Determination of the endurance limit of structural elements of fixed offshore platforms with accumulated damage based on experimental studies

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Abstract. Russia has a large number of fixed offshore platforms, which were built during the Soviet era and are in operation for more than 20 years. In connection with such a long life platform for a long time was exposed to various loads that cause stresses and variables as a consequence of fatigue damage. In connection with this very urgent becomes the problem of estimation of residual resource of elements of the platforms with consideration of cumulative damage. Obviously, the residual resource it is long maintained elements of platforms subjected to intense impact, will differ from that caused by changes in the metal structure and the accumulation in it of fatigue damage. In this article the solution to the problem of determining the fatigue limit for the elements of the platforms with accumulated damage based on the experiments is proposed.

1. Introduction

The Russian Federation is actively producing on the shelves of the Caspian, Baltic, Sakhalin and other regions. In Russia fixed offshore platform commissioned more than 20 years ago are assertively operated. In connection with this significant period of operation during which the platform was exposed to various loads of alternating voltages and as a result the fatigue damage is extremely urgent becomes the problem of estimating the residual life of the platforms based on cumulative damage. In accordance with Federal law No. 116 “On industrial safety of hazardous production facilities” after 20 years of operation of the platform should be subjected to comprehensive technical diagnostics, the results of which of the elements having unacceptable defects should be replaced, and for the remaining elements must be calculated, the residual resource in the framework of the preparation of the conclusions of industrial safety expertise. In preparing these opinions, the online platform is determined based on various conditions (for corrosion rates, compliance strength, etc.), including assessment of resource for each element based on fatigue life under the action of cyclic loads [1-20]. Obviously, the residual resource it is long maintained parts of the platforms differs from a recently commissioned. However, to determine the impact of variable stresses on such elements is only possible by defining in any way the limit of endurance of these elements. In this article we will talk about the experimental method of determining the fatigue limit for the elements of the platforms with accumulated damage. In addition, it should be noted that the construction and operation of offshore platforms can be applied to new structural materials, fatigue properties which go beyond existing normative and technical documentation and is not yet investigated. Therefore, laboratory test methods can be used not only to solve the problem
of estimation of residual resource of elements with the accumulated damage, but also to study the
durability of welded joints after repair, the use of steels with ultimate strength and yield strength, beyond
the existing regulations and to deal with other unusual problems.

To date, various theories describing the process of damage accumulation in metals under the action
of cyclically varying loads and the resulting alternating voltage have been developed. One of them is
the wood model, its schema is depicted in figure 1 (a) and figure 1 (b) [7-10].

During part of the cycle during which the load increases (for example, when strong waves), one of
the well-situated planes of the structure shift occurs. When the load is reduced on a parallel slip plane,
too, there has been a shift, but in the opposite direction, since the shift of the first plane hampered by
mechanical hardening and oxidation of the newly formed free surface. In the first cycle shift may occur
squeezing or pressing the metal surface. Sequential load changes in the conditions of the continuous
plastic flow the indentation can develop into a crack (figure 1 (a). If in the process of the cycles is
dominated by tensile stresses, the effect is amplified, as occurs when the load increases the plastic
defformation during unloading can cause residual compressive stresses [7-10]. An example of the
formation of cracks under cyclic changing process loads is shown in figure 1 (b).

Figure 1 (a). The origin of a fatigue crack by indentation and extrusion. Figure 1 (b). The origin of a fatigue crack
formed due to shear

It should be noted that if the nominal stresses in the cross sections of structural elements and welded
joints of FOPs is much below the yield limit, local - due to the presence of stress concentrations at
inclusions or mechanical damage can be above this limit.

The process of fatigue damage accumulation in the elements of the offshore platform has a nonlinear
character. This can be explained by changes in the characteristics of resistance to fatigue fracture and
reduce the fatigue limit of the material of construction FOPs. This decrease is caused, first and foremost,
the level and the relative duration of the generated alternating voltage.

2. Methods
To determine the endurance limit, the author proposes to use a formula that describes this limit as a
function of the temporary tear resistance of the metal elements of the platform. In 2015 GUP RK
“Chernomorneftegaz” carried out research of physical-mechanical characteristics of steel is carved with
elements of FOP samples. The endurance limit in this case is calculated depending on the time of the
resistance of the samples according to the following formulas given in

\[
\sigma_{-1} = 0.432\sigma_B + 2.2 \\
\sigma_{-1} = 0.765\sigma_B - 123.4
\]

(1)
(2)

Table 1. Test results of steel samples of structural elements of FOPs.

| Steel, grade | Initial temporary resistance, MPa | Initial endurance limit (average, | Temporary resistance of the sample with | Endurance limit of a sample with accumulated damage (average, |
|--------------|----------------------------------|---------------------------------|------------------------------------------|--------------------------------------------------|

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However, in table 1 the values of the endurance limits obtained from grinding metal elements of the platform do not take into account the real geometric dimensions of the elements compared to laboratory samples depending on the stress ratio, the size of cross sections, the sensitivity of the metal to stress concentration, etc. And all these factors should be considered together, because they are reciprocal.

Let’s consider the technique of taking into account mutual influence of the key operational and technological factors on the change in the value of endurance limit and other parameters of the fatigue curve for the main structural elements of FOPs. Such options should consider the ratio of the size of the laboratory sample and items of the constructive elements (CE) FOP, asymmetry of the stress cycles, the surface roughness and the influence of methods of surface hardening. The net effect of these parameters on the endurance limit is taken into account by introducing the coefficient of the interaction $K_{\sigma CE FOP}$ according to the formula:

$$\sigma - 1_{CE FOP} = \frac{\sigma - 1_{CE FOP}}{K_{\sigma CE FOP}}$$  \hspace{1cm} (3)

where: $\sigma - 1_{CE FOP}$ – the endurance limit of the structural element of the FOP; $\sigma - 1$ – the endurance limit of a laboratory sample of material; $K_{\sigma CE FOP}$ – the coefficient of mutual influence of various factors.

In turn, the coefficient $K_{\sigma CE FOP}$ is determined by the formula:

$$K_{\sigma CE FOP} = \left( \frac{K_{\sigma}}{K_{d} \sigma} + \frac{1}{K_F} - 1 \right) \frac{1}{K_V}$$  \hspace{1cm} (4)

where:
- $K_{\sigma}$ – effective stress concentration coefficient;
- $K_{d} \sigma$ – scale factor;
- $K_F$ – coefficient taking into account the effect of roughness;
- $K_V$ – factor of technological hardening.

The value of $K_{\sigma}$ is determined by the formula:

$$K_{\sigma} = 1 + q_{\sigma} (\alpha_{\sigma} - 1)$$  \hspace{1cm} (5)

where:
- $q_{\sigma}$ – coefficient of sensitivity of the material to stress concentration, $\alpha_{\sigma}$-theoretical stress concentration coefficient.

Figure 2. The graphic of the dependence of the coefficient of sensitivity of the material to stress concentration and temporary tensile strength of the metal.

Figure 3. Determination of the coefficient of the influence of corrosion on roughness in an offshore field.
The value of $K_{d\sigma}$ can be set in various ways. As is known, with an increase in the area of test samples over 4000 mm$^2$, a decrease in the endurance limit practically does not occur, and the value of $K_{d\sigma}$ can be approximately taken equal to 0.6.

The value $K_F$ is calculated by the formula:

$$K_F = 1 - 0.22 \log(R_z) \cdot \left(\log \frac{\sigma_B}{20} - 1\right)$$ (6)

$R_z$ – surface roughness of the real CE of FOPs, $\sigma_B$ – temporary resistance.

The normative documentation indicates that in the presence of corrosive effects $K_F$ in the calculations should be replaced by $K_{cor}$, the value of which is determined by figure 3.

$K_V$ values for steels are taken according to table 2, depending on the type of hardening treatments.

**Table 2.** The dependence of the coefficient $K_V$ on the type of hardening treatments.

| Hardening type                  | $K_V$        |
|---------------------------------|--------------|
| High frequency quenching        | 1.2 – 1.6    |
| Nitriding to a depth of 0.1 – 0.4 mm | 1.10 – 1.15 |
| Cementation to a depth of 0.2 – 0.6 mm | 1.10 – 1.15 |
| Rolling surface                 | 1.10 – 1.25  |
| Surface shot peening            | 1.10 – 1.20  |

In the absence of data on hardening treatments the $K_V$ value shall be equal to 1.

Calculate the magnitude of the coefficient that takes into account the main operational and technological factors for elements made of steel and used in an offshore field, which will consist of the following stages.

### 3. Result

Determination of the sensitivity of the metal to stress concentration, which can be determined according to the schedule depending on the time of tear resistance and the theoretical stress concentration factor, which according to GOST 25-504-82 is determined from the ratio of maximum stresses to the nominal. In terms of offshore field stress concentration due primarily to corrosive cavities. As shown by statistics obtained as a result of processing of reports on carrying out of complex technical diagnostics of fixed offshore platforms in the Black sea, the depth of corrosion cavities does not exceed 4 mm. of the author's calculations showed that the maximum stress concentration in these conditions does not exceed 2. Therefore, the theoretical stress concentration factor for fixed offshore platforms (at least in terms of the Black sea) $\alpha_{\sigma}$ can be taken equal to 2. An alternative method of determining the sensitivity of a metal to stress concentration is calculated by the formula:

$$\alpha_{\sigma} = 0.211 - 0.000143 \cdot \sigma_B$$ (7)

where: $\alpha_{\sigma}$-theoretical stress concentration factor, $\sigma_B$ - rupture strength.

Defining the interim baseline data, calculate the coefficient of mutual influence of the various factors for the conditions of offshore $K_{\sigma CE FOP}$:

$$K_{\sigma CE FOP} = \left(\frac{1.5}{0.6} + \frac{1}{0.4} - 1\right) = 4$$ (8)

Guided by the principles described above we will make the calculation for elements made of steel VSt3Sp5 (column), the tensile strength for samples of pipes with accumulated damage, made according to GOST 8696-74 is 316 MPa. The fatigue limit of smooth specimens calculated by the formulae (1) and (2) is equal to 125 MPa. Thus we come to the conclusion that considering the basic factors of operating conditions offshore for the structural elements of the support block, made of steel VSt3Sp5
(columns), in terms of offshore endurance limit is 31.25 MPa. Performing the appropriate calculations, the author found that the fatigue limit for structural elements of the support block, made of steel 09G2S (braces and horizontal elements), in terms of the offshore fields is 41.5 MPa.

Separately it is necessary to consider the question of determining the base number of cycles \( N_G \) for elements made of steel 09G2S and VSt3Sp5 with accumulated damage. Pursuant to clause 4.2 GOST 25-504-82 in that case, if the number of cycles is not established experimentally, the value of the base number of cycles \( N_G \) to all steels should be taken as equal to \( 2 \times 10^6 \). However, according to the author, the value base of cycles in the resource definition it will give low values that do not correspond to the reality. Therefore, the author proposes to consider the following solution.

\[
\sigma, \text{MPa}\\\hline\hline\hline 50 & 100 & 150 & 200 & 250 & 300\\\hline 1 & 1 & 1 & 1 & 2\\\hline
\end{tabular}
\]

\[
\sigma_{\text{ref}} = 194 \text{ MPa}
\]

\[
\begin{align*}
\sigma &= 5 + \frac{\sigma_{\text{ref}}}{80} \\
m &\approx \frac{1}{K_{\sigma}} \left( 5 + \frac{\sigma_{\text{ref}}}{80} \right) \\
N_G &= N_G \left( \frac{\sigma_{\text{ref}}}{\sigma_1} \right)^m
\end{align*}
\]

As a result of the calculation, it was found that for the CE of FOPs with accumulated damage from steel VSt3Sp5, the slope of the fatigue curve is 2.24. Then, taking the value of 194 MPa as the endurance limit of the intact sample \( \sigma_1 \), we calculate the number of cycles for the fatigue limit of 31.25 MPa for platform elements with accumulated damage from VSt3Sp5 steel according to the formula [19]:

\[
N_G = N_G \left( \frac{\sigma_{\text{ref}}}{\sigma_1} \right)^m
\]

Thus on the basis of the calculations, come to the conclusion that taking into account the main factors of operation, specific to the conditions offshore, the structural elements of the support block with the accumulated damage, made of steel VSt3Sp5 (columns) will have the limit of endurance 31.25 MPa. Accordingly, the number of cycles for the items with accumulated damage \( N_G = 3.1 \times 10^8 \).

Guided by the considerations given above, the results of calculations for elements made of steel 09G2S with accumulated damage. As a result of calculations it was found that for structural elements of offshore stationary platforms of steel 09G2S in the slope index chart of fatigue equal to 2.44. Then the number of cycles for the items with accumulated damage \( N_G \) is:

\[
N_G = 6 \times 10^6 \cdot \left( \frac{2.34}{4.15} \right)^{2.44} = 4.08 \times 10^8
\]

\[
\text{Figure 4. A fatigue diagram for steel VSt3Sp5.}
\]
4. Conclusion
Comparing the obtained results with the results obtained by the method described and in accordance with the requirements of normative documents that uses a generic chart of fatigue for welded joints for steel offshore platforms, which defines the generic limits of elements with the accumulated damage of 14 MPa in $6 \times 10^8$ cycles, we can conclude that despite the fact that all of these values lie in the same region, obtained in the pilot study, the values will more accurately calculate the residual life for items with accumulated damage. Due to the fact that these values of endurance limits higher than the universal value of fatigue limit, and the amount of residual life will be more.

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