Study of efficiency of methods for determining fatigue limits through the example of its determination for welded joints of marine stationary platforms

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Abstract. Currently, the world is actively engaged in the extraction of oil, gas and other useful resources at offshore fields using offshore stationary platforms. Due to the fact that the platforms are operated for a long time, fatigue damage accumulates in them. This issue becomes especially important when assessing the residual life of welded joints of the offshore platform, the repair of which is carried out using various technologies. The resource of such compounds is determined on the basis of the fatigue diagram, the key value of which is the fatigue limit. A large number of theories have been developed to determine the fatigue limit. However, calculations based on these theories do not always give a correct estimate. Therefore, the purpose of this article is to study the effectiveness of various methods for determining endurance limits using welded joints of offshore stationary platforms as an example and to select a method that allows obtaining the most accurate value of fatigue limit.

1. Introduction
Currently, the world is actively producing oil, gas and other useful resources in offshore fields [1-9, 16-20]. This production is carried out using offshore stationary platforms (figure 1). To date, such a situation has developed that these platforms have a long service life, which leads to the accumulation of fatigue damage in them. This problem is especially acute when assessing the resource of welded joints of the offshore platform, the repair of which is carried out using various technologies. The resource of such compounds is determined on the basis of the fatigue diagram, the key value of which is the fatigue limit (also called the endurance limit in the literature). Therefore, the purpose of this article is to study the effectiveness of methods for determining endurance limits in relation to its determination for offshore stationary platforms [1-9].

Typically, the endurance limit (or fatigue limit) is determined based on laboratory tests. An important practical point of view is the task of scaling the results obtained during testing of laboratory samples to real welded joints of fixed offshore platforms (FOPs). Modern research offers various theories for assessing the influence of the scale factor, depending on the surface roughness of the real structural element of the FOP and the welded joint as compared with a smooth sample (roughness within 0.16-0.32 microns) As well as the real geometric dimensions of the structural and welded joints of the offshore platform in comparison with laboratory samples, the concentration of stresses due to the type of weld and possible defects, residual stresses in the seam and the heat-affected zone, as well as the dependence on the asymmetry coefficient of the cycle, the probability of the presence of metal sections with different mechanical properties, cross-sectional dimensions, etc.
The objective of this article is to choose a method for scaling the fatigue limit obtained as a result of experimental studies on real welded joints of the offshore platform. A fatigue diagram has been developed for tubular welded joints of offshore stationary platforms (figure 2). According to this diagram, the endurance limit is at the level of 20 MPa.

Taking this diagram as a basis, we analyze how various methods of calculating the endurance limit allow obtaining a result close in value to 20 MPa.

2. Methods
To implement this technique, initially it will be necessary to determine the tensile strength of the welded joint. An analysis of the project materials showed that in the construction of offshore platforms for welding elements made of steel grade VSt3Sp5, electrodes of the E42A grade and the UONI-13/55 grade were used. The tensile strength of welded joints made in accordance with GOST 9467-75 is 420MPa. And for welded joints obtained from pipes of steel 09G2S (D) with electrodes E50A of the UONI-13/55 brand according to GOST 9467-75, the tensile strength of the weld should be 490MPa. To observe the similarity of the experiment, pipes made of material according to DIN 2393-1994 RSt37-2 standard were used as the column model, and 9MnSi5 steel was used for modeling the waist pipe.

Various methods are proposed to determine the tensile strength of an experimental weld.
2.1. Method of determining the fatigue limit depending on the value of the hardness of the metal
The following formula is well known:

\[ \sigma_{-1} = 95.5(\sqrt{149 + \frac{H}{12.2}}) \]  

(1)

where \( H = \frac{HV}{8.2} \) (HV - hardness, MPa); \( \sigma_{-1} \) - fatigue limit, MPa.

In turn, the hardness of welded joints can be determined by the equation of B. D. Lebedev

\[ HV = 4160 \cdot C_{e}^{1.08} \cdot \theta_{cool}^{0.17} \]  

(2)

where \( C_{e} \) - carbon equivalent; \( \theta_{cool} \) - cooling speed.

It is quite obvious that to better match the experimental sample to the real object, not only geometrically similar samples with similar loading conditions should be used, but also materials with similar mechanical characteristics. Therefore, during the experiment, welding materials were used that provide similar values of tensile strength, grades E4303-P for the "T" connection and E4903-P for the "K" connection according to ISO2560-2009, providing a tensile strength of the welded joint equal to 490 MPa. The results of this experiment are given in [12-15].

We calculate the coefficient of influence of the scale factor by the formula:

\[ K_{D\sigma} = 0.5\{1 + [(1/88.3)(L/\bar{G}_{1})]^{-0.2}\} \]  

(2)

where: \( K_{D\sigma} \) - scaling factor; \( \bar{G}_{1} \) - the relative gradient of the first principal stress; L - characteristic size of the working part of the seam perimeter. The relative gradient of the first principal stress is determined by the formula:

\[ \bar{G}_{1} = \left(\frac{1.6}{r}\right) \sqrt{\sin \varphi + 2/\delta} \]  

(3)

where: \( r \) - the height of an isosceles triangle formed by an angular seam (according to project data); \( \varphi \) - an angle equal to 45; \( \delta \) - thickness of the smallest of the welded SE.

Let us calculate the characteristic dimensions of the working part of the perimeters of the seams formed by connecting structural elements of various diameters. Then, according to the above formulas, we calculate the voltage gradient and scaling factor, and the results are summarized in table 1:

| Diameters of connected elements | The size of the working part of the perimeter of the seam in meters | The relative gradient of the first principal stress | Scaling factor |
|---------------------------------|---------------------------------------------------------------|-----------------------------------------------|----------------|
| 325                             | 426                                                           | 530                                           | 325           | 426           | 530 |
| **720**                         | 1.035                                                         | 1.373                                         | 1.742         | 346.3         | 288.6         | 288.6        | 3.81          | 3.55          | 3.46          |
| **1080**                        | 1.027                                                         | 1.352                                         | 1.693         | 346.3         | 288.6         | 288.6        | 3.78          | 3.51          | 3.4           |

It should be noted that this method of calculating the scaling factor has shown itself well in relation to machine parts. However, for welded joints, in the presence of residual stresses, the condition for the distribution of maximum stresses in the elastic region is not fulfilled and it should be used with caution for welded joints of FOPs.

2.2. Method of determining endurance limit depending on temporary tensile strength
It’s well known, that the scale factor may be due to the influence on the destruction process of the total elastic energy accumulated in the loaded system. This statement is rather well confirmed in practice. As experimental data show, with an increase in the size of the sample, the propagation speed of the
crack increases, since larger samples also have a large reserve of elastic energy. However, certain characteristics of the time dependence of fatigue on the sample size and the actual weld size disappears, i.e. in other words, there is a certain boundary, after which the differences in the fatigue characteristics of the test specimens and the actual welded joints disappear. So, on the basis of experimental studies, it is known that when the cross-sectional area of the studied samples is more than 4000 mm², the scaling factor should be taken equal to 0.6. Modern energy theories make it possible to correct this value; a coefficient of 0.58 can be used in relation to the welded joints of the MSP support block.

Since the experiment was carried out on samples from pipes with an untreated surface, the results of this experiment are of practical interest, determining the endurance limit for samples with an untreated surface by the formula:

\[ \sigma_{-1} = K_D\sigma(92 + 0,125\sigma) \]  

(4)

Having obtained the values described above, we proceed to the process of transferring the obtained experimental results to a real welded joint. In [13], the following main parameters were identified that should be taken into account: the ratio of sample sizes to real objects, roughness, asymmetry of stress cycles, and residual stresses. In particular, formulas are given that make it possible to calculate the amplitudes of the first principal stresses, taking into account the above parameters, depending on the characteristics of the cycle. So, in the area of an alternating cycle, this limit amplitude will be determined by the formula:

\[ \sigma^n_{1a} = \frac{\sqrt{6}a\sigma_{-1}}{K + [M_a/(1 - R_{\sigma 0})][\eta_1 + R^{\eta_2} \eta_3]} \]  

(5)

And in the field of permanent:

\[ \sigma^n_{1a} = \frac{\sqrt{6}a(1 - c_1 R^{\eta_2} M_{\text{res}})\sigma_{-1}}{K + \eta_1 M_a} \]  

(6)

Where \( \alpha \) is determined by the formula:

\[ \alpha = \frac{0.249\sigma_H + 2.5}{0.35\sigma_H + 70} \]  

(7)

It is important to pay attention to the fact that residual stresses play a large role in determining the endurance limit. And, depending on the size of the elements to be welded, they can create a linear, flat or volumetric stress state. As shown in [1-6] in elements of considerable length and with a thickness of less than 30 mm, they create a plane stress state. When external loads act on the welded element, plastic deformations occur and the fibers elongate (which received plastic compression deformations during welding). As a result of this, the initial residual stresses, if they coincide along the line of action and sign with the stresses from the external load, after unloading, in the case of a linear stress state they decrease by \( \sigma_{\text{max}} \):

\[ \sigma_{\text{res}} = \sigma - \sigma_{\text{max}} \]  

(8)

Where \( \sigma_{\text{max}} \) – maximum stresses from external load at the site of the initial residual. With a flat stress state, the main residual stresses \( \sigma_{1\text{res}}, \sigma_{2\text{res}} \) coincide in sign and line of action with the main \( \sigma_{1\text{max}}, \sigma_{2\text{max}} \) from external loads. In this case, we can write that after unloading, the main residual stresses are equal to:

\[ \sigma'_{1\text{res}} = \sigma - \sigma_{1\text{max}}; \sigma'_{2\text{res}} = \sigma - \sigma_{2\text{max}} \]  

(9)

We calculate the values of the asymmetry coefficients of the cycles, taking into account the residual stresses according to the formula:

\[ \frac{R_{\text{res}}}{\sigma_H} = \frac{(\sigma_{\min})_{\text{res}}}{(\sigma_{\max})_{\text{res}}} = \frac{\sigma_{1\text{min}} + \sigma_{2\text{min}} + \sigma_{3\text{min}} + \sigma_{1\text{res}} + \sigma_{2\text{res}} + \sigma_{3\text{res}}}{\sigma_{1\text{max}} + \sigma_{2\text{max}} + \sigma_{3\text{max}} + \sigma_{1\text{oct}} + \sigma_{2\text{res}} + \sigma_{3\text{res}}} \]  

(10)
Where \( \sigma_{1\text{res}}, \sigma_{2\text{res}}, \sigma_{3\text{res}} \) – main residual stresses; \((\sigma_{\text{min}}^0)_{\text{res}}, (\sigma_{\text{max}}^0)_{\text{res}}\) – octahedral, equal to the sum of residual and stresses from external loads; \(\sigma_{1\text{max}}, \sigma_{2\text{max}}, \sigma_{3\text{max}}\) – maximum main cycle stresses; \(\sigma_{1\text{min}}, \sigma_{2\text{min}}, \sigma_{3\text{min}}\) – minimum principal stresses of the cycle. The remaining values are given in [12-15].

3. Result
We carry out numerical and analytical modeling of the endurance limit according to the method described in part 2.1. We calculate the values of the limiting amplitudes of the principal stresses taking into account the influence of the asymmetry of the cycle of principal stresses, characterized by the values of the coefficients \(R_{\sigma_1}, R_{\sigma_2}, R_{\sigma_3}\).

We carry out numerical and analytical modeling for the first case. We will build a model of the experimental setup in the software packages StructureCAD (figure 3) and SolidWorks (figure 4). Both models show approximately the same stress distribution, with SolidWorks having a built-in algorithm for calculating tubular joints taking into account local stress concentration. We determine the nominal and ultimate stresses.

![Figure 3. Analytical model of an experimental setup simulating tee joints made in a software package StructureCAD.](image)

![Figure 4. Stress distribution in the analytical model of an experimental setup simulating tee joints in a software package Solid Works.](image)

As a result of the load simulation, it was found that the maximum stress amplitude in the conditions of the Black Sea deposits for the T-type connection is 91.2 MPa. We calculate the fatigue limit of a welded T-joint under the conditions of the first fracture. We determine the values of residual stresses. In accordance with the project materials for the welded spatial nodes of the support blocks in the area of non-shaped joints made of 09G2S steel, the yield strength of the weld material with a thickness of 10 to 80 mm should be at least 280 MPa. We obtain the values of the main residual stresses \(\sigma_{1\text{res}} = 188\) MPa and \(\sigma_{2\text{res}} = 273\) MPa (under the condition that the maximum load from the bending moment is 4 kNm, with other values of the bending moment the figures of the residual stresses will also change).

As it is shown by numerical and analytical modeling, the first major stresses make the main contribution to the determination of the limiting voltage amplitudes. The effects of the second and third major stresses are less. At the same time, it should be noted that, if we follow the rule of distribution of a greater voltage along an algebraic sign, then we will violate the physical meaning of the process under study, since in this situation, we get not a symmetric cycle, but zero-to-compassion. We determine the values of the limiting amplitudes of the main stresses. We will make all the necessary calculations and bring the results to the table.
Table 2. Results of calculating a fatigue range of T-joints according to method 2.2.

| $\sigma_{1a}$ | $R^{\text{cov}}$ | $M^{\text{cov}}_{\text{max}}$ | $C^{\text{cov}}_1$ | $K$ | $\alpha$ | $\eta_1$ | $\eta_2$ | $\eta_3$ | $\sigma_{-1}$ | $\sigma_{1a}$ |
|----------------|-----------------|-----------------|-----------------|-----|-------|---------|---------|---------|----------|----------|
| 91.3           | 0.63            | 2               | 0.53            | 1.41| 0.5   | 0.1     | 0.4     | 0.24    | 91.95    | 24.9     |

Designation:

- $\sigma_{1a}$ - a limiting amplitude for the first primary stress;
- $R^{\text{cov}}_{1a}$ - an asymmetry coefficient of residual stresses;
- $M^{\text{cov}}_{\text{max}}, C^{\text{cov}}_1, K$ - auxiliary coefficients
- $\eta_1, \eta_2, \eta_3$ - an influence coefficient of tension, compressive and bending normal stresses, respectively
- $\sigma_{-1}$ - a fatigue range
- $\sigma_{1a}^{\text{lim}}$ - a limiting amplitude for the first primary stress

4. Conclusion

If we compare the diagrams obtained in normative documents [239] and [459], we can see that the authors use such concepts as the voltage span equal to the difference between the maximum and minimum voltage of the cycle, as well as the concept of the amplitude of the cycle equal to half of this difference. In both cases, the results are similar and correspond to the values. Therefore, the fatigue range $\sigma_{-1}$ can be approximately taken equal to the value of the limiting amplitude of the first principal stress equal to 25 MPa. Thus, we can conclude that the described method for determining the fatigue limit depending on the temporary tensile strength well satisfies the requirements for calculating the fatigue limit of welded joints of offshore stationary platforms. If we compare the diagrams obtained in normative documents [239] and [459], then we can see that the authors use such concepts as the range of stresses equal to the difference between the maximum and minimum stresses of the cycle, as well as the concept of the amplitude of the cycle, equal to half of these differences. In both cases, the results are similar and correspond to the values. Therefore, the fatigue range $\sigma_{-1}$ can be approximately taken equal to the value of the limiting amplitude of the first principal stress equal to 25 MPa. Thus, we can conclude that the described method for determining the fatigue limit depending on the temporary tensile strength well satisfies the requirements for calculating the fatigue limit of welded joints of stationary offshore platforms.

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