Evaluation of efficiency of the “K” welded repair technology of marine stationary platform with account of accumulated damages

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Abstract. The article discusses the problems associated with calculating the residual life of welded joints of offshore stationary platforms using the example of “K” -type joints. It should be noted that the residual life of such repaired compounds is still not well understood. The author built computer models of offshore platforms, which made it possible to determine the values of the maximum amplitudes of the alternating stresses that arise during the operation of the platform. Based on this information, the author justified the conditions of the experiment. The article describes the method of repairing a crack by the method of its welding with the establishment of so-called “crack traps” along the edges of the crack. The experiment was carried out under conditions of primary and repeated fracture of the welded joint "K" – type. As a result of the studies for the described repair technology, the endurance limits of the repaired K-type welded joints were calculated, which is 13.3 MPa based on the cycle N₉ = 3 * 10⁶.

1. Introduction
The Russian Federation has rich oil and gas deposits at the bottom of marine areas [1, 6-10]. In the Black Sea, offshore oil and gas facilities (OOGF) are used to extract these valuable minerals, which are stationary platforms of various design purposes (figure 1), with various production cycles, etc. Most of these platforms have been in operation for more than 30 years - they were established back in Soviet times. It should be noted that the wear of welded joints of offshore fixed platforms (OFP) is very large, which is explained by their work in adverse conditions and the destructive effect of sea waves, currents and other adverse factors [1, 3, 6-10].

In connection with such difficult operating conditions of offshore platforms, it is of great practical interest to study the residual life of welded joints taking into account accumulated damage [2] and the effectiveness of various methods of their repair in terms of extending their life. Currently, there is no methodology for assessing the residual life of such repair joints as applied to the support block of the OFP. Such compounds, in addition to the negative factors arising as a result of the welding process itself (residual stresses, heat-affected zone, etc.) are also affected by fatigue processes (for example, accumulated fatigue damage) and other factors [1, 3, 6-10].
Consider the main types of welded joints used in the construction of offshore stationary platforms, which are shown in figure 2. Generally speaking, two types of compounds are used in offshore oil and gas facilities (OOGF). The joint of two pipes at a right angle (T-joint or in foreign literature the so-called “T”-connection), shown in figure 3 and the joint of pipes at an angle (brace or in foreign literature “K”-connection), shown in figure 4. Each of them has its own performance features. In a number of cases, the T-joint and brace do not have a common nodal joint, since, as proved by the author’s calculations, the stresses in the knot increase slightly. In some cases, the nodes will share in common.

Figure 2. Various manufacturing schemes for welded joints of offshore fixed platforms.

It should be noted that in recent years the projects of offshore oil and gas facilities (OOGF) feature special nodal connections. However, in the offshore oil and gas facilities (OOGF), built more than 30 years ago, these technologies were not applied, and the designs shown in figure 3 and figure 4 were used.
Earlier, the author published the results of a study of the resource of a repaired T-joint. This article will discuss the study of "K"-connection. As mentioned earlier, the resource of both a new and a repaired welded joint is determined by the accumulation of fatigue damage in it. Fatigue damage is caused by the action of alternating stresses that occur under the action of external forces and environmental influences. Therefore, to assess the residual life of welded joints, it is necessary to obtain a picture of their stress state. The solution to this problem is impossible without the use of modern computer technology. Therefore, the author built a model of an offshore stationary platform in the StructureCAD software package, on which the effect of loads on the welded joint was simulated based on the following conditions: loads from the platform’s own weight, from the weight of the equipment and sea fouling, the buoyancy force of the aquatic environment (combination of K1 loads) and from wind and wave exposure (combination of loads K2 and K3). Moreover, to take into account the mutual influence of the elements, the direction of development of the wind-wave load was set both along the X axis (combination of loads K2) and in the direction at an angle of 45° to the X axis (combination of loads K3). The value of the wave load was chosen corresponding to the wave action at a wind speed of 25 m/s and a wave height of 6.8 m. The calculation was carried out by the method of determining the main stresses in order to go on to the values of equivalent stresses. As a result of calculating the maximum-stress "K"-connection (at a static voltage of 80 MPa), the following values of the main stresses were obtained:

| Load combination | Direct exposure to wave | Inverse wave load | Cycle asymmetry coefficient |
|------------------|-------------------------|------------------|----------------------------|
| n                | \( \sigma_1 \) | \( \sigma_2 \) | \( \sigma_3 \) | nt | \( \sigma_1 \) | \( \sigma_2 \) | \( \sigma_3 \) | R |
| K1               | 160                     | 12.4             | 2.1 | 1          | -             | -             | - |
| K2               | 194                     | 17.8             | 3.6 | -33        | 7.8           | 1.2           | \( \approx 0.17 \) |

\( \sigma_1, \sigma_2, \sigma_3 \) - major stresses, MPa

The obtained values of the principal stresses were reduced to equivalent values. The analysis of these values suggests that in the case under consideration, the maximum values of the amplitudes of the variable equivalent stresses, which cause fatigue failure, are equal for the combination K1=81 MPa...
and for the case $K_2=115$ MPa. Having determined the values of the stresses acting in the welded joint, we turn to the question of assessing the resource of welded joints with accumulated damage.

2. Materials and methods
Due to the fact that the endurance limit of such a welded joint cannot be determined theoretically, the author developed an experimental setup and performed a series of six experiments.

The experiment was carried out as follows. From the high-pressure pipeline with compressed air, a tap was made to the control module for the experimental pressure values. Then the pressure was reduced to a certain specific value, which was set in the control module. After that, the pressure was transferred to the switching unit of the experimental load vector, where the pressure was transformed due to a certain value, which acted in different directions along the vertical axis, destroying the welded joint. The experiment consisted of two stages. Bringing the compound to primary destruction (figure 5), repairing it and then secondary destruction. It should be noted that the duration of the extension of the resource very much depends on the chosen method of repair. For research purposes, the following repair method was chosen. After receiving the primary crack, a hole with a diameter of 8 to 12 mm was drilled at a distance of 20 mm from its ends (figure 6). The metal along the crack was removed with abrasive wheels with at least 25 mm beyond each side of the crack visible. And at the crack site, the metal was chosen in such a way as to simulate a V-shaped groove of the edges (to ensure penetration of the crack mouth). It should be noted that the hole created during the repair process itself is a stress concentrator. When mating pipes 720x20 and 530x12 in the presence of a hole with a diameter of 8 mm, the voltage increases by 1.3 times, and if a hole with a diameter of 12 mm - 1.7 times. With the pairing of pipes 1020x25 and 530x12 and the presence of a hole with a diameter of 8 mm, the voltage increases 1.25 times, and with a hole with a diameter of 12 mm - 1.6 times. Therefore, the author sets the task to scale the applied load so that the voltage values remain unchanged. In view of the fact that the diameters of real structural elements differ from elements of a laboratory sample, and the length of an experimental welded joint is significantly less than the real one, the diameter of the crack collector is 8 mm. In order to preserve the values of the operating stresses, the experimental load was reduced from 3.9 kN and 4.8 kN to 2.3 kN and 3.25 kN respectively.

Figure 5. Primary crack in the experimental "K"-connection.

Figure 6. Experimental "K"-connection after repair.

Briefly describe the methodology for processing the results of the experiment. When conducting multiple measurements of the same type of a certain value, it is necessary:
1. Carry out these multiple measurements under the same conditions and write them in a table.
2. Calculate the average value according to the formula:
\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  

(1)

3. Calculate the variance estimate

\[ \sigma^2 = s^2 = \frac{\sum (x_i - \bar{x})^2}{(n-1)} \]  

(2)

4. Calculate the standard error of the mean

\[ s_\bar{x} = \frac{s}{\sqrt{n}} \]  

(3)

5. At the required level of confidence \( \rho \), the student’s t test \( t(\rho, n-1) \) and the module of the confidence interval. In industry, a probability level of 95% is acceptable, if the number of experiments is four, the student’s t test is 3.18.

\[ \Delta x = s_\bar{x} \cdot t(\rho, \nu) \]  

(4)

6. Rounding off the corresponding results, write down the answer in the form

\[ X = \bar{x} + \Delta x \]  

(5)

### 3. Results

Series of six samples of repaired welded joints of the “diagonal” type was tested at a level of stress amplitudes of 82 MPa and 115 MPa, and additional points at a level of 44 and 27 MPa. The following results were obtained (see table 2)

| Model №1 | Model №2 | Model №3 | Model №4 | Model №5 | Model №6 | Model №6 | Voltage amplitude | Number of cycles obtained during the experimental test of the repaired diagonal brace |
|----------|----------|----------|----------|----------|----------|----------|-------------------|------------------------------------------------------------------|
| Voltage amplitude = 115 MPa |
| 4332 | 3975 | 4672 | 4348 | 4301 | 4359 | 4332 | 221 | 111 | 352 | 4332 ± 352 |
| Voltage amplitude = 82 MPa |
| 10253 | 9071 | 10798 | 10803 | 10164 | 10504 | 10253 | 643 | 321 | 1022 | 10253 ± 321 |
| Voltage amplitude = 44 MPa |
| 699444 | 702333 | 700123 | 704553 | 692341 | 702324 | 700363 | 4251 | 2125 | 6759 | 700363 ± 6759 |
| Voltage amplitude = 27 MPa |
| 1006330 | 1011202 | 1007330 | 1010920 | 1009486 | 1009497 | 1009128 | 1941 | 971 | 3086 | 1009128 ± 3086 |

The endurance limit was calculated by the formula:
\[ \sigma_R = \frac{\sqrt{\sigma_{1}^2 N_1 - \sigma_{2}^2 N_2}}{(N_1 - N_2)} \]  

(6)

Where: \( \sigma_{1} \) is the maximum voltage amplitude taken equal to 115 MPa, and \( \sigma_{2} \) is the voltage amplitude taken equal to 82 MPa; \( N_1 \) is the experimentally set number of cycles to failure equal to 10253 and \( N_2 \) is the experimentally set number of cycles to failure, equal to 1009128.

4. Discussion

As a result, the endurance limit equal to 43 MPa was calculated. Using the Klykov method [4], which takes into account the limiting amplitudes of the principal stresses, the coefficients of the influence of normal stresses, residual stresses, and other factors, it was found that the endurance limit of the compound under study is 13.3 MPa.

Let us construct a schematic diagram of the fatigue of repair welded joints of the “diagonal” type of the brace block.

The fatigue curve (figure 7) equation for a “K”-connection with accuracy sufficient for practice can be represented as follows:

\[ \sigma_a = -14.5539 \cdot \ln(1.51603 \cdot 10^{-7} N) \]  

(7)

where: \( \sigma_a \) is the amplitude of the alternating stresses acting in the welded joint; \( N \) is the number of cycles. Having made the calculation based on the Baskvin equation, we obtain the value of the fracture point of the fatigue curve \( N_G = 3 \cdot 10^6 \).

We calculate the values of endurance limits for some cycle asymmetry coefficients. With a zero cycle, the endurance limit will be equal to \( \sigma_0 = 26 \text{MPa} \), and with asymmetry coefficients \( R = 0.17 \), the endurance limit calculated on the basis of the Goodman equation will be \( \sigma_{R=0.17} = 10.79 \text{MPa} \).

![Figure 7. Schematic representation of the fatigue diagram of the welded joint "K"-connection of the OFP after repair.](image)

5. Conclusion

The results of the study showed that the value of the endurance limit, as well as the number of cycles for both types of joints studied are almost the same, from which we can conclude that the \( \sigma_i \) parameters of offshore oil and gas facilities welded joints are determined by the mechanical properties of the material and the type of repair.

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