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FIRE RESISTANCE OF OFFSHORE CONCRETE STRUCTURES

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A B S T R A C T

Offshore platforms are constructed in marine environments and designed with special criteria to ensure structural adequacy against environmental conditions. Unexpected factors during the construction and operational phases can impose an extra load on the platform, which may lead to the deterioration of the structural performance. This study focuses on reviewing how these factors induce further loading, such as the effect of fire on a concrete offshore platform. This study considers a case study approach regarding the effects of fire, which acts in conjunction with all other real-life loads that the platform can face. In the modeling, a heat transfer analysis was carried out using DIANA finite element analysis software. The analysis results indicated that the fire resistance of the structure increased almost linearly with an increase in the wall thickness. The increase in wall thickness allows the structure to be exposed to fire to withstand heat for a longer period, thereby enabling the structural elements to resist the fire more effectively. Moreover, the fire duration has been identified as a key factor in determining the overall performance of a structure. As the fire duration increased, significant increases in both the compressive and tensile stresses were observed in various segments of the structure. These mechanical stresses, induced by high temperatures, play a critical role in maintaining the structural integrity and help explain the differences in performance during a fire. The results obtained are expected to contribute to a better understanding of the effects of fire on offshore design, assessment, and construction.

Keywords: fire; thermal analysis; finite elements; fire modeling; offshore fire; spalling; concrete fire analysis; DIANA FEA.

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Introduction

Modern industries consume large amounts of energy which are partially accommodated by means of offshore oil and gas platforms. Offshore installations are designed to extract hydrocarbons from the seabed in the most efficient way in terms of structural integrity and cost efficiency. The critical factors that determine the design of the platform include the water depth where the installation is to be located, environmental conditions, and the function of the platform. There are two main types of platforms: mobile and fixed, which are usually made of steel or concrete. The mobile platforms are placed on the surface of the water and thus can heave in waves, wind, and currents, whereas the fixed platforms are attached to the seabed or held in place by heavy concrete structures.

Condeep platforms are normally used in deep waters for longer periods of time. The main advantage of Condeep platforms is that they can accommodate storage reservoirs inside the structure. These platforms have hollow legs that are insulated from severe environment of the sea or ocean. Therefore, equipment can be installed inside the structure. In contrast, one of the disadvantages of steel platforms is that the weight of the production equipment and living quarters can be a limiting factor, unlike in Condeep structures, where this is rarely a problem. Condeep platforms are essentially composed of storage cells, towers, and deck structures [1-3] and have steel skirts that make them more stable and efficient. Running below the tips of the skirts is a steel pipe dowel that protects the skirt tips during installation. The three main functions of skirts are to improve the stability at the foundation, to prevent scour or erosion by holding the structure in place, and to enable the use of empty space inside the structure for storage and operation processes [4].

Number of researches demonstrate that nearly half of the largest offshore accidents involve fires, either as a cause or as a chain of adverse events. Furthermore, approximately 40% of the fatalities occurred in accidents involving fires, and in almost all cases of blowout occurrence, fires occur through the ignition of released hydrocarbons [5]. In cases where an accident is expected to occur, the demolition, fragmentation, crushing, disposal, and recycling of offshore structures are

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theoretically possible. However, such demolition has never been performed on offshore structures. Failure at any stage of the refloating, towing, or modification process results in severe consequences, including loss of life, health hazards, environmental damage, and huge economic losses [6].

The structural failure of concrete under fire conditions depends on several factors, such as the nature of the fire and the status of load bearing at the time of fire; therefore, different forms of structural failure are possible with respect to this variability. The tensile strength might be exceeded in concrete, which would lead to a decrease in the resistance of the material to other forces that would arguably take the material into the state of bending or stretching. The other is the strength loss in the bond of concrete to steel reinforcement, which results in a weaker acceptable level of structural strength and impending failure. Furthermore, the tensile strength of concrete in shear or torsion decreases, reducing its capability to resist external forces that tend to cause the construction to slide sideways or twist. Fracture energy reduction is brought about by other significant concerns, since this drastically affects the ability of concrete to carry applied loads directly. Finally, concrete spalling (i.e., the falling of layers of concrete from surfaces) leads the embedded framework structure vulnerable to more damage with decreased durability [7]. The induced mechanical and thermal stresses, along with pore pressure, that lead to spalling, are generally explosive and critical regarding the integrity of the structure. It usually takes place at high temperatures but has been observed in some cases as low as 200 °C. There is, however, an extreme risk involved with spalling since it might cause layers of concrete to break away from the surface, thus exposing the underlying structure to further damage and causing reduced durability and stability of a concrete structure. This directly implies that spalling issues must be factored in when designing concrete structures to be fire-resistant [8, 9]. Generally, the mechanical behavior of concrete is better during exposure to high temperatures than after cooling, while the opposite is true for rebar. When compared to concrete, rebar is more sensitive to high temperatures, with degradation already occurring at approximately 300 °C, while concrete experiences sharp degradation starting from approximately 400 °C only. The bond strength between the concrete and steel bars at high temperatures also varies depending on the type of rebar; plain bars indicate a far more highly reduced bond strength compared to deformed bars [10].

Because offshore platforms are always in contact with flammable substances such as oil and natural gas, the possibility of fires is higher in such structures [11]. More precisely, Condeep-type concrete structures not only provide storage areas but can also accommodate various operations inside the columns. Hence, the possibility of internal fire in these elements under the influence of human and other factors cannot be disregarded.

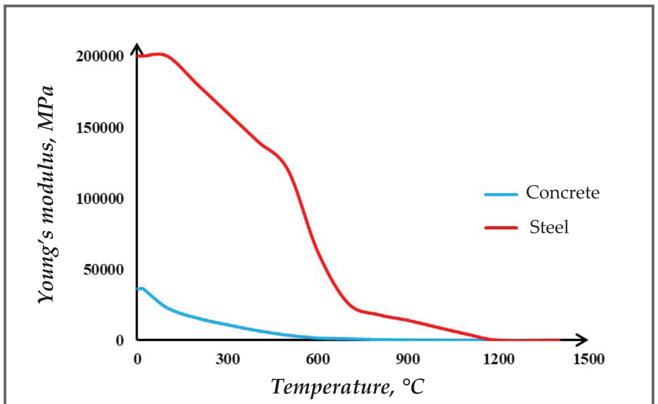

Fig. 1. Young's modulus and temperature relationship of concrete and steel

In this study, finite element (FE) method was used to analyze the interaction of internal fires emanating from columns on the general performance of a Condeep-type offshore platform structure. This research was conducted as a case study on an already-constructed Monopile Draugen platform in Norway [12, 13]. The Draugen Condeep platform rests on the seabed at a depth of approximately 250 m and operates the Draugen Oil Field. Its concrete gravity base, rugged in this rough North Sea environment, withstood strong winds and waves throughout the years [12]. Several studies have described in detail how its cross-sectional area and wall thickness vary with the depth of the water, elaborating on how the platform changes to tune the increasing depth of the water and the resultant effect of such changes on the structural soundness and modes of the column [14].

In this study, all loads and environmental effects of the platform are considered, and the fire action on the holding column is studied at different time instances to understand its influence on the total behavior of the structure. On this basis, the actual performance of the structure during and following the fire was modeled for the intensity and period of burning; it revealed the effects of fire on the structural system of the platform.

2. Case Study

2.1. Modeling of the structure

In this case study, the Draugen Monopile Condeep platform was modeled using the DIANA FE software [15]. The monopile has varying wall thicknesses with base cross-sectional diameter of 45 m which gradually decreases to 15 m above the water level, and to 26 m just below the deck in the model. The wall runs from bottom to top, with thickness varying appropriately from as high as 1.9 meters at the lowest point to as low as 0.7 meters at the top [14]. The compressive strength of concrete is 60 MPa to provide adequate resistance against all harsh underwater conditions. The tensile strength of the reinforcement and post-tensioning steel are 676 and 1860 MPa, respectively. For the details of the members used in the modeling, circular hollow sections are designed with a longitudinal reinforcement of 25 mm in diameter and circular reinforcement of 8 mm in diameter. In addition, the diameter of the tendons to be used in the post-tensioning process is 45 mm. For concrete, the thermal expansion coefficient, thermal conductivity, and thermal capacity are used as 0.00005, 1.32 W/m°C and 2.3e+6 J/m^3°C respectively. Young's modulus for concrete and steel are considered with variations in temperature, as presented in figure 1, and the analysis was performed based on these considerations.

3D solid elements were used to provide adequate realism and stability in the structural simulation of the FE model. Hence, the modeling approach can more precisely depict the mechanical properties of the structural elements and their interactions [16]. A post-tensioning tendon is one of the basic components applied in the model, together with conventional reinforcement, to enable proper cohesion of the segments and considerably improve overall structural performance. The keyword «embedded» had been used in the DIANA software, which relates the reinforcement and concrete closely so that an accurate problem of their complex interaction could be formulated. It is considered that a fire takes place and spreads through the depth of the structure, followed by an extensive investigation concerning the manner in which the fire influences the entire monopile (fig. 2a). This case study examines the extent to which fire can penetrate an overall column structure and evaluates the strength and safety of the structure under such conditions.

The modeling methodology for the analysis in this study consists of a progressive refinement of the overall modeling approach to provide insight into the general behavior of the platform under mentioned fire scenario. The first model developed is based on representing the whole platform structure, with figure 2b showing the first model developed for this purpose. At the next level of refinement, a more detailed dynamic interaction analysis between the structure and surrounding fluid environment was carried out by immersing the platform in the actual fluid domain, as illustrated in figure 2c. Longitudinal reinforcements and stirrups were strategically arranged within the structure in a double-row configuration; tendons were carefully designed to span the entire length of the platform, as shown in figure 2d. The approach provides better structural integrity and durability of the platform and hence improves its performance with respect to fire impact.

2.2. Loads and impacts

The structural response assessment is a requirement in the design of offshore structures which underpins regulatory requirements by determining design loads for direct calculations. For a particular application in an offshore project, an appropriate concrete structure type is chosen based on site conditions, structural requirements, and cost effectiveness to ensure the safety and economic viability of the structure [17, 18].

The first of the major forces acting on underwater structures is hydrostatic pressure. The Draugen platform is designed to lie at a depth of approximately 250 m and the hydrostatic pressure increased linearly with the depth of the water forming the largest load on the structure [19].

Offshore structures experience dynamic wind forces within the marine environment, which give rise to large stresses created within structures. Wind flow and offshore structures interact with one another. This interaction consequently leads to wind-induced stresses, which in turn act on the outer surface and the internal elements of the structure. Wind loads that act on the Draugen platform are calculated according to the recommendations that are made in the DNV-OS-C502 [20, 21]. Wind speed is generally chosen as one of the most critical parameters for driving the dynamics of wave-induced loading in marine environment. This implies that wind speed is the most representative statistical parameter that has been extracted from a multi-decadal dataset compiled in such a way as to produce a smooth joining of the data along the four principal compass directions. This study considered the wind speed statistics dataset for 10 years acquired in Meteoblue 2022 obtained from the Meteoblue dataset API [22]. Wave loading calculations were performed using a maximum wind speed value of 24 based on site-specific data. Wave loading was performed using the classical Morison equation [23, 24].

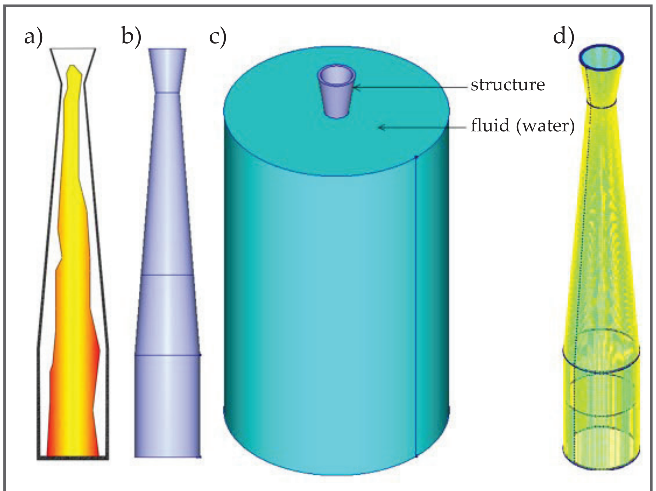

Fig. 2. DIANA FE model of Draugen Condeep platform: a) Fire analysis model, b) Main structure, c) Fluid – structure interaction model, d) Reinforcement model

It is stated in DNV-OS-C502 that platforms should be analyzed using at least one of the spectrum or time-history dynamic analysis methods [21]. As Norway is a non-seismic country, it is only necessary to design platforms that will perform adequately under a Strength Level Earthquake (SLE) scenario. In the present study, seismic analysis of the structure was performed using spectrum values relevant to Norwegian data [25] in which the response reduction factor was set at 3 for structures of this type, according to the guidelines provided related studies [26, 27]. During the analysis, in addition to the own weight of the structure's own weight, additional loads on the top of the structure resulting from the living spaces, devices, and other construction elements were also taken into consideration as dead load. The total of these loads is estimated to be approximately 27800 tons [12].

2.3. Theoretical framework of the analysis

In this study, a heat transfer analysis for heat flow was conducted as part of the analysis phase to evaluate the performance of the structure with respect to its fire resistance. In the present study, the temperature boundary condition was initially set to 1 °C, which increased linearly at certain time intervals up to 1400 °C. The boundary conditions were correlated with time for transient analysis. For each case, a linear diagram scan was carried out with respect to the multiplication factor of the boundary conditions in relation to a certain time interval, and the overall boundary conditions at any one time were assumed to be a superposition of all the multiplied interpolated factors relating to the conditions. The geometry and size of the element were modeled using the FE mesh of the general flow continuity elements. Specific formulas were used to determine the conductivity coefficients (k) of the elements. The volumetric capacity (c) is required only for transient analysis and is always isotropic [15]. Conductivity, and volumetric capacity, were considered either constant or variable, with the variable property being a function of potential, namely temperature or concentration, time, or both, as formulated in Equation 1.

$$\begin{cases} q = -k(t, \Phi) \cdot \nabla \Phi \\ q_V = c((t, \Phi)) \cdot \dot{\Phi} = c \cdot \dot{\Phi} + \beta \cdot \nabla \Phi + div\, q \end{cases} \quad (1)$$

Where, Φ is potential, q – specific flux vector, k – diffusivity tensor, β – field connectivity vector, t – time interval and c – volumetric capacity

The heat flow transfer equation is transformed into a form that can be applied to the FE method. Therefore, the Galerkin procedure was used to solve this equation [28]. One of the most common methodologies for obtaining numerical solutions of differential equations in FEM is the Galerkin procedure. The working principle involves constructing the weak form of the original equation and integrating it using the appropriate weighting functions. It is a discretization of the continuous problem into a set of finite elements that must be solved numerically. In this method, the analysis domain is divided into small elements, and equations are formulated for each element. The formulated elemental equations were assembled to obtain a global equation system for the entire structure [29-31].

$$\int_V v \cdot q_V dV = \int_V v \cdot \left(c \cdot \dot{\Phi} + \beta \cdot \nabla\Phi + div\, q \right) dV \qquad (2)$$

Where, q_V is external flux per volume.

Assuming the FE is the potential field and the test function, we take it to vary linearly with the values of the element at its nodes. This allows us to model complex fields in a simplified way by expressing them in terms of the value of the nodal points, thus making the FE Analysis more tractable. Let u be the vector of the nodal potentials. The components of u are the potential values at the nodes of the element under consideration. Similarly, the components of v are the values of the test function at the element nodes. The potential field within an element can be defined in terms of interpolation functions, which are often referred to as shape functions. The interpolation functions provide a relationship between the nodal values and values at any point within the element. If we denote the interpolation matrix by it follows that the potential field Ø at any point within the element can be expressed in terms of the shape functions contained in N and B:

$$\Phi = Nu \qquad \& \qquad v = Bv \qquad (3)$$

Where, N is interpolation matrix for the shape function, B is interpolation matrix for the test function, u and v are vector of nodal potentials.

After proper placement of the relevant equations, the FEM equations for the heat flow analysis were derived. Therefore, the mathematical expressions and boundary conditions required to model and analyze the thermal behavior of structural elements were established at this stage. This provided an opportunity for a detailed examination of the heat transfer process within the system.

$$Q = K_\Phi + C_{\dot{\Phi}} \Rightarrow$$

$$\Rightarrow \begin{cases} C = \int_V N^T \cdot c \cdot N dV \\ K = \int_V B^T \cdot k \cdot B dV + \int_V N^T \cdot \beta \cdot B dV + \int_B N^T \cdot K \cdot N dV \\ Q = \int_V N^T \cdot q_V dV + \int_B N^T \cdot q_B dV + \int_B N^T \cdot K \cdot \Phi_E dV \end{cases} \qquad (4)$$

Where, K is conduction matrix, C is capacity matrix and Q is external flux vector.

A certain temperature field was used as an initial estimate of the solution for nonlinear state analysis. At this stage, this estimate, taken as the initial temperature field within the transient analysis, was used as the starting point for all analyses regarding heat flow. The Diana program considers the conductivity of model properties and boundary conditions as the default settings. The capacity was also taken as the default within the transient analysis.

3. Result and discussion

The primary objective of this study is to evaluate the fire resistance of concrete structures in marine environment. The case study considered in this research was the Draugen Condeep platform. In this study, the fire resistance performance of an existing structure was evaluated under all loads and impacts to which it is subjected.

During the analysis, it was assumed that the fire was uniform at all depth locations of the structure for which the interior walls were being studied. This assumption was intended to facilitate an easy comparison of fire effects at all depths of the structure in the comparison and analysis process. Observations show that the temperature variations within the structure are characterized by marked differences along the depth of the structure. Specifically, with thicker walls, it was observed that the heat-flux capacity of the fire was reduced in its ability to transfer to the exposed surface of the wall. This capacity was observed to degrade when the experiments were performed across the thickness of the building. For instance, studying various wall thickness relative to the depths, at thicker walls, the values of temperature imposed on the outside of the structure are also lower. Figure 3 illustrates that, for the platform temperature at the bottom (t=1.9 m), the average temperature is approximately 500 °C, whereas at the top of the platform on the surface of the outer wall, it is approximately 1100 °C in this type of fire scenario. These results clearly reveal the importance of wall thickness in terms of heat transfer performance in fires.

The heat conduction in the wall of the structure during a fire, with time-dependent Cauchy stresses, contains adequate information on the effect of the fire on the structure. By studying the evolution of the Cauchy stresses distribution over time acting on the structural part above water (t=700 mm) and diffused through the wall, one gradually realized that the stress in the fire-affected wall already amounts to approximately 25 MPa within the first hour, and that this value increases to close to 52 MPa in the following hours (fig. 4). On the outer surface of the wall, the stress increased from an initial value of approximately 10 MPa in the first few stages

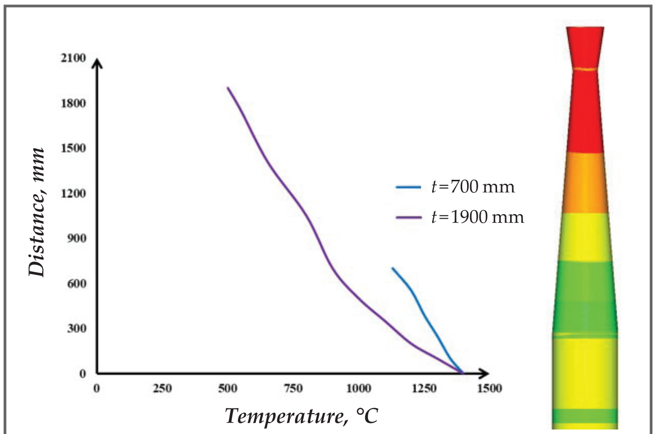

Fig. 3. Temperature distribution over the thickness of the wall

of the fire to approximately 20 MPa after 5 hours. The results show that the early failure locations in the structure can predict the direction of cracks in the concrete in terms of stress and distance from inner. Moreover, in thicker walls, fire-induced weakening and corresponding concrete cracking take a longer time to occur. Therefore, because the wall is thicker at the bottom of the platform (*t*=1900 mm), it can be assumed that in this area, the impact of the fire will be less critical. However, because this is the area where greater stresses develop under any other form of load, the conditions for the augmentation of the overall stress can also be satisfied.

In the case of a fire, with increasing temperature, the profile of Cauchy stresses along the depth of the structure sheds important light on how the structure that is exposed to the fire will behave. As shown in figures 3 and 4, one of the major parameters controlling heat diffusion in the structure is its wall thickness. In this context, assuming that the fire affects the interior structure parts homogeneously according to the results of the nonlinear analysis, it is observed that stress, regarded as negative compression stress, reaches the maximum value at the top of the structure (*t*=700 mm), as shown in figure 5a. Furthermore, owing to both the combined fire and other loads, the tensile stress attains a maximum value at the point at which the cross-section of the structure begins to narrow down, as can be seen in figure 5b. This is primarily because the internal compressive stress developed within the structure owing to the fire weakens the wall to a certain extent; therefore, looking at this lateral face, it will obviously be under tensile forces. It follows that both the region where the cross section starts to decrease, and the most highly stressed region of the reduced cross section are in tension. As the temperature increased, the maximum Cauchy stress distribution along the depth of the structure (fig. 5c) occurred according to a parabolic shape, creating a «mirror» effect between the compressive and tensile values. Even though these stresses do not appear at the same points and are not of the same value, this phenomenon provides very accurate information about the general behavior of the symmetric structure.

In this study, a detailed analysis of offshore concrete structures exposed to fire was conducted. This research is aimed at analyzing the performance of structures under fire conditions, identifying critical fire performance criteria, and modeling the capacity of structures in high-temperature scenarios. This study established that after exposure to fire, there is a sharp drop in the reliability index of structures [32]. However, the reliability index decreased asymptotically with time.

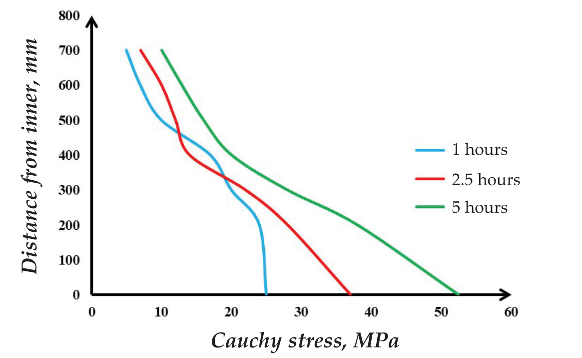

Fig. 4. Cauchy stress distribution over structure wall thickness

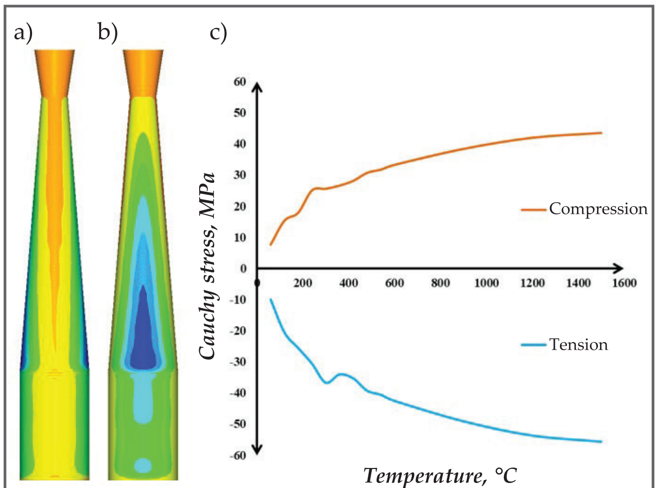

Fig. 5. Cauchy stress distribution along the structure: a) Front view, b) Side view, c) Temperature-dependent stress distribution

Conclusion

This study thoroughly investigated the fire performance of offshore concrete platforms, with a focus on how fire, in combination with operational loads and harsh environmental conditions, impacts structural integrity. Using the Draugen monopile platform as a case study, heat transfer analysis was conducted with DIANA FE software, converting analytical heat transfer formulas into finite element methods to model temperature distribution over time.

The key findings of this study are:

1. The results clearly demonstrate a nearly linear relationship between wall thickness and fire resistance. Thicker walls enhance the platform's ability to withstand prolonged exposure to high temperatures, allowing structural elements to maintain their integrity under fire conditions.
2. The duration of the fire emerged as a critical factor in determining the structure's performance. As fire exposure time increases, significant rises in both compressive and tensile stresses were observed, particularly in different segments of the platform. These temperature-induced mechanical stresses play a crucial role in maintaining the structure's overall stability.
3. The combined effects of fire and operational loads significantly influence the stress distribution within the structure. The study highlights the importance of accurately characterizing key thermal parameters such as temperature distribution, thermal diffusivity, and material degradation at high temperatures.
4. To improve the accuracy of fire performance analysis, future research should focus on refining the modeling of thermal effects and material behavior at elevated temperatures. Additionally, the development of advanced methods that effectively integrate fire-induced temperature effects with the load combinations considered in offshore structural design is essential.

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