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Failure analysis during the operation of offshore oil and gas structures

Analiza awarii podczas eksploatacji podmorskich złóż ropy i gazu

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ABSTRACT: Failures caused by offshore oil and gas structures operations are investigated. This work is based on the description and analysis of real case studies of accidents on offshore stationary and floating platforms; it combines foundational knowledge and current research on the latest developments in the field. It was shown that strength characteristics of offshore reinforced concrete and steel elements change during operation and cause the accumulation of defects and damages. It was established that corrosive wear, corrosion-mechanical processes, and crack-like defects are the decisive causes of element failure. It was shown that up to 60–75% of all damages to and failures of offshore engineering facilities' steel structures occur due to the corrosion-mechanical influence of an aggressive environment and force loads. This means that issues of corrosion-mechanical failure of such structures have become an industrial-scale problem. It thus allows us to draw the following conclusions: improvement of steel offshore drilling platforms (ODPs) maintenance system involves the development of new models and methods of managing the operational reliability of these structures, aimed at making decisions that take into account the crack resistance and fatigue-corrosion strength of steel ODPs in contact with the corrosive-active environment. Only on the basis of such scientifically and economically grounded models can rational strategies be shaped for carrying out revisions of the ODPs technical condition, ensuring the necessary level of their reliability during the operation period. This investigation can be very helpful to improve the design and construction of more reliable and durable offshore stationary and floating platforms.

Key words: offshore drilling platforms, failure analysis, corrosion, damage, concrete and metal structures.

STRESZCZENIE: W artykule omówiono uszkodzenia powstające w trakcie eksploatacji podmorskich złóż ropy i gazu. Niniejsza praca opiera się na opisie i analizie rzeczywistych przypadków wypadków na morskich platformach stacjonarnych i pływających, łączy ona podstawową wiedzę z bieżącymi badaniami nad najnowszymi osiągnięciami w tej dziedzinie. Wykazano, że charakterystyki wytrzymałościowe elementów betonowych i stalowych konstrukcji morskich w trakcie eksploatacji zmieniają się i kumulują wady i uszkodzenia. Ustalono, że decydującymi przyczynami uszkodzeń elementów są zużycie korozyjne, procesy korozyjno-mechaniczne oraz defekty spękaniowe. Wykazano, że do 60–75% wszystkich uszkodzeń i wypadków stalowych urządzeń morskich powstaje w wyniku korozyjnego i mechanicznego działania agresywnego środowiska oraz obciążeń siłowych. Oznacza to, że kwestie korozyjnego mechanicznego uszkodzenia takich konstrukcji stały się problemem na skalę przemysłową. Na tej podstawie można wyciągnąć następujące wnioski: doskonalenie systemu utrzymania morskich stalowych platform wiertniczych wiąże się z opracowywaniem nowych modeli i metod zarządzania niezawodnością eksploatacyjną tych konstrukcji, ukierunkowanych na podejmowanie decyzji uwzględniających odporność na pękanie oraz odporność na korozję zmęczeniową stalowych platform wiertniczych stykających się ze środowiskiem korozyjno-aktywnym. Tylko w oparciu o tego typu, naukowo i ekonomicznie ugruntowane modele, można kształtować racjonalne strategie przeprowadzania przeglądów stanu technicznego morskich platform wiertniczych, zapewniające niezbędny poziom ich niezawodności w okresie eksploatacji. Badania te mogą być bardzo pomocne w ulepszaniu projektowania i budowy bardziej niezawodnych i trwałych morskich platform, zarówno stacjonarnych, jak i pływających.

Słowa kluczowe: morskie platformy wiertnicze, analiza awarii, korozja, uszkodzenie, konstrukcje betonowe i metalowe.

Introduction

About 30% of the world's oil production and 27% of the world's natural gas production takes place on the shelf (Planete Energies. Offshore Oil and Gas Production, 2021). Offshore oil and gas facilities are exposed to extreme weather conditions, sea level rises, and increased storm activity (Khan et al., 2022). All this causes unprecedented damage to the infrastructure and increases the costs of construction, maintenance, and operation (Katopodis and Sfetsos, 2019). Damage to offshore oil and gas

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facilities infrastructure can cause spillage and release of oil and other hazardous pollutants, leading to health and environmental risks (Dong et al., 2022). For example, a comparative statistical analysis of average losses per offshore platform by region is $28.3 million in South America, $20.3 million in Australia, $17.9 million in North America, $17.3 million in Africa, and $16.2 million in Europe (Kaiser, 2007).

In general, the system of offshore platforms has entered a period of intensive aging and wearing out, since the beginning of operation dating back to the 1970s, as evidenced by the analysis of the technical condition of these objects (Holand and Awan, 2012; Ibrion et al., 2020). Their resources are affected by the degradation of steel and alloys, the influence of aggressive working environments, difficult operating conditions, and regimes, the formation and development of defects (Dmytrakh et al., 1997; Kryzhanivs'kyi et al., 2018; Necci et al., 2019), etc.

The purpose of this work is to describe and analyse real case studies of accidents on offshore stationary and floating platforms by combining foundational knowledge with current research on the latest developments in the field.

Unfortunately, in the literature there is currently insufficient systematic information on the corrosion-mechanical failure of the ODPs elements caused by metal degradation after a long period of operation in corrosive-aggressive environments and under fatigue loads. Therefore, additional specialized experimental investigations are needed to study the influence of various factors on the crack resistance of offshore engineering structures in direct contact with corrosive environments. Tasks for such research can be formulated based on the failure analysis during the operation of offshore oil and gas structures, reflecting the novelty of this research.

General overview of corrosion mechanisms

Steel and reinforced concrete are mainly used for the construction of offshore drilling platforms (ODPs) (Amaechi et al., 2022a, 2022b). Most concrete platforms use Portland cement, which is characterized by high uniformity, strength, and high-quality chemical composition. However, the durability and service life of reinforced concrete structures in seawater is dependent on the resistance of concrete to the penetration of chlorides. Corrosion of fittings caused by carbonization or penetration of chlorides is one of the main reasons for the deterioration of such structures (Taffese and Nigussie, 2020) in an aggressive environment; their durability is greatly reduced by physical/chemical/mechanical processes that lead to corrosion of fittings.

Carbonation of concrete is a reaction between CO_2 and Ca-rich hydrate phases (e.g., portlandite, calcium silicate hydrates, and ettringite), the kinetics of which depends on external conditions. It causes changes in the mechanical properties and microstructure of cement-based materials (Savija and Lukovic, 2016). The result of carbonation is the formation of calcium carbonates $CaCO_3$, since calcite is the most stable phase (Savija and Lukovic, 2016). Despite the possible self-recovery of concrete, carbonation decreases the pH of the pore solution from ~13 to ~9, which leads to the dissolution of the reinforcement concrete passive layer when the carbonation front reaches its surface (Huet et al., 2005).

Chlorides appear in concrete (Huet et al., 2005; Savija and Lukovic, 2016) as a result of diffusion processes when the surface comes into contact with seawater or during the use of de-icing salts (e.g., $CaCl_2$, $MgCl_2$, NaCl) in winter. Chlorides mainly enter through the pores in the form of free Cl^- chlorides by capillary absorption, diffusion, or penetration. Thus, the time of corrosion initiation strongly depends on the diffusion coefficient of total chloride in concrete. In addition, cracks in concrete or defects at the steel-concrete interface contribute to the penetration of chloride into the steel surface (Khan et al., 2017).

Corrosion of steel in concrete is known to be an electrochemical process involving the anodic dissolution of iron and, in general, the cathodic reduction of oxygen. Depending on the presence of oxygen and pH near the steel surface, water/proton reduction can also be observed (Stratmann and Müller, 1994).

Seawater is a well-aerated electrolyte with high electrical conductivity and neutral pH. It contains mainly chlorides and sulphates of sodium, magnesium, calcium, and potassium. Due to the high content of chlorides, seawater is characterized by a high ability to depassivate steels (Keshe, 2003). Depending on the type of used steel (NACE SP0176, 2007), either general (uniform) (Keshe, 2003; Abbas and Shafiee, 2020) or pitting (Keshe, 2003; Fatoba et al., 2018) corrosion is observed. The average rate of steel corrosion in seawater, calculated by the mass loss (Keshe, 2003), equals 0.05 to 0.20 mm/year, and pitting corrosion is up to 1 mm/year. The rate of metal corrosion in seawater is influenced by several factors (Keshe, 2003; NACE SP0176, 2007; Abbas and Shafiee, 2020; Shcherban and Mazur, 2022). Thus, the general salinity of seawater does not greatly affect the corrosion rate, while the presence of various pollutants or hydrogen sulphide can significantly accelerate it. The movement of seawater increases the flow of oxygen to the cathode areas on the steel surface, which accelerates the corrosion rate (Keshe, 2003) of steel elements. At the same time, for corrosion-resistant steels, an increase in oxygen diffusion leads to increased surface passivation and protection against pitting (Keshe, 2003; Fatoba et al., 2018). Significant speed of seawater can cause corrosion-erosion damage as electrochemical corrosion is greatly accelerated by the destruction of the protective film on the metal caused by the flow of water.

Water temperature affects the corrosion rate in two ways (Keshe, 2003): an increase in temperature accelerates the diffusion of oxygen and the reaction on the anodic and cathodic sites on one hand, and reduces the solubility of oxygen, and hence the corrosion rate on the other. The contact between dissimilar metals in seawater results in the increased corrosion of more electronegative metal and the reduced failure of more positive metal. In the case of incorrect selection of contacting metals and the absence of protection means, there is a danger of quite a significant corrosion damage. The intensity of corrosive processes in seawater can be affected by fouling of the surface by offshore organisms (biocorrosion) (Pratikno and Titah, 2016). Fouling has no particularly noticeable effect on the failure of carbon and low-alloy steels, and corrosion can either increase (Little et al., 2008) (in the presence of sulphate-reducing bacteria, the existence of differential aeration vapours) or decrease (Little et al., 2008) (the formation of a protective film on the surface which limits the access of oxygen to it). The effect of fouling on the corrosion of stainless steel is ambiguous (Little et al., 2008), but in general, it can be argued that it is negative. This is explained by the fact that these materials are prone to crevice corrosion in gaps or places of damage to the passive protective surface film formed by algae and molluscs.

Analysis & discussions

Analysis of statistical data shows that corrosion of metal structures of offshore oil and gas facilities causes 50% of the damage (Shcherban and Mazur, 2022). Steel for offshore oil and gas structures corrodes in two stages (NACE SP0176, 2007; Shcherban and Mazur, 2022). The initial stage takes place when the object enters seawater conditions. The stage of the long-term operation occurs when the object is under specific conditions for a long time and other factors come to the fore in the weight of influence (Shcherban and Mazur, 2022). At the initial stage, the main impact falls on protective coatings of offshore oil and gas facilities. The process of corrosion damage develops and enters a long-term phase with the degradation of this passive protection, as well as with the deactivation of active protection (or its irrational functioning). In addition to the external surfaces of oil and gas structures, the internal surface of the equipment that come into contact with the transported hydrocarbons also corrode. This is caused by the influence of oxygen, sulphur compounds, and transported abrasive particles. These processes do not differ from the processes of ground pipelines corrosion (Standard DNVGL-ST-F101, 2017; Shcherban and Mazur, 2022), in particular, various failure mechanisms, such as hydrogen-induced cracking, hydrogen embrittlement, corrosion fatigue, stress corrosion cracking, and microbiologically influenced corrosion, etc.

A thorough analysis of emergencies on offshore infrastructure facilities, including truss platforms, semi-submersible, concrete structures, barges, cargo buoys, self-lifting (FPSO/FSU), and platforms with tension supports (TLP) was conducted over the period of more than 40 years (from March 1972 to November 2013) (Ibrion et al., 2020). The Norwegian Continental Shelf area, which includes: the North Sea, the Norwegian Sea, the Barents Sea, and areas in the Arctic Ocean were considered. The Norwegian Continental Shelf area covers about $2.04 \cdot 10^6$ km^2, almost six times the land area of mainland Norway, Svalbard, and Jan Mayen.

In total, there were 296 accidents (Ibrion et al., 2020) during this period. It is worth noting that the highest peaks of accidents were registered in 1985 and 2009. During 1981–1995, a large number of accidents were registered with high peaks in 1984, 1985, and 1993. A high number of accidents was also registered in 2011. Possible reasons and explanations for why the number of accidents was high in these years could be related to the fluctuations in the price of oil and increased pressure on expanding oil and gas production. Other reasons could be related to the increase in the number of old offshore structures and the need to extend the design period of operation and the introduction of new technologies.

If seasonal changes are taken into account, it is observed that the largest number of accidents occurred in September, followed by November and March. A large number of accidents were also registered in January, May, and August. These observations correlate with the high number of accidents during certain months and the environment, as well as with such conditions as wind, waves, and currents, particularly in the North and the Norwegian Seas.

In particular, it was noticed (Ibrion et al., 2020) that the highest waves – 25 meters high – extreme values – were registered in January and December. It was revealed that the same offshore structure was twice hit by 25 m high waves during 6 years and suffered significant damage both times, even though it was designed for 30 m waves occurring over a long period. Waves higher than 15 m were also recorded in June. High waves of about 10 m or more were persistent in January, March, April, and September; waves of 8 m – in March, September, and November. It is quite obvious (Piedras Lopes and Ebecken, 1997) that such a wave load causes a significant fatigue load on offshore structures.

An analysis of the accident situation on the Norwegian Continental Shelf area (296 cases) shows that a significant number of accidents over more than 40 years are related to truss and semi-submerged platforms, and a large number of accidents are also related to concrete structures. In addition, it is noted that worldwide the largest number of emergencies is associated with truss foundations since most existing offshore structures in the world are represented by truss structures (Shabakhty, 2011; Lin et al., 2019).

During long-term operation, ODPs are exposed to temperature effects, as well as fatigue loads and corrosive environments, which significantly affect their long-term and safe operation (Shabakhty, 2011). Offshore drilling rigs are designed to withstand fatigue loads and corrosive environments. However, a significant part of cyclic loads in the nodes of these platforms arises as a result of the wave load, which changes in time and direction (Tovo, 2002). As a result of the seawater effect and fatigue due to random loads, damage accumulates, and eventually leads to the formation of corrosion-fatigue cracks (Tovo, 2002). Developing over time, these cracks reach critical dimensions, causing corrosion fatigue damage (Dmytrakh et al., 1997; Kryzhanivs'kyi et al., 2018).

An analysis to determine the number of accidents on the Norwegian Continental Shelf area by type of offshore structure was carried out in a more precise way; the number of accidents for each type of structure was divided by the number of structures (Ibrion et al., 2020). The highest accident rate for each type of offshore structure is associated with concrete structures, with 5.5 accidents for each concrete structure. The high rate is also associated with the loading of oil on loading buoys, trusses, and TLP.

When it comes to the emergencies on concrete structures – 17 accidents occurred on one of them over 40 years. In addition, 12 accidents occurred on another concrete platform. At the same time, the main factors of accidents are fire, explosion, release of liquid or gas, falling of cargo or dropped object, or release and collision of offshore installations. The third place is shared by concrete and truss structures, both associated with 8 accidents. In these cases, the emergencies were related to fire, explosion, the release of liquid or gas, falling cargo, or falling objects. All three of these concrete structures, where such a large number of accidents occurred, are located on the deposits of the North Sea.

It is worth noting that emergencies of offshore structures are accompanied not only by material damage but also by significant human casualties (Ibrion et al., 2020). The death toll from each accident on the Norwegian Continental Shelf area sometimes reached 5–15, except for 1980, when the Norwegian semi-submersible drilling rig Alexander L. Kielland capsized while working in the Ekofisk oil field, killing 123 people. The death toll included both crew and support personnel.

However, the information on the causes of drilling platform accidents on the sea shelves and their consequences is scarce (Necci et al., 2019; Ibrion et al., 2020), as it was considered confidential information until recently. In addition, companies that own destroyed platforms on metal support both in our country and abroad, are not interested in disseminating accurate information about the real causes of accidents and often falsify examination results. The second important aspect is the possibility of assessing material and environmental damage from accidents (Kaiser, 2007; Necci et al., 2019). The most in-depth studies on the failure of ODPs are presented in investigations based on many years of experience in performing inspection (Shabakhty, 2011; Ibrion et al., 2020). The main technical (operational) causes of offshore structure accidents are summarized in Figure 1.

The importance of the problem for investigating the corrosion-mechanical resistance of metal structures operating for a long period in aggressive marine environments is due to a large number of corrosion losses, which have already become almost equal to the costs for the development of entire branches of industries (Syrotyuk and Dmytrakh, 2014).

The dependence of the specific indicator of the intensity of failures and unauthorized stops on the operational life of ODPs is shown in Fig. 2. The intensity of failures is the ratio of the number of failed objects per unit of time to the average number of objects, which continue to work properly in a given time interval is:

$$\lambda = \left[\frac{\Delta n(\Delta t)}{N(t) \cdot \Delta t} \right] \tag{1}$$

where:

$\Delta n(\Delta t)$ – the number of object failures during the time interval from $(t - \Delta t/2)$ to $(t + \Delta t/2)$;

$$N(t) = \frac{N_{i+1} + N_i}{2}$$

N_{i+1} – the number of properly functioning objects at the beginning of the time interval Δt;

N_i – the number of properly functioning objects at the end of the time interval Δt.

Analysis of data shown in Figure 2 points to three characteristic periods (zones):

I – adjustment, as a period of failures with the reduction in their intensity, when design, construction, and installation defects are revealed;

II – normal work with mostly random failures;

III – the age-related intensity of failures.

This regularity of failures intensification is associated with the strengthening of the degradation processes of the offshore facilities' structural material aging and corrosion, first of all, stress corrosion cracking (Lin et al., 2019; Shabakhty, 2011) and local types of corrosion, in particular, pitting (Fatoba et al., 2018), etc.

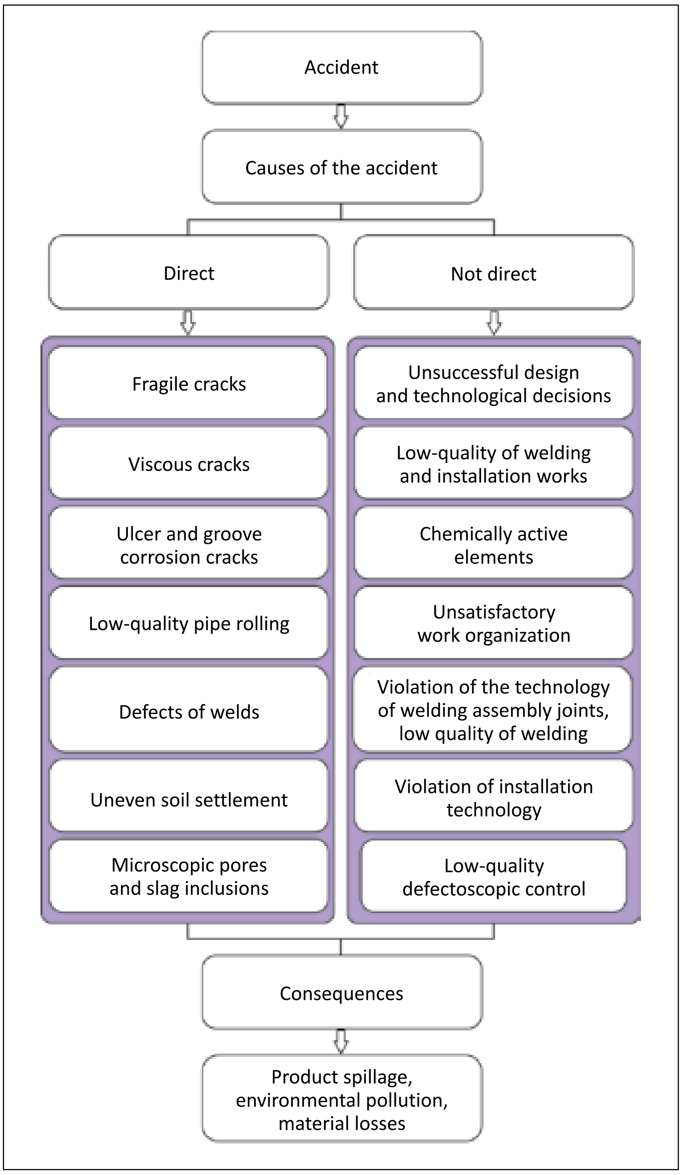

Figure 1. Analysis of causes and consequences of ODPs accidents

Rysunek 1. Analiza przyczyn i skutków awarii morskich platform wiertniczych

The experience of operating ODPs over a long period shows that it is possible to both prematurely exhaust the design resource (40–50 years), which manifests itself in the failure of steel supporting structures (Ibrion et al., 2020), and trouble-free operation of objects after the end of the established (design) terms of exploitation.

It is seen that with the aging of offshore engineering structures, the number of defects grows (Ibrion et al., 2020). A significant part of them exceeds the maximum allowable sizes. However, the main part of all failures is caused by stress corrosion cracking (Lin et al., 2019; Shabakhty, 2011) and local types of corrosion, in particular, pitting (Fatoba et al., 2018) (Figure 3).

The above-mentioned data indicate the relevance and importance of the problem for increasing the corrosion-mechanical

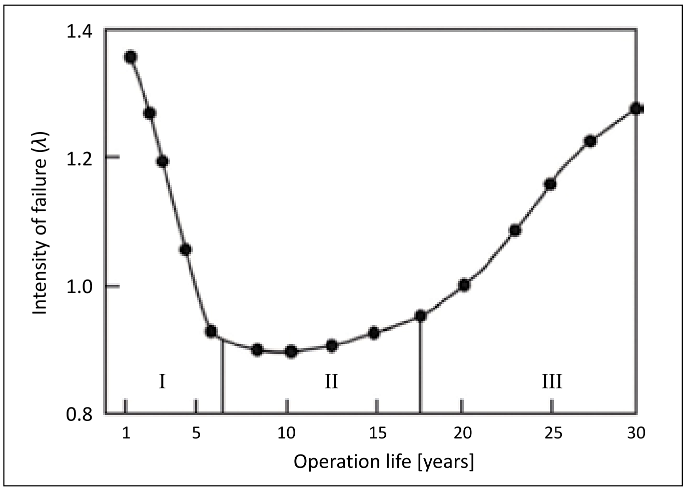

Figure 2. Intensity of failure (λ) vs operation life of the offshore structure (Kopey, 2018)

Rysunek 2. Intensywność uszkodzeń (λ) a żywotność konstrukcji morskich (Kopey, 2018)

resistance of long-term offshore engineering structures in aggressive technological environments.

At the same time, it is worth noting that offshore oil and gas production has recently become an important direction for the growth of national energy security for several states (Li et al., 2022). This determines the rapid development of several key basic technologies through theoretical research, as well as their practical investigation and testing. In addition, the need for the development of new equipment and the development of methodology for assessing the strength of the structure (Lin et al., 2019) and for monitoring the fatigue of stationary offshore platforms (Piedras Lopes and Ebecken, 1997), as well as for the use of new structural corrosion-resistant materials, is becoming obvious.

The authors expressed the opinion that the main causes of platform accidents include the distortion of the pipe columns' shape and shells due to the low quality of their installation or poorly executed foundation; the influence of low ambient temperatures; the vibration effect of pumping units, and drilling rigs during liquid production and pumping; erosion of the bearing layer of the base by the liquid in case of damage to the bottom of the platform; corrosion, as well as uneven base settling and local subsidence of the base, and the failure of welded joints (Ibrion et al., 2020). It is known (Cwiek, 2005) that a welded joint consists of a base material, a weld seam material, and certain thermal influence transition zone. Then, from the point of view of (electrochemical) corrosion, it can be considered a complex multi-electrode system. In such a system, a whole spectrum of often competing physical and chemical processes can occur with varying degrees of probability. These processes lead to the degradation of the mechanical properties of the welded joint as a result of intensive anodic dissolubility

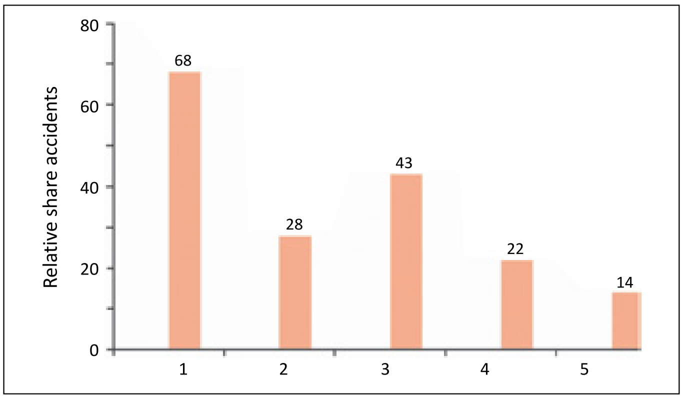

Figure 3. The relative share of ODPs accidents with a long service life (40–50 years) during 2010–2021: 1 – corrosion damage under stress; 2 – defective plant-produced hull steels; 3 – local corrosion; 4 – corrosion-fatigue damage; 5 – general corrosion of the inner surface of pipe walls and shell containers (Kopey, 2018)

Rysunek 3. Względny odsetek wypadków na morskich platformach wiertniczych o długim okresie eksploatacji (40–50 lat) w latach 2010–2021: 1 – uszkodzenia korozyjne pod obciążeniem; 2 – wadliwe stale kadłubowe; 3 – korozja miejscowa; 4 – uszkodzenia korozyjno-zmęczeniowe; 5 – ogólna korozja wewnętrznej powierzchni ścian rur i zbiorników płaszczowych (Kopey, 2018)

of the material (the appearance of pitting, corrosion ulcers, etc.), as well as by hydrogen embrittlement of the welded zone (acceleration of the processes of microcracks formation, nucleation, and development of macrocracks).

Failures of offshore structures which allowed to distinguish the typical causes of the platform failure are described in general in (Shabakhty, 2011; Holand and Awan, 2012; Ibrion et al., 2020):

1. The influence of low temperatures on the physical and mechanical properties of offshore facilities' metal structures.
2. Violation of the Rules for the ODPs technical operation, i.e., production and transportation of oil and gas products at a rate exceeding the maximum throughput capacity of oil and gas pipelines; filling the shell containers with oil with high gas content and light fractions of hydrocarbons; violation of technical inspection frequency of main structural elements of offshore surface, underwater structures, and others.
3. Corrosive wear of the bottom of the platform from the inside in the seawater environment, from the outside – due to the violation of the hydrophobic layer of the insulating coating, which results in the flow of oil products and the erosion of the bearing layer of the base.
4. Defects in welded joints and curving of the pipe support shape caused by insufficient quality of their installation or improperly prepared base.
5. Some steel brands' propensity to brittle fracture at low temperatures.

It is known that over recent years, up to 60–75% of all damages and failures of offshore engineering facilities' steel structures have occurred due to the corrosive-mechanical influence of an aggressive environment and force loads (NACE SP0176, 2007; Abbas and Shafiee, 2020 and long-term observations). This means that the issues of corrosion-mechanical failure of such structures have become an industrial-scale problem. The lower levels of pipe foundation structures and their welded joints are most susceptible to specific corrosive and corrosive-mechanical damage under working environments and force influences.

It was established (Syrotyuk and Dmytrakh, 2014) that during long periods of operation, the inner and outer surfaces of metal structures and shell containers are exposed to corrosion-mechanical failure caused by the influence of variable deformations and the working environment.

In most cases, emergencies in some sections of structures are associated with the corrosion of pipe structures of ODPs and similar engineering structures as a result of chemical interaction with a corrosive environment (NACE SP0176, 2007; Shcherban and Mazur, 2022). Thus, researchers focus mainly on the development of technological methods for increasing the corrosion-mechanical stability of steels which are used in manufacturing offshore platforms. For example, such methods as forming various types of coatings (Little et al., 2008; Lin et al., 2019; Abbas and Shafiee, 2020), diffusion nitriding, alitization, chrome plating, as well as plastic deformation (in the process of manufacturing hull profile steels), high-frequency current surface hardening, creation of surface layers for sheet steel of specific structures not etched by acid, use of inhibitors, microalloying of steel with modifying impurities, etc.

As it is known (Standard DNVGL-ST-F101, 2017), the regulatory and technical documentation governing the construction and operation of oil and gas industry metal structures of ODPs implicitly assumes the stability of the mechanical properties of the metal over a long period of operation. At the same time, both steel and reinforced concrete structures are known to degrade due to years of use. In particular, the degradation of metal (pipe steels and reinforcing rods) during the operation of drilling platforms is revealed during impact strength tests carried out in harsh conditions. That is the presence of a sharp stress concentrator, the influence of a corrosive-active environment and hydrogen, etc. at low test temperatures.

Conclusions

1. The analysis of literary sources showed that during operation, reinforced concrete and steel structures of ODPs are subject to degradation, change of strength characteristics,

and accumulation of defects and damages. It was established that corrosive wear, corrosion-mechanical processes, and crack-like defects are the decisive causes of structures failure.

2. Improvement of the system of steel ODPs maintenance involves the development of new models and methods of managing the operational reliability of these structures, aimed at decision-making taking into account the crack resistance and fatigue-corrosion strength of steel ODPs in contact with the corrosive-active environment. Only by using such models, scientifically based and economically rational strategies for carrying out revisions of the ODPs technical condition can be formed, ensuring the necessary level of their reliability during the operation period.

The obtained results can be used to predict the reliability and durability of offshore reinforced concrete and metal structures.

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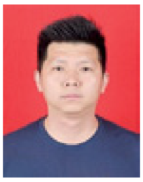

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