Problems of evaluating the stressed state of welded joints of offshore fixed platforms of type “jacket” through the example of the Black sea region

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Abstract. Offshore stationary platforms are actively used for oil and gas production on offshore fields in the world. Thus only in the Gulf of Mexico, approximately 4,500 such structures are used. Actively offshore stationary platforms are used by Norway, Azerbaijan, Iran and other Persian Gulf countries, China, Brazil, the USA and many other countries. The offshore platforms considered in the article are structures welded from pipes of various diameters. These platforms are affected by wind, wave and other loads, which cause them to vary in direction and magnitude of voltage. The article analyzes methods for calculating stress values for welded joints of platforms. Based on these methods, the author carried out numerical and analytical modeling of the stress state of the welded joints of the offshore stationary platform, obtained practical results on the example of a “T” type welded joint.

1. Introduction

The world has significant marine resources of oil and gas located on offshore and oceanic shelves that are produced using offshore fixed platforms. Since the platforms operate in adverse marine conditions with significant loads, significant stresses arise in welded joints, which subsequently lead to fatigue failure. The purpose of this article is to study methods for assessing the stress state of welded joints of an offshore platform and to select the most effective of them [1-14].

The world has significant marine resources of oil and gas located on the sea and ocean shelves. In recent years, offshore deposits of the Black Sea have been actively developed, the production of which is carried out using offshore oil and gas facilities. These structures are offshore fixed platforms of the “JACKET” type for various purposes. Offshore stationary platforms are actively used for oil and gas production on offshore fields in the world. So, for example, in the Gulf of Mexico alone, approximately 4500 such structures are used. Actively offshore stationary platforms are used by Norway, Azerbaijan, Iran, some of Gulf countries, China, Brazil, the USA and many other countries. Those we can confidently say that these structures are widespread and play a key role in the extraction of oil and gas resources on the shelf [15-20].

Since the platforms operate in adverse marine conditions, characterized by significant loads from the effects of waves, currents and other climatic factors, significant stresses arise in welded joints, which subsequently lead to fatigue failure. The purpose of this article is to study the stress state of the welded joints of the offshore platform, which will allow further assessment of their resource. This article studies the stress state of two types of compounds: T-joint or in foreign literature the so-called “T”-connection, pipe connection at a certain angle, called a brace or in a foreign “K”-connection.
2. Methods

2.1. Strength Stress Analysis Method

Nowadays, various assessments of the stress state of structures made of round and square pipes have been developed. Based on the theory of the strength of welded joints and methods for calculating and designing structures made of round pipes, the following methodology can be proposed to study the stress state of welded joints of OFP:

1. First of all, it is necessary to numerically calculate the forces and stresses arising from the action of the gravity of the structural elements of the OFP, the installed technological equipment and the buoyancy force of the aquatic environment.
2. Determine the parameters of wind and waves in the studied field.
3. Calculate the loads arising from the wave action.
4. Determine the load moments from the wave action in the welded joint of the OFP.
5. Calculate the total stress from the wind-wave load in the welded section.
6. Determine the sum of the stresses from the wave load and the total weight of the structure with the technological equipment installed on it, taking into account the buoyancy force and the weight of the sea fouling.

We illustrate the developed methodology. To do this, we choose a welded joint at the OFP installed at the Subbotinskoye field. This welded joint is a T-joint, it is a horizontal element made of a cylindrical pipe with a diameter of 530 mm, cut at a right angle into a vertical column (column) - a pipe with a diameter of 720 mm (figure 1). The schematic diagram of the connection is shown

![Figure 1. Connection "T" -type offshore platform.](image1)

![Figure 2. Connection of the horizontal element to the column.](image2)

According to the project of the OFP, welded joints are isosceles triangles with legs \( k_f = 1.56 \) cm. When calculating the strength of corner joints, including T-joints, it is assumed that, regardless of the current load, they work for a conditional cut. Destruction occurs along the smallest slip area of the joint under the influence of both bending and torque moments, as well as longitudinal or transverse forces. The calculated cross section of the fillet is taken in the form of an isosceles triangle inscribed in the cross section of the weld. The side of the triangle will be considered equal to the height of the seam, and the influxes are not taken into account. Consider a simplified scheme of the action of the following forces on a welded joint: 1. The force \( P \) and the bending moment from the wave action on a vertical column (column) with a diameter of 720 mm, perpendicular to the surface of the column; 2) The distributed force \( q \) and its moment caused by the wave action on a horizontal element with a diameter of 426 mm. This force is directed perpendicular to the surface of the horizontal element and has its own calculation features that are different from determining the wave load on the vertical
element. The welded joint, as well as all the structural elements of the OFP support block, is affected by the gravity of the elements of the support block and equipment, the weight of the sea fouling, as well as the Archimedean force on the elements immersed in water. The resultant of all forces is denoted by N. The total moment arising in the welded joint is $M_N$. The stress in the welded joint, in the case of the perpendicularity of the force and moment action vectors, is calculated by the formula:

$$\tau = \frac{N}{\beta_f k_f L} + \frac{6M_N}{\beta_f k_f L^2},$$

where: $M_N$ - moment of force from the action of the total load; $N$ - is the resultant force; $L$-seam length, in this example, equal to 1.74 m; $k_f$ -a cathetus of the seam, which should be at least 6 mm, and in accordance with GOST 16037-80, is assumed to be 1.3 times the thickness of the thinner part. Considering that the thickness of the pipe with a diameter of 426 mm is 12 mm, we get 12 mm x 1.3 = 15.6 mm = 0.0156 m; $\beta_f$ -coefficient depending on the type of welding, position of the welded joint, weld leg and the choice of calculation method (i.e., for the metal of the fusion boundary or the metal of the welded joint), taken equal to $\beta_f = 0.7$.

The described method for determining the stress state follows from the theory of calculating the strength of a welded joint according to the given values of the maximum forces and moments arising from the offshore platform. However, this does not take into account the heterogeneity of the stress state of this compound, the presence of points with stress concentration, and many other factors, which are analyzed in detail below. Therefore, when calculating the stress state of a welded joint, this method should be used with caution.

2.2. Determination of the stress state of welded joints using StructureCAD software

The determination of the stress state in a welded joint is a difficult task, for the solution of which it is necessary to take into account the mutual influence of many structural elements of the support block. According to the author, it is advisable to use the displacement method and the automated design complex StructureCAD, which allows automatic calculation of the values of displacements and angular deformations. If we build a model of the support block in it and subject it to the appropriate loads, it becomes possible to determine the magnitude of the linear and angular deformations that occur in the nodes. However, to obtain these deformation values does not mean solving the problem of the stress state in the welded joint of the offshore platform. For this, according to the author, a transition is necessary from the values of linear and angular strains to the values of "equivalent strains" and already from them to the values of equivalent stresses.

Let us consider this question in more detail. As it is known know, at any point it is possible to distinguish three orthogonal directions (with indices 1, 2, 3), called the principal axes of deformation, for which the angular deformations are equal to zero, while the linear ones get their extreme values ($\epsilon_1$ - is the maximum, $\epsilon_3$ - is the minimum, $\epsilon_2$ - minimax). To find the values of the main strains, it is necessary to solve the following equation:

$$\epsilon^3 - J_1 \epsilon^2 - J_2 \epsilon - J_3 = 0$$

The invariants of the strain tensor are defined as follows:

$$J_1 = \epsilon_x + \epsilon_y + \epsilon_z$$

$$J_2 = -\epsilon_x \epsilon_y \epsilon_z - \epsilon_y \epsilon_x \epsilon_z - \epsilon_x \epsilon_y \epsilon_z + \frac{\gamma^2_{xy} + \gamma^2_{yx} + \gamma^2_{yz} + \gamma^2_{zy}}{4}$$

$$J_3 = \epsilon_x \epsilon_y \epsilon_z - \frac{1}{4} \gamma_{xy} \gamma_{yx} \gamma_{yz} - \frac{1}{4} \left( \epsilon_x \gamma_{yz}^2 + \epsilon_y \gamma_{zx}^2 + \epsilon_z \gamma_{xy}^2 \right)$$

where: $\epsilon_x, \epsilon_y, \epsilon_z$ - linear deformations along the corresponding axes, $\gamma_{xy}, \gamma_{yx}, \gamma_{yz}$- values of angular deformations.
When the values of the principal strains are calculated, it becomes possible to go on to determine the equivalent stress through the dependences
\[ \sigma = \frac{2G}{\sqrt{3}} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_1 - \varepsilon_3)^2} \]  
(6)

where: \( G \) - shear modulus, \( E \) - elastic modulus, \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) - major deformations, \( \sigma \) - equivalent stress, \( \mu \) - Poisson's ratio.

2.3. Analysis of the stress state of the welded joints of the platform in the SolidWorks software package

SolidWorks – it is a computer-aided design and engineering analysis system that uses the so-called finite element method as a calculation method. This software package has a long history of application and has proven itself in mechanical engineering and solving other problems of engineering analysis.

3. Result

Let us consider the stress state of the support block of the offshore fixed platform using the example of an OFP installed at the Subbotinskoye field. The design experience and the practice of operating such platforms indicate that taking into account the mutual influence of various platform elements is an extremely difficult task. To analyze the stress state of the welded joints of the platform, a computer model was built in the StructureCAD software package (figure 3).

![Figure 3. Model of the offshore platform built in the software package StructureCAD.](image)

In order to assess the stresses arising in the platform elements, the model was subjected to loads from its own weight, the severity of the equipment and marine fouling, as well as the buoyancy of the aquatic environment and from wind-wave exposure. 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 \( K_1 \)) and in the direction at an angle of 45° to the axis X (combination of loads \( K_2 \)). Using the StructureCAD software package, we simulate the effect of a wind-wave load in three loading combinations at a wind speed of 25 m/s and a wave height of 6.8 m, the values of linear and angular deformations in the nodes, which are the connection of the column with horizontal elements and braces. Table 1 shows the maximum results obtained for the "K" connection.
Table 1. Stress state of the welded joint with various load combinations calculated by the deformation method

| Combinations downloads | $\varepsilon_x$ | $\varepsilon_y$ | $\varepsilon_z$ | $\gamma_{yz}$ | $\gamma_{xz}$ | $\gamma_{xy}$ | $J_1$ | $J_2$ | $J_3$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$ | $\sigma$, MPa |
|----------------------|----------------|----------------|----------------|---------------|---------------|---------------|------|------|------|--------------|--------------|--------------|-------------|
| K₁                   | $6 \cdot 10^{-4}$ | $4.2 \cdot 10^{-6}$ | $6.12 \cdot 10^{-6}$ | $1.5 \cdot 10^{-5}$ | $-3.69 \cdot 10^{-5}$ | $-3.3 \cdot 10^{-5}$ | $6 \cdot 10^{-4}$ | $-5.22 \cdot 10^{-9}$ | $-2.6 \cdot 10^{-14}$ | $5.9 \cdot 10^{-4}$ | $1.2 \cdot 10^{-5}$ | $3.5 \cdot 10^{-6}$ | $82$         |
| K₂                   | $8 \cdot 10^{-4}$ | $6.2 \cdot 10^{-6}$ | $8.98 \cdot 10^{-6}$ | $2.2 \cdot 10^{-5}$ | $-5.41 \cdot 10^{-5}$ | $-4.8 \cdot 10^{-5}$ | $8 \cdot 10^{-4}$ | $-1.12 \cdot 10^{-8}$ | $8.1 \cdot 10^{-14}$ | $8 \cdot 10^{-4}$ | $1.9 \cdot 10^{-5}$ | $5 \cdot 10^{-6}$ | $115$        |

The author also analyzed the values of the interconnection of linear and angular displacements of the “T”-connection and the “K”-connection with a brace, which made it possible to compare the nature of the stress-strain state in both.

Table 2. Values of the relations of linear and angular displacements of the T-joint and the connection with the brace

| Combinations downloads | The values of the relations of linear and angular displacements of the T-joint and the connection with the brace |
|------------------------|-------------------------------------------------------------------------------------------------|
|                        | X   | Y   | Z   | Uₓ  | Uᵧ  | Uᵦ  |
| K₁                     | 2.69| 1.52| 1.05| -0.75| -1.90| 2.13|
| K₂                     | 1.54| 1.34| 0.93| -5.23| 0.65 | 1.44|
| K₃                     | 1.28| 1.43| 7.06| 0.53 | 0.23 | 2.43|

In addition, the author built a platform model in the SolidWorks software package. We studied both the general stress state of the platform and the stresses in individual welded joints of “T” and “K” types (figure 4).

Figure 4. Weld model in SolidWorks software package.
4. Conclusion
After modeling using various methods, the author comes to the conclusion that the solution based on the strength method does not meet modern requirements, because this method does not take into account local over stress in the weld, which distorts the real picture of the stress state of the welded joint, presenting it as uniformly distributed stresses. SolidWorks software package showed good results, which allows simulating the geometry of each individual welded joint, which allows obtaining fairly accurate results. However, to obtain accurate results, it is necessary to specify a high-density finite element grid, which requires very serious computing resources, which not all design organizations possess. In addition, it is worth noting the complexity of calculating large structures in SolidWorks, such as a platform more than 70 meters high with a large number of large diameter elements. Very accurate results were shown by the StructureCAD software package, which allows working with large-sized structures, however, the calculation of the stress state of welded joints required an additional labor-intensive data processing procedure. In recent years, the development of new CAE-programs, specializing in the analysis of the stress state of building structures. The results of their experimental application in relation to the assessment of the stress state of welded joints of offshore platforms will be published by the author later.

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