Varieties and kinetics of fatigue cracking of fixed offshore platforms for oil and gas production

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Abstract. The article investigates the different types of cracks and kinetics of propagation of cracks in main structural components and welds of the support blocks of fixed offshore platforms. Describes the process of metal fatigue for offshore installations. The article provides methods for calculating of the stress intensity factor and describes the methods of calculation for some cases. Based on the analysis of scientific studies, the author provides methods allowing to calculate two parameters describing the kinetics of crack propagation in relation to the elements and welded joints of offshore fixed platforms, namely the methods of calculation of threshold and critical stress intensity factor. On the basis of the conducted research the author constructed the kinetic chart of the development of fatigue cracks in relation to the elements and welded joints of the supporting blocks of fixed offshore platforms. In addition, the author gives the equation in which it is possible to determine the growth rate of fatigue cracks in various areas of the kinetic diagram.

1. Introduction
Oil and gas production work in difficult conditions, which are characterized by adverse environmental conditions. Among these unfavorable factors are both the impact of the extracted product and the impurities contained in it (including the co-containing bacteria that enhance the corrosion processes) [1-4] and vibrational, temperature and other types of effects. Offshore oil and gas facilities, including fixed platforms for oil and gas production (FOP), are an object of the oil and gas industry, which are in extremely adverse environmental conditions [5-15].

The use of a large assortment in the design of FOPs has led to increased resistance to dynamic loads and impacts. Signs have become unique to metal welds. This leads to the fact that with an increase in the level of tension additional conditions arise for the occurrence of fatigue cracks. Stable cracks occurring in various sections of the FOP are a serious danger. The situation is especially aggravated with insufficient viscosity of the material or at low temperatures, which can lead to the destruction of coarseness. In addition, fatigue cracks can disrupt the tightness of the design of the FOP. Elimination of the resulting cracks is associated with unplanned downtime, which affects the economic profitability of structures. The importance of taking into account the requirements associated with the development of offshore oil and gas fields [6, 7].
1.1. Fatigue and fatigue crack
Metal fatigue is a process of gradual accumulation of material under various stresses caused by various loads and effects (temperature, corrosion, vibration, etc.), leading to a change in the properties of the metal and the formation of cracks. A crack that gradually develops and weakens the sections causes a sudden destruction of both structural elements of the FOP and welded joints. Moreover, in the process of testing model specimens of the support block, mainly cracks originated in welded joints, however, there was a case where a crack during testing originated in the base metal and caused the test specimen to fail before cracks appeared in the welded joints. It should also be noted the presence of nascent cracks in the zone of attachment of the experimental sample to the ground. This explains the presence of values from different points.

Let us single out the main types of cracks: longitudinal, transverse, radial, separate, branched. The most dangerous are cracks with a depth of 2-3 mm, because at such parameters, crack propagation occurs abruptly even at much smaller than nominal ones. In many normative documents, the criteria for the presence of tracks have such depths. The author conducted experiments simulating the development of cracks in FOPs. In almost all cases, cracks began precisely from the FE surface. This is due to increased values of tension gradients. In addition, it should be noted that microcracks pass into macrocracks.

Analysis of the results of the diagnostic examination of the MSP-4 of the Golitsynskoye field carried out by the Ikar NPP in 2004 confirms the conclusion that most of the cracks in the support block begin to form precisely from the surface, because In addition to the reasons listed above, in the conditions of an offshore field, a corrosive effect, which changes in the relatively smooth shape of the metal and causes stress concentration, has a strong influence. Almost all cracks discovered during the study can be detected in the inhomogeneities of the metal and other microdefects at the transition points (figure 1 and figure 2).

![Figure 1. Photo of a crack in a horizontal element of an offshore platform.](image1)

![Figure 2. Photo of a crack in a vertical element of an offshore platform.](image2)

1.2 Fatigue cracks in welded joints
During the operation of FOPs, cracks form in the welds, which can be further developed. It should be noted that a crack formed in the weld metal, which was also proved by the author in his experimental work, can, under certain conditions, go into the base metal of the structural element of the FOP and vice versa. As it was already noted, a crack formed in the weld metal, under certain conditions, can go into the main metal of the structural element of the FOP and vice versa. Consider the main types of propagation of fatigue cracks in welded joints.

Fatigue crack growth from the top of the weld to the base metal. An analysis of the performed experiments on models allows us to state (figure 3) that fatigue cracking from the top of the weld to the base metal most often occurs. Fatigue cracks start from small defects at the top of the weld and gradually develop with increasing stress. This is also due to a significant gradient of stresses arising in the surface layers of the welded joint. However, during the experiments, other models of the development of fatigue cracks were noted.
Figure 3. The crack that arose during experimental tests of the model of the support block of the FOP, developed from the top of the weld to the base metal.

Fatigue crack growth from the root of the seam into the section under the weld (figure 4). As shown by experimental studies conducted by DNV, the growth of a fatigue crack from the root of the weld to the section under the weld can occur throughout the entire life of the SME. It was experimentally confirmed that the number of cycles until complete destruction of the sample is comparable to fatigue cracking from the top of the seam.

Figure 4. Crack of MSP-4 of the Golitsyn gas condensate field developed from the root of the weld into the base metal.

Fatigue crack growth due to surface defects or a defect in the base metal (figure 5). Fatigue cracking in a metal occurs as a result of a significant alternating cyclic stress arising from the loads and effects described in the first chapter. In this case, fatigue cracks begin from even minor surface defects. In the conditions of an offshore field characterized by high corrosion activity, corrosion damage often occurs, including through damage. Such defects cause local stress concentration and initiate the development of an extended fatigue crack. Despite the fact that such damage is considered unacceptable, it is not always possible to repair them in a timely manner. In this situation, it is extremely important to predict the crack growth parameters, and based on these data, allow temporary operation for a limited period of time or completely ban it until the identified defect is eliminated.

Figure 5. Corrosion damage and a crack developing from it into the base metal at OB MSP-4 of the Golitsyn gas condensate field.
2. Methods
Great practical interest is the process of the occurrence, development and opening of cracks for the main structural elements and welded joints.

The development of cracks under variable cyclic loading is associated with the formation of dislocation clusters at obstacles and their subsequent "crushing". The processes that occur during viscous or brittle fracture proceed in the following sequence:
1) the movement of dislocations along the most favorably oriented slip planes;
2) braking and accumulation of dislocations in front of an obstacle (large particles of the second phase, grain boundaries, seated dislocations, etc.);
3) crushing of the accumulated dislocations and the formation of a germinal crack — a pore;
4) crack growth to critical sizes and fracture.

Around the crack in the process of its nucleation and development, an alternating stress field arises, which can initiate the work of nearby dislocation sources, which leads to a partial decrease in stresses, a decrease in the crack growth rate, and plastic flow in other previously unaffected areas. Fatigue microcrack under certain conditions develops into brittle. The development of cracks can occur with the help of intergranular fracture, cup, transcrysalline cleavage, etc., i.e. The structure of steels affects the kinetics of crack growth.

Crack development processes are described using stress intensity factors $K$, which determine the change in the stress-strain state at the crack apex. The values of $K$, taking into account the type of applied load, at which the unstable crack fracture begins under conditions of plane deformation, are called the critical values of the stress intensity factor $K_{\text{IC}}, K_{\text{IIC}}, K_{\text{IIC}}$. Depending on the type of applied load, deformation of a body with a crack can occur according to one of the following basic schemes:

I (bracing, figure 6. a), the crack surfaces diverge from each other.

II (transverse shift, figure 6. b) the surface of the crack glides one over the other in the transverse direction.

III (longitudinal shift, figure 6. c) the surface of the crack one on the other in the longitudinal direction glide away.

![Figure 6](image)

**Figure 6.** Crack classification according to the type of load applied.

It is possible to determine the crack growth rate knowing stress intensity factors, which is a function of them and is described using the kinetic diagram of the growth of a fatigue crack, the diagram of which is shown on the Figure 8. It should be noted that this growth is uneven and can be conditionally described by three sections with different growth rates:

$I - \text{low} \left(0 < \frac{da}{dN} < 5 \cdot 10^{-5} \, \text{mm round}\right)$,

$II - \text{middle} \left(5 \cdot 10^{-5} < \frac{da}{dN} < 10^{-3}\right)$,

$III - \text{high} \left(da/dN > 10^{-3}\right)$

The boundaries of the transition from one section to another are the liminal $K_{\text{th}}$ and critical $K_{\text{fc}}$ values of the stress intensity factors, and the growth rate is calculated by the formula:
\[
\frac{da}{dN} = C(\Delta K)^n, \tag{1}
\]

where: \(a\) is the incrementation of the crack length per cycle, \(\Delta K\) is the range of the stress intensity factors, \(n\) and \(C\) are some material constants. The liminal stress intensity factor for steel structures, including for the support blocks of FOPs, can be calculated in accordance with the work data according to the formula:

\[
K_{th} = 15.86 - 1.05 \cdot \frac{\sigma_{yr}}{100} \tag{2}
\]

where \(K_{th}\) is the liminal stress intensity factor, MPa\(\cdot\)m\(^{0.5}\); \(\sigma_{yr}\) is the temporary resistance of steel, MPa.

The proposed equation is valid until the critical value of the stress intensity factor \(K_f\) is reached, which characterizes the start of unstable crack development, which can be determined by direct experimental methods according to State All-Union standard 25.506-85 or to use this value to the dependence:

\[
K_{fc} = \sqrt{\frac{2kEa_v}{1-\nu^2}}, \tag{3}
\]

where \(E\) is the coefficient of elasticity; \(\nu\) is the Poisson's ratio; \(a_v\) – impact elasticity on Charpy’s type specimens; \(k\) - dimensionless proportionality coefficient.

3. Result

Based on formula (2) and the fact that the temporary resistance of the welded joint is 420 MPa, the value of the threshold stress intensity factor will be 11.45 MPa\(\cdot\)m\(^{0.5}\). As a result of calculations based on formula (3), it was found that for the experimental welded joint under study, it is 29 MPa\(\cdot\)m\(^{0.5}\).

![Figure 8. Kinetic diagram of fatigue fracture of welded joints of support blocks of fixed offshore platforms.](image)

The same principles for constructing the kinetic diagram of fatigue are applicable to the main structural elements of the support block of the FOP.

4. Conclusion

The article describes varieties of fatigue cracks and the process of occurrence, development and opening of cracks for the main structural elements and welded joints. The crack development patterns are described and the value of the stress intensity factor is explained. An algorithm has been developed to calculate the stresses acting in cracks. An increase in the crack length per cycle depends on the magnitude of the stress intensity factor. The crack growth rate for elements and welded joints of offshore platforms is uneven, and is described using the kinetic diagram of the growth of fatigue cracks. Important parameters of this diagram are the threshold and critical stress intensity factors. This kinetic diagram is described by three sections of the crack growth rate in millimeters per cycle: low (up to \(5 \cdot 10^{-5}\)), medium (up to \(10^{-3}\)) and high (over \(10^{-3}\)). The boundaries of the transition from...
one section to another are the threshold $K_{th}$ and critical $K_{fc}$ values of stress intensity factors. The work carried out calculations that made it possible to establish that for the studied welded joint, the value of the threshold stress intensity factor will be 11.45 MPa$\cdot$m$^{0.5}$, and the critical 29 MPa$\cdot$m$^{0.5}$.

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