Assessment of jacket-type platform stress state in corrosive environment: Case study

I Starokon and A Ermakov
Russian State Gubkin University of Oil and Gas, Russia

Corresponding authors: Starokon79@mail.ru, AlexanderIE@yandex.ru

Abstract. The structural tubular elements of the offshore platform substructure work in combined conditions of bending, tension, compression and torsion loading. Evaluation of the platform stress state is an important task. Effective solution of which can be received by a CAD modelling. The real stress state of the structure depends on the characteristics of corrosion processes. Therefore, corrosion defects should be taking into account for numerical and analytical modelling to determine/predict actual state of stress of bottom fixed offshore platforms. The stress concentration factor is the real characteristic of stress value for the structural elements of the platform in the zone of corrosion. The paper deals with the methods of the actual stress state calculation for the structural elements and welded joints of stationary platform under corrosion. The features of corrosion defects are also a subject of analysis. The proposed a calculation method of stress concentration factors for the primary tubular members of platform substructure in condition of corrosion.

1. Introduction
Offshore fixed platforms play an important role in offshore hydrocarbon production [1-5]. To ensure reliable and safe operation of the offshore structures, it is important to determine the real stresses acting both in structural elements and in welded joints of the offshore fixed platform (OFP), in due time preventing overstress of structures and possible accidental situation.

The considered offshore Jacket-type platforms are the most common steel structures welded from tubular members of different diameters. Methods for calculating the values of the loads and stresses are described in the normative documents and specialized literature. Most elements of the support block (SB) for the OFP are in a complex-stressed state under the action of wind, wave, vibration, temperature and other influences [4-6]. They often subjected to the common action of bending, tension, compression and torsion. Therefore, the assessment of the actual stress state, taking into account the mutual interaction of elements, is a difficult and time-consuming task. An effective solution of task can be found by using a computer aided FE models in the software environment of StructureCAD, ANSYS, SolidWorks, etc.

2. Considered platform and stress evaluation
The authors of the report have analyzed the inspection reports of offshore platforms located on the Black Sea shelf. This data showed that the greatest damage of the platform is in the splash zone located from (below) -10 meters from sea level and (above) +14 meters from sea level. According to the normative documents, the fatigue damage occurs in this zone at a wave height of 13.9 meters with 1%
probability. However, in fact, as shown by the authors' calculations according to [5, 6], the wave height directly causing fatigue failure does not exceed 6.3 meters. Only the impact of extreme winds at a speed of more than 49 m/s can cause a wave height of 13.9 m.

The authors carried out an analytical study, which showed that in the elements of the underwater part of the platform there are large stresses due to both the weight characteristics of the platform and the action of bending and torque from wind-wave load (WWL). In the absence of WWL, these stresses are static and operate in the platform columns along their axes. Studies of platforms a computer aided FE models prove that the maximum total values of stresses from static and dynamic loads for columns will be achieved both in the areas of fixation to the ground and in the points of the wave load action. For horizontal elements, maximum stresses arise due to the action of wave, ice and other dynamic loads, which reach their maximum values in the splash zone. For braces, both of these provisions are true, since in addition to the dynamic loads on them, part of the load is redistributed from the weight of the structure. Therefore, the zone of greatest stress for braces can be identified only during the calculation.

This paper presents results of the stressed state study of the supporting block platform installed at the Subbotinskoye field in the Black Sea (Figure 1 and Figure 2). To assess the stresses in the platform elements by SCAD (Rev. 2017) software package, a platform model was developed. The structure was subjected to the following loads: equipment weight and marine fouling, buoyancy force of the aquatic environment (combination of loads K1) and wind wave load action (WWL). Moreover, to take into account the mutual interaction of elements, the direction of the wind-wave load was set both along the X axis (combination of K2 loads) and in the direction at an angle of 45° to the X axis (combination of K3 loads). The magnitude of the wave load was chosen to correspond to the wave action at a wind speed of 25 m/s and a wave height of 6.8 m. Structural architecture of the platform is a truss constructed by tubular members. It has five sections, each of which is approximately ten meters high. The platform is installed at a depth of 52 meters. The following results were obtained (Table 1).

| Load combinations | Section numbers of the platform support block | Values of equivalent stress, MPa |
|-------------------|---------------------------------------------|---------------------------------|
|                   | Columns          | Horizontal elements | Bracing |
| $K_1$             | 45 43 18 32 51 | 6 7 32 17 20 | 77 50 104 112 114 |
| $K_2$             | 104 99 39 58 68 | 19 25 54 62 23 | 136 116 133 138 131 |
| $K_3$             | 101 100 61 93 105 | 35 37 59 121 92 | 135 110 138 132 127 |

![Figure 1](image1.png) **Figure 1.** Offshore platform Support Block of the Subbotinskoye field in the Black Sea.

![Figure 2](image2.png) **Figure 2.** The model of the platform SB in the software package StructureCAD.
3. Analysis of factors affecting the platform elements stress state

3.1 Influence of cracks on the stress state of the platform elements

It is important to conduct a stress study of the platform structural elements with the cracks. Depending on the orientation and type of crack, a concentration of annular, radial or longitudinal stresses occurs. The increase of stress is described using the Stress Concentration Factor (SCF). For a longitudinal surface crack, the stress concentration is calculated primarily from the values of ring stresses, and for a circumferential crack by the values of longitudinal stresses.

Change of stress state due to presence of various sizes of cracks were observed by a parametric study. As an example, the influence of crack on the stress state of structure legs is evaluated. The initial low static stress of 45 MPa was considered (see Table 2).

| Depth of crack, mm | 5  | 10  | 20 | 30 | 40 | 50 |
|-------------------|----|-----|----|----|----|----|
| 1                 | 68 | 74  | 79 | 81 | 84 | 81 |
| 2                 | 72 | 97  | 106| 114| 118| 119|
| 3                 | 74 | 108 | 131| 141| 147| 151|

From the Table 2 it becomes obvious that in the presence of a 3 mm deep crack, even insignificant static stresses in a column of 45 MPa can significantly increase and exceed the permissible level.

3.2. The effect of corrosion defects on state of stress of the members

The aggressive marine aquatic environment causes the metal corrosion of the operating platforms. In the presence of stresses, caused by various loads, the corrosive effect creates a concentration of stresses, including those exceeding the normative level.

Various theories of stress corrosion have been analyzed. However, in this process of studying the corrosive effect on the platforms stress state, the authors refer to the classical theory of fracture mechanics. It is obvious that various forms of corrosion on the surface of the platform structural elements have a significant impact on the stress state. It is considered that continuous surface corrosion leads to a uniform thinning of the wall thickness of the pipes with a uniform decrease in the total bearing capacity. Corrosion defects (CD), extending deep into the base metal and having a small radius at the end of the defect, have a much more serious increasing effect on stress. Such CD dramatically change the surface shape of the platform structural members, leading to a change in the overall, and become potentially overstressed of the member, known in classical fracture mechanics as stress concentration (SC). This state is characterized by Stress Concentration Factor (SCF). Provided studies show that the magnitude of the stress concentration is the greater when corrosion defect is sharper [5, 6].

A corrosive defect in the form of a cavity is characterized by the parameters of length, width, depth, and radius of curvature at the end of CD. The method for determining the parameters of corrosion defects for offshore platforms is described in detail in [8]. In order to control the changes in the stress state of a platform, it is necessary to determine the corrosion rate (CR).

The studies do not consider the influence of electrochemical protection systems, insulating coatings, sacrificial protection, and other options. But the intensity of the corrosion process is different and depends largely on the locations of the elements, their design features and the quality of structure manufacturing. The elements of platform structures in the splash zones have the mostly surface and through corrosion damages.
The analysis of diagnostic examinations data shows that the entire surface of a structural element is damaged by corrosion. It is about 500-600 and more ulcerative CD with a complex spatial form were identified. This makes the calculation process difficult enough. Assessment of joint effect of CD on the platform stress state is a task that can be resolve by schematization and assembling of separate corrosion defects. To solve this problem, the entire surface of the studied structural element was divided into sections with ulcerative CD, allocated against the background of general surface corrosion.

Then a single CD of a cylindrical structural element is analyzed [5, 6]. The tube element has outer diameter \(DH\) and wall thickness \(\delta\). It was considered the a cavity has the height \(H\), length \(L\) along the tube axis, angular size is \(\Theta\), linear width is \(W\). Based on this schematization, stress concentration factors for the most common defect sizes was calculated (Table 3). Analysis of the table showed that the stress concentration is growing with increasing of depth and decreasing of the length and angle of the corrosion defect.

3.3. The effect of uniform surface corrosion on state of stress of the members

The authors have analyzed the effect of surface corrosion defects of tube elements on the stress concentration. Based on the data of corrosion rates for various elements of the platform [2, 5, 6], the stress concentration effect under the action of uniform surface corrosion was investigated. Consider that all types of loads can be classified as compression-tension, bending and torsion. The stresses arising under these loads will depend on the cross-sectional areas of structural elements (SE), values of axial moments of sections resistance under bending and torsion.

The analysis was performed for the tube legs with diameter from 720 to 1020 mm with wall thicknesses from 16 mm to 30 mm. Analysis have shown that the values of the rate of corrosion processes obtained as a result of examination of platforms at various fields of the Black Sea differ from the rate (Table 4), recommended by norms [3, 4].
Table 3. Stress concentration factors of typical platform structural elements with different parameters of corrosion defects

| Depth of corrosion defect, L, mm | Corrosion defect length L, mm | Corner size of corrosion defect Θ, degrees |
|---------------------------------|-------------------------------|-----------------------------------------|
|                                 | 10                            |                                          |
| 004                             | 100                           |                                          |
| 052                             | 1.11                          |                                          |
| 1                               | 1.21                          |                                          |
| 1.52                            | 1.32                          |                                          |
| 2                               | 1.42                          |                                          |
| 2.52                            | 1.54                          |                                          |
| 3                               | 1.64                          |                                          |
| 004                             | 100                           |                                          |
| 052                             | 1.10                          |                                          |
| 1                               | 1.19                          |                                          |
| 1.52                            | 1.29                          |                                          |
| 2                               | 1.38                          |                                          |
| 2.52                            | 1.49                          |                                          |
| 3                               | 1.58                          |                                          |
| 004                             | 100                           |                                          |
| 052                             | 1.07                          |                                          |
| 1                               | 1.15                          |                                          |
| 1.52                            | 1.22                          |                                          |
| 2                               | 1.30                          |                                          |
| 2.52                            | 1.38                          |                                          |
| 3                               | 1.45                          |                                          |
| 004                             | 100                           |                                          |
| 052                             | 1.07                          |                                          |
| 1                               | 1.15                          |                                          |
| 1.52                            | 1.22                          |                                          |
| 2                               | 1.30                          |                                          |
| 2.52                            | 1.38                          |                                          |
| 3                               | 1.45                          |                                          |
Table 4. Corrosion rates of tubular structural elements, taking into account the zone of their location.

| Name of elements | Location zone | Golitsinskoе | Strelkovoе | Shtromovoe |
|------------------|---------------|--------------|------------|------------|
| **Columns**      |               |              |            |            |
| Underwater zone  | 0.0531        | 0.0641       | 0.0804     |            |
| Splash zone      | 0.2468        | 0.1957       | 0.2993     |            |
| Overwater zone   | 0.1029        | 0.0467       | 0.0436     |            |
| **Braces**       |               |              |            |            |
| Underwater zone  | 0.08053       | 0.0896       | 0.0701     |            |
| Splash zone      | 0.2532        | 0.1886       | 0.269      |            |
| Overwater zone   | 0.0103        | 0.0182       | 0.0024     |            |
| **Horizontal**   |               |              |            |            |
| Underwater zone  | 0.0654        | 0.0668       | 0.0780     |            |
| Splash zone      | 0.167         | 0.172        | 0.185      |            |
| Overwater zone   | 0.00813       | 0.0063       | 0.0175     |            |

The table shows that, for example, the corrosion rate of the columns located in the splash zone is 0.2993 mm/year, which is as much as 1.89 times higher than recommended by norms [3, 4]. As well known, the stress concentration coefficient is determined from the ratio of actual and nominal voltages. Compressive or tensile stresses are calculated as the ratio of the force to the cross-sectional area of the tube element of the platform. Since surface corrosion in an offshore field leads to a thinning of the outer surface of the structural elements of the platform, reducing the value of the cross-sectional area while the magnitude of the action of the loads is constant, the actual stress increases.

Knowing the corrosion rates, which depend on the location of the platform elements, it is possible to predict a decrease in the cross-sectional areas of the elements. Based on the ratio of design and reduced as a result of the corrosion effects of the transverse areas, it becomes possible to determine the stress concentration factor.

By a fifth-degree polynomial approximation, which gives a result with an accuracy of 90%, the authors has proposed the following formulas for calculating the SCF for columns located in different zones under the action of longitudinal forces, bending and torsional moments.

For underwater zone:

$$K = 2.7 - (2628\rho + 67.06t - 132.7\rho^2 - 10.45pt) \cdot 10^{-4} - (219.1\rho^3 - 6.02t^2 + 21.12\rho^2t - 1.983pt^2) \cdot 10^{-6} - 3.153 \cdot 10^{-19}t^3,$$  (1)

For splash zone:

$$K = 3.429 - (3770\rho + 95.61t - 191.1\rho^2 - 13.68pt) \cdot 10^{-4} - (317.3\rho^3 - 116.1t^2 + 22.56\rho^2t + 3.997pt^2) \cdot 10^{-6} + 24.68 \cdot 10^{-8}t^3,$$  (2)

For surface zones:

$$K = 2.441 - (2261\rho + 9.106t - 115.9\rho^2 - 3.773pt) \cdot 10^{-4} - (193.7\rho^3 - 17.16t^2 - 7.069\rho^2t - 3.44pt^2) \cdot 10^{-6} - 98.77 \cdot 10^{-8}t^3,$$  (3)

Where, (for Eqs. 1-3): $K$-value of stress concentration factor, $\rho$-relative coordinate, determined from the ratio of the radius of the studied structural element to its wall thickness. Taking into account the values of corrosion rates in surface, splash and underwater zones, the authors carried out numerical-analysis of the structure stress state. As a result, the values of stress concentration factors were...
calculated depending on the operation time of the reference platform and the dimensions of the test element. The obtained stress concentration factors (SCF) indicate that their values in cases of compression-tension forces and bending or torsional moments differ from each other no more than 2%. This allows calculate them by using a common formulation.

In the considered structures, all horizontal, transverse and diagonal members have diameters from 325 mm to 530 mm with wall thicknesses from 10 mm to 18 mm. They are connected with columns or with other elements, like inclined transverse and longitudinal elements. For analysis in accordance with [2], the corrosion rate is 0.18 mm/year for underwater, splash and surface zones. As in the previous case, CCS values are equal for various forms of loading. On the base of the CCS value calculation and approximation of the obtained results, the following formula was performed:

\[
K = 1,035 + 0.07193t - 0.2372\rho - 0.00592tp + 0.2512\rho^2 - 0.05864t\rho^2 + 0.6685\rho^3 + 0.02765tp^3 - 0.2376\rho^4 + 0.03548t\rho^4 - 0.3197\rho^5
\]  

(4)

Where, \(K\) is the value of the stress concentration factor, \(\rho\) is the relative coordinate determined from the ratio of the radius of the studied structural element to the thickness of its wall; \(t\) is the time of operation.

As a result of the analysis, it was revealed that the corrosion rate of 0.2993 mm/year for columns located in the splash zone is 1.89 times greater was indicated (0.16 mm/year). Therefore, when using formulas for calculation (1-4), it is advisable to multiply the value of \(t\) by 1.89 for columns and 1.49 for diagonal lines. At the same time, for all elements located in the underwater zone, the corrosion rate is significantly lower (approximately 0.02 mm/year), which is explained by significant marine fouling.

To determine the SCS values of welded joints (WJ) depending on the operation time, the WJ models of the platform were built using SolidWorks (Rev. 2018) software. The values were calculated by points with the maximum stress concentration taking into account the form of loading. The results are shown in Table 5.

The significant effective amplitudes of alternating stresses lead to early exhaustion of the structural elements resource. This is especially important when assessing the resource of restored (repaired) welded joints. The authors [7] have proposed the structural elements that allow reducing the amplitudes of alternating stresses acting in a welded joint. This will increase their remaining life.

Table 5. The stress concentration coefficients of WJ under corrosive effects, taking into account the shape of the applied load at the points with the maximum stress concentration

| Tube structural elements | Duration of corrosion exposure, years |
|--------------------------|--------------------------------------|
|                         | 3         | 9         | 15        | 21        | 27        | 30        |
| Action of a bending moment in the plane |           |           |           |           |           |           |
| Horizontal transverse in the area of connection with columns (CR - 0.18 mm / year) |           |           |           |           |           |           |
| 325x10                   | 1.04      | 1.16      | 1.34      | 1.52      | 1.88      | 2.00      |
| 426x12                   | 1.05      | 1.16      | 1.25      | 1.44      | 1.72      | 1.86      |
| 530x14                   | 1.04      | 1.16      | 1.26      | 1.41      | 1.72      | 1.87      |
| Inclined longitudinal in the area of connection with columns (CR - 0.15 mm / year) |           |           |           |           |           |           |
| 325x10                   | 1.04      | 1.12      | 1.26      | 1.41      | 1.55      | 1.73      |
| 426x12                   | 1.04      | 1.13      | 1.20      | 1.30      | 1.54      | 1.68      |
| 530x14                   | 1.03      | 1.14      | 1.25      | 1.34      | 1.48      | 1.53      |
| Underwater parts of columns (CR - 0.12 mm / year) |           |           |           |           |           |           |
| 325x10                   | 1.03      | 1.08      | 1.17      | 1.30      | 1.41      | 1.51      |
| 426x12                   | 1.03      | 1.10      | 1.14      | 1.23      | 1.31      | 1.40      |
| 530x14                   | 1.03      | 1.12      | 1.20      | 1.24      | 1.31      | 1.47      |
| Action of axial force on the waist tube and bending moment outside the plane |           |           |           |           |           |           |
| Horizontal transverse in the area of connection with columns (CR - 0.18 mm / year) |           |           |           |           |           |           |
| 325x10                   | 1.10      | 1.32      | 1.52      | 1.56      | 2.13      | 2.37      |
4. Conclusions
The stress state of the platform elements in marine conditions is affected by cracks, caverns, and general metal degradation resulting from corrosion. The real rate of corrosion processes for the structural elements of the platform in the marine environment, determining its stress state and stress concentration, differs from the values recommended by the normative design documents.

References
[1]. Borodavkin P P 2006 Offshore oil and gas facilities: Textbook for universities. Part 1. Design. – M.: OOO «Nedra-Biznestsentro», 555 (in Russian)
[2]. Gudmectad O T, Zolotukhin A B, Ermakov A I et al. 1999 Basics of Offshore petroleum engineering and development of marine facilities: with emphasis on the arctic offshore-oil and gas, Neft’i Gaz, Moscow.
[3]. SP 38.13330.2010 "SNiP 2.06.04-82 2011 Loads and impacts on hydraulic structures (wave, ice and from ships) "Ministry of Regional Development of Russia. 116 p. (in Russian)
[4]. Rules for the classification, construction and equipment of floating drilling rigs and offshore fixed platforms - Russian Maritime Register of Shipping, St. Petersburg., 2014. -484p. (in Russian)
[5]. Starokon I V 2015 Assessment of the fatigue life of welded joints and the main structural elements of the supporting blocks of offshore stationary platforms, Basic Res. J., 2015 (7-4) 691-696.
[6]. Starokon I V 2012 Fundamentals of the theory and practice of the formation of fatigue cracks in offshore oil and gas facilities, Modern problems of science and education. - 2012. - № 4; URL: www.science-education.ru/104-6605
[7]. Starokon I V, Golovachev A O and Nadyrov R I 2019 Methods for increasing the fatigue life of repaired welded joints of offshore oil and gas facilities, IOP Conf. Series: Earth and Environ. Sci., 272(3) 8.
[8]. Starokon I V, Golovachev A O 2019 Method of determining the sizes of corrosion defects of elements of marine oil and gas industrial constructions on the basis of data on temperature contrasts, IOP Conf. Series: Earth and Environ. Sci., 272(3) 8.