4359      | **4332**        |
| 82                              | 10253     | 9071      | 10798     | 10803     | 10164     | 10504     | **10253**       |

Various methods are proposed for determining the fatigue limit of a weld metal:

- **Method number 1.** Goltsev Method:

$$\sigma_{-1} = \sqrt{\frac{O_{sa}^2 - O_{sa}^2}{N_1 - N_2}}, (1)$$
Where: $\sigma_{\text{I}}$ - endurance limit, MPa; $\sigma_{\text{I}}$ and $\sigma_{\text{II}}$ - certain level of test stress values, MPa; $N_{\text{I}}$ and $N_{\text{II}}$ – number of cycles before fracture for the corresponding stress level.

- **Method №2.** Muratov’s Method:

$$\sigma_{\text{I}} = \frac{\sigma_{\text{I}}\sqrt{N_{\text{I}}} - \sigma_{\text{II}}\sqrt{N_{\text{II}}}}{\sqrt{N_{\text{I}}} - \sqrt{N_{\text{II}}}},$$  \hspace{1cm} (2)

Where the values are the same as in Eq. 1

- **Method №3.** Panteleev’s Method:

$$\sigma_{\text{I}} = \frac{\sigma_{\text{I}}\sigma_{\text{II}}(N_{\text{I}} - N_{\text{II}})}{\sigma_{\text{II}}N_{\text{II}} - \sigma_{\text{I}}N_{\text{I}}},$$  \hspace{1cm} (3)

Where the values are the same as in Eq. 1

We will carry out calculations and calculate the endurance limit values in accordance with these methods and present them in Table 1.

**Table 2. Endurance limits obtained by the methods of Goltsev, Muratov and Panteleev**

| Number of method | Value of the endurance limit $\sigma_{\text{I}}$ |
|------------------|-----------------------------------------------|
| 1                | 44,3                                          |
| 2                | 38,8                                          |
| 3                | 27,3                                          |

However, the endurance limits defined in Table 1 do not take into account the following important factors that determine the functional relationship between laboratory tests and real samples:

1. The proportionality of the size of the samples and real objects;
2. Asymmetry of stress cycles [16, 17];
3. The value of residual stresses.

We define the amplitudes of the first principal stresses for an alternating cycle by the equation:

$$\sigma_{1\text{e}}^p = \frac{\sqrt{6}\sigma_{\text{I}}}{K + [N_d/(1 - R_{\text{eq}})](R_{\text{eq}} + R_{\text{eq}} \alpha)},$$  \hspace{1cm} (4)

Where: $\sigma_{\text{I}}$ endurance limit, endurance strength, obtained by one of three methods, mentioned above, and $R_{\text{eq}}^\text{req}$ is obtained by equation:

$$R_{\text{eq}}^\text{req} = \frac{(\sigma_{\text{min}}^0)_{\text{rez}}}{(\sigma_{\text{max}}^0)_{\text{rez}}} = \frac{\sigma_{1\text{rez}} + \sigma_{2\text{rez}} + \sigma_{3\text{rez}} + \sigma_{1\text{rez}} + \sigma_{2\text{rez}} + \sigma_{3\text{rez}}}{\sigma_{1\text{max}} + \sigma_{2\text{max}} + \sigma_{3\text{max}} + \sigma_{1\text{rez}} + \sigma_{2\text{rez}} + \sigma_{3\text{rez}}},$$  \hspace{1cm} (5)

Where $\sigma_{1\text{rez}}, \sigma_{2\text{rez}}, \sigma_{3\text{rez}}$ – first, second and third (main residual) stresses; $(\sigma_{\text{min}}^0)_{\text{rez}}, (\sigma_{\text{max}}^0)_{\text{rez}}$ – octahedral stresses, defined as the sum of residual and stresses caused by the sum of all the loads; $\sigma_{1\text{max}}, \sigma_{2\text{max}}, \sigma_{3\text{max}}$ maximum principal stresses of a cycle; $\sigma_{1\text{min}}, \sigma_{2\text{min}}, \sigma_{3\text{min}}$ minimum principal stresses of a cycle, and $\alpha$ is obtained by the equation:

$$\alpha = \frac{0.249 \sigma_{\text{p}}}{0.35 \sigma_{\text{p}} + 70},$$  \hspace{1cm} (6)

Where: $\sigma_{\text{p}}$ temporary resistance to endurance, MPa. The remaining values are given in [15–20].
The author developed a model of an offshore platform in the Structure CAD software package presented in fig. 2. This model allows to determine with high accuracy the stress acting in welded joints, taking into account the different directions of action of the wave load. Using the example of an offshore platform located in the Black Sea region, the maximum possible wave impact once a hundred years was simulated. As a result, the following data were obtained characterizing the range of stresses in the welded joints of the platform. Data are given in the table 2.

![Platform model in the StructureCAD software package](image)

**Table 3.** Stress amplitude in welded joints of the offshore platform

| Load combination | Direct exposure to wave load | Inverse wave load |
|------------------|-----------------------------|------------------|
|                  | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ |
| K1               | 160       | 12,4       | 2,1       | 1         | -        | -        |
| K2               | 194       | 17,8       | 3,6       | -33       | 7,8      | 1,2      |

**Table 4.** The endurance limits adjusted by the Klykov method obtained by the methods of Goltsev, Muratov and Panteleev

| Number of the method | 1 | 2 | 3 |
|---------------------|---|---|---|
| Value of the endurance limit $\sigma_{ij}$ | 21,6 | 18,9 | 34,3 |
We correlate the endurance limit obtained by the three methods described above with real welded joints of the platform and the results are summarized in table 3, having obtained data on the stress state of welded joints and acting according to the method developed by Klykov [18].

3. Conclusion
Calculations by Method №1 and Method №2 gave a result close to the point stated in the standards. The result calculated by method №3 is close to the point stated in the standard. It should be noted that all methods showed good convergence of the results and, according to the author, can be applicable in assessing the endurance limits of welded joints of fixed offshore platforms. The choice of the method of calculating the endurance limit will be especially important when determining the resource of welded joints of offshore platforms, taking into account the accumulated damage [18, 19] and the selected repair technology.

References
[1] DNV-RP-C103. 2008 Recommended Practice. Fatigue Calculation of Marine Steel Structures (Norway: DNV)
[2] DNV-RP 2A-WSD 2005 Recommended practice for the planning, design and construction of offshore stationary platforms-calculation of permissible stresses (New York: American Bureau of shipping)
[3] 2014 Rules for the Classification, construction and equipment of floating drilling rigs and offshore stationary platforms (St. Petersburg: Russian Maritime Register of Shipping)
[4] Guseynov Ch 2020 In Arctic - new technical means and technologies for the development of oil and gas fields in long-term freezing deepwater areas Mater. Sci. and Engineering 734 012174
[5] Bezkorovayniy V, Bayazitov V and Bobov D 2018 Management of the Design and Construction of Offshore Oil and Gas Facilities with Bim Base Mater. Sci. and Engineering 463(4) 042056
[6] Efimenko L, Kapustin O, Gusev V, Merkulova A and Nikiforov N 2014 Evaluation of structural and phase composition and corrosion resistance properties of coatings made by laser surfacing Chemical and Petroleum Engineering 50 402-411
[7] Efimenko L 2015 Methodological fundamentals of the evaluation of the weldability of structural materials using oil and gas pipes as an example Welding Int. 9(28) 727-731
[8] Efimenko L, Elagina O, Ramus A, Volkov I, Ladyzhanskii A, Rakhmanov D, Konovalov A and Kurkin A 2015 Repair features of mechanical and corrosion damage in a main gas pipeline under pressure Chemical and Petroleum Engineering 50 749-757
[9] Elagina O, Efimenko L and Volkov I 2015 Study of the strain ageing on corrosion failure and submicrostructure of low-carbon steels for gas-distribution pipelines Chemical and Petroleum Engineering 51 433-437
[10] Efimenko L, Kapustin O, Merkulova A, Subbotin R, Puyko O and Shchkalova A 2016 Features of transformation kinetics of austenite in heat treatment of stamped and welded components made of 10G2FBYU steel Welding Int. 30 472-478
[11] Efimenko L and Ramus A 2016 Effect of the morphology of structure on the resistance of welded joints of high-strength pipe steels to brittle fracture Metal Sci. and Heat Treatment 57 559-563
[12] Efimenko L, Kapustin O, Ramus A and Ramus R 2016 Control of softening processes in the heat-affected zone during welding of high-strength steels Metal Sci. and Heat Treatment 58 435-441
[13] Efimenko L, Kapustin O, Merkulova A, Subbotin R, Puyko O and Shchkalova A 2016 Features of transformation kinetics of austenite in heat treatment of stamped and welded components made of 10G2FBYU steel Welding Int. 30 472-478
[14] Makarov G 2014 Modernization of systems of pipeline transport of gas and oil Welding Int. 28(9) 744-747
[15] Starokon I 2019 Varieties and kinetics of fatigue cracking of fixed offshore platforms for oil and gas production Mater. Sci. and Engineering 734 012055
[16] Antonov A 2014 Investigation of fields of residual stresses in welded structures Welding Int. 28 966–969
[17] Starokon I 2020 Features of fatigue processes occurring in restored welded joints of offshore fixed platforms Mater. Sci. and Engineering 734 012171
[18] Starokon I 2020 Resource of repaired welded compounds of marine oil and gas structures Mater. Sci. and Engineering 734 012193
[19] Starokon I 2019 On the results of studying the influence of vibration-fluctuations processes on the resource of welded joints of marine stationary platforms for oil, gas and other useful minerals on the shelf J. Akustika 285 148-151