



Article Structural Response Analysis of FPSO under Pool Fire

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Abstract: There is a large proportion of pool fire occurrence on the upper part of offshore platforms. In order to reduce the occurrence of fire disasters, the fire risk assessment of FPSOs should be carried out. According to the temperature characteristics of offshore platform fires based on computational fluid dynamics, the temperature field of the superstructure of the offshore platform under pool fire has been analyzed, the regularities of the distribution of the wall temperature of the platform of FPSO under different wind speeds are studied, and research on the distribution of heat radiation flux of different fire is made. Based on the finite element method, the structural response of the platform structure in different fire scenarios has been made. In consideration of the pool fires caused by liquid leakage of the upper part of the platform structure, with the basis of the changes of temperature field and radiation field being obtained by CFD, a structural response analysis of the offshore platform structure using the finite element method and a risk assessment method based on quantitative analysis for pool fires caused by liquid leakage is proposed.

Keywords: pool fire; risk assessment; structural response; finite element method



Citation: Zhang, D.; Zhao, B.; Zhu, K. Structural Response Analysis of FPSO under Pool Fire. *Buildings* **2022**, *12*, 1665. https://doi.org/10.3390/ buildings12101665

Academic Editor: Elena Lucchi

Received: 7 September 2022 Accepted: 9 October 2022 Published: 12 October 2022

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1. Introduction

With the rapid development of science and the economy, the demand for oil and natural gas is increasing year by year, and human beings are not satisfied with the development of land energy. As an important facility of marine resources, the number of offshore oil platforms, especially FPSOs, is increasing. An FPSO, floating production storage and offloading unit, also known as a floating production storage offloading tanker, can be initially used to store crude oil [1], and have been widely used in deep sea areas. The processing equipment of the FPSO is built into the modules and located on the vessel deck. The fluid transferred from underwater is processed into oil, gas, and water. The FPSO stores the processed oil. The processed gas is exported through an export riser or injected again into the subsea reservoir. Among all floating devices, the FPSO has functions and advantages such as strong wind wave resistance, wide water depth range, large oil storage, unloading capacity, and reuse [2]. In addition, its vessel-shaped features make it more popular than other offshore platforms such as spars and jack-ups [3].

Although this platform has many advantages, the high level of congestion caused by pipe networks and upper crude oil processing equipment poses a higher risk to the FPSO [4–6]. As the offshore platform or FPSO are far from the land, once fire and explosion accidents occur, it is difficult to conduct a timely rescue, which results in disastrous loss [7]. The UK health and safety research report shows that fire accidents are the most common of all marine accident reports and blowouts [8]. Pipeline leakage, ship collision, structural failure, and other accidents can lead to a fire. A pool fire is a kind of fire that is common in marine fires. It has a large scale of combustion and is difficult to extinguish. When a fire occurs, the platform structure of the FPSO is completely exposed to fire, the temperature of the structure rises, the elastic modulus and yield strength of steel decrease, and the bearing capacity of the platform will be reduced. All of these factors can lead to the collapse of the platform and make the entire FPSO invalid.

The fire load was first defined in the structural fire protection, which laid the foundation for the quantitative assessment of fire. Anderberg [9] defined the fire load of the steel structure through the risk assessment method and then conducted a limit analysis and collapse analysis of the whole platform and gave the fire analysis program. Ruert A. and Schaumann P. [10] conducted the fire resistance test of different steel structure frames; through the analysis of a large number of data fitting, the temperature distribution of various forms of frame structure was calculated and the failure temperature of different structures was obtained which provided reference data for the analysis of fire resistance of steel structures for later scholars. Walker et al. [11] evaluated marine structures for fire safety and being explosion-proof, the overall structure and components were analyzed, the structural dynamic response analysis under fire and explosion was obtained, and the deformation analysis and structural dynamics under the temperature and pressure time curves were conducted. Tolloczko [12] proposed some general situations for fire research which should be used for marine structures and studied the dynamic response of structures under fire loads. Wingerden et al. [13] conducted analysis through the principle and method of computational fluid dynamics (CFD) and developed special analysis software for the risk of fire and explosion of platform structures. Soares and Shetty [14] firstly applied the joint probability method to the fire risk assessment of offshore platforms and applied it to the passive fire protection design of the superstructure. From 2008 to 2010, Pusan National University, Nowatec AS, and other research institutions studied fires and explosions of upper deck modules of FPSOs based on the CFD principle and the nonlinear finite element theory and established an integrated analysis and evaluation system [15].

In the past 30 years, offshore oil engineering accidents caused by fire and explosion have occurred frequently, which not only led to casualties and economic losses but also caused damage to the marine environment. Given the serious consequences, it is necessary to model accident scenarios and their consequences in order to assess and manage fire risks in such situations. In recent years, considerable efforts have been made in maritime fire modeling and risk assessment. Kim et al. [16], for example, evaluated the load characteristics of steel and concrete tubular members under jet fire. To obtain reliable load values, jet fire tests were carried out in parallel with a numerical study. Paik et al. [17] described a few procedures for the quantitative assessment and management of fire and gas explosion risks in offshore installations. Kim and Paik [18,19] studied the feasibility of applying the computational fluid dynamics (CFD) method for the analysis of fire heat flow in an FPSO upper module, taking into account wind effects. The CFD results agreed well with the experimental results. Luketa [20] and Vasanth et al. [21] studied the characteristics of two fire pools with fuel surfaces at different elevations using CFD. Sun et al. [22] studied the load characteristics in process modules of offshore platforms under jet fire conditions. The effects of different parameters on the load characteristics of the considered scenarios were discussed. Betteridge and Steven [23] described an empirical model to account for the reduced pool fire size and discussed the effect of water on combustion. Wu et al. [24] derived the available safe evacuation time estimation equation by simulating the fire development process using a fire dynamics simulator field model. Yi et al. [25] and Ahmadi et al. [26] established a CFD model to accurately predict the incident radiation of large LPG pool fires and the consequence of large-scale pool fires in storage terminals, respectively. Xu et al. [27] introduced a quantitative risk assessment method for offshore platforms exposed to gas explosions. Bhardwaj et al. [28] proposed a methodology for risk assessment and probabilistic modeling of fire and explosion accidents in FPSO. Li et al. [29] focused on the use of CFD to simulate the fire risk of offshore facilities caused by subsea gas release.

According to the literature, past studies mainly concentrated on the characteristics of fire occurrence and the assessment of the damage caused by fire; the structural response of an FPSO caused by a fire load and explosion was seldom reported in the literature. In fact, the high temperature of a fire will cause the platform steel structure to lose its structural

capacity and result in large deformation, and the blast wave of an explosion can cause devastating damage to life and equipment. Therefore, a detailed study of fire risk assessment and structural response analysis of FPSO is urgent for developing safety measures.

In this paper, based on the finite element analysis software ABAQUS, a finite element analysis of the response of a platform structure in different fire scenarios has been made. In consideration of the pool fires caused by liquid leakage of the upper part of the platform structure, with the basis of the changes of temperature field and radiation field being obtained by CFD, the structural response analysis of the offshore platform structure is made by ABAQUS using the finite element method. The novelty of this paper is to present some results and analysis to reveal the impact of pool fires on offshore platform structures. The wall temperature of the FPSO under different wind speeds and the distribution of heat radiation flux are studied. The structural response of the offshore platform caused by a pool fire is analyzed. The rest of this paper is organized as follows: Section 2 presents some principles of fire risk assessment for FPSO. Section 3 presents the simulation modeling of pool fires and analyzes the flame shapes, temperature field, and heat radiation of a pool fire under different wind speeds. Section 4 illustrates the structural response and mechanism of FPSP under a pool fire. Besides, the validity of the numerical method is verified in this section. Finally, Section 5 summarizes the conclusions drawn from this work.

2. Principle of Fire Risk Assessment for Platform Structure of FPSO

2.1. Fire Types

Quantitative risk analysis of marine structure fire assessment includes deck fire and fire in the sea. The most serious structural unit of the offshore platform fire is the deck structure, so a platform fire risk assessment usually takes the fire on deck into consideration. Types of fire include pool fire, jet fire, ball fire, and flash fire. As the operating conditions of the offshore platforms are different, the fire types are different. When the leakage is liquid, a pool fire usually occurs.

Offshore platform fire is mostly hydrocarbon fire, the heat of the fire is large and the release is fast, so the temperature rise of the steel structure is fast. As a result, the strength of the steel structure decreases rapidly; when the temperature is above 600 °C the strength of the structure almost disappears. Therefore, when a fire happens to large steel structures, it is prone to distortion, deformation, and collapse. Although there are four types of platform fire, pool fire and jet fire are the main form. As oil and gas leakage occurs mostly on the platform deck, the deck structure is a typical unit affected by fire, so it is of practical significance to study the deck fire.

2.2. Pool Fire Risk Assessment Method Based on Quantitative Analysis

Risk assessment includes risk identification, probability analysis, and consequence analysis, as shown in Figure 1. When carrying out a quantitative risk assessment for offshore platforms, it makes no sense to analyze the safety of the entire offshore platform directly. First, it is necessary to identify the hazard sources of liquid leakage, which can be used to determine the fuel information. After the hazard identification, we need to determine the geometry of the structure, the pool size, the pool location, wind speed, and wind direction, which make a leak and fire scene clear. The main cause of the risk is the failure of some equipment and parts. Failure of equipment and parts will cause fuel leakage. In order to determine the probability of fire, we must first determine the probability of leakage, and the leakage probability of an offshore platform can be determined according to the failure probability of equipment and parts, as shown in Table 1 [30,31].

The probability of leakage is calculated according to the quantity of the equipment:

$$= np$$
 (1)

The assumption for the equation that the events are independent is necessary. Among them, P is the probability for some components of the leakage, p is the leakage probability for a single component, and n is the number of a certain part. If the leakage probability of

Р

1 flange is 2.34×10^{-9} , the leakage probability of the 10 flanges is 2.34×10^{-8} , the leakage probability of 1 m pipeline is 1.71×10^{-8} , and the leakage probability of 100 m is 1.71×10^{-6} .

In this paper, a method for the quantitative analysis of marine fire is put forward according to some specifications and related literature. It needs to be pointed out that this method is a pool fire scenario that is caused by liquid leakage on an offshore platform.



Figure 1. Quantitative risk assessment method for fire risk.

Table 1. Probability of different components.

Device Name	Manual Valve	Emergency Shutoff Valve	Flange	Pipeline	Pressure Vessel	Heat Exchanger
Failure Probability	$3.5 imes 10^{-9}$	$4.39 imes 10^{-8}$	$2.34 imes 10^{-9}$	$1.71 imes 10^{-8}$	$1.16 imes 10^{-9}$	8.43×10^{-81}

 1 The data in the table indicate the failure probability of the unit. The unit of the pipeline is m.

2.3. Risk Matrix and ALARP Principle

To determine the level of the risk matrix, the probability of the occurrence and the consequences of fire are put into a matrix, which is the risk matrix, as shown in Figure 2. The risk matrix is divided into three levels and the consequences are expressed in terms of temperature. Risk consequences are expressed in terms of temperature and the risk matrix is used to screen the simulated fire scenarios. I represents an unacceptable risk as a high risk, when it is at this level, further evaluation will be needed. II represents critical risk also known as medium risk. III represents an acceptable risk which means it is a low risk. This method is a rough analysis of the probability of the size and the consequences of the accident; the general calculation will ignore the effect of low risk. The analysis focuses on the medium and high risk. When it is a medium risk, the direct assessment of the consequences will be made without structural analysis.



Figure 2. Risk matrix.

The ALARP principle, as shown in Figure 3, (as low as reasonably practicable) is the principle of risk evaluation at present, which is a high degree of risk evaluation at home and abroad. It is a kind of minimum feasibility principle. If the risk is in the ALARP region, the risk can be accepted.



Figure 3. ALARP principle.

2.4. Risk Measurement

The general measure includes three aspects: personnel risk, property damage, and environmental risk of fire accident consequences. In the actual calculation of risk, the probability of the occurrence of different events should be calculated separately, and then the probability of all events will be accumulated.

Although individual risk can be used to measure the risk of death, the largest concern is the risk of the entire group of the accident, so the consequences of group risk are generally calculated by an f-N curve.

The f-N curve, as shown in Figure 4, represents the relationship between the probability of an accident and the number of casualties, the value of which is cumulative, indicating an acceptable level of risk.



Number of Casualties N



For the risk assessment method proposed in this paper, due to limited time and energy, in addition to the risk probability structural analysis of fire and temperature, the risk assessments of other aspects are not the focus of this paper, the results of which can be

found in related documents and specifications. Therefore, this paper focuses on the study of fire characteristics and the structural response analysis of a platform structure under the action of a pool fire; the characteristics of the temperature of a platform structure of a pool fire under different wind speeds are obtained by the CFD principle. The characteristics of fire heat flux are studied under different wind speeds, and the ABAQUS software is used to conduct the thermal–mechanical coupling analysis of the platform.

There are numerous possibilities for simulating pool fires of offshore platforms. Because of the numerous possibilities, the choice of a fire scenario is more complicated in the fire simulation. In order to simulate a fire, the equipment on the platform is simplified to the uniform load, which simplifies the deck model.

3. Analysis of the Temperature Field of the Platform under Fire

The traditional temperature field for the steel structure usually adopts the ISO834 standard heating curve, but the actual fire environment is different from the temperature curve. Offshore platform fires occur outdoors, where oxygen and combustion are more complete, the fire generated by heat radiation is relatively strong, and harm is relatively large [32]. The study of the characteristics of fire is the premise of the fire resistance for the structure; the temperature response of the offshore platform and the temperature changing with time seem to be the known conditions for studying the structural response of the platform. It is very difficult to calculate the temperature distribution and temperature field of the platform with the theoretical model. Therefore, the simulation of a pool fire based on FDS and the analysis of different fire scenarios of a pool fire are the key link of fire analysis and the premise of the structural response analysis, which makes it consistent with the real ones.

In this paper, the platform of the superstructure of an FPSO on active service in the South China Sea was studied. The platform has two decks. The first deck is for the oil and gas transmission area, in which the simulation of the fire caused by a pipeline leakage is made. The range of a pool fire is generally very small compared with the whole platform, so only a part of this platform was studied. In an FDS simulation, the size of the upper deck is 20 m \times 14 m \times 6 m and the size of the bottom deck is 20 m \times 14 m \times 6 m. The FPSO model is shown in Figure 5.



Figure 5. FPSO CAD model.

3.1. Simulation Principle of FDS

FDS (fire dynamic simulation) is a software based on the fluid dynamics model, which can be used for the numerical simulation of the thermal smoke propagation and spread of fire.

The large eddy simulation theory is used to simulate the turbulent motion of fire and the basic equations of the dynamic model in the fire process are as follows.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \overrightarrow{u} = 0 \tag{2}$$

Momentum equation:

$$\rho\left(\frac{\partial u}{\partial t} + \left(\vec{u} \cdot \nabla \cdot\right)\vec{u}\right) + \nabla p = \rho g + f + \nabla \cdot \tau_{ij}\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0$$
(3)

Component equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \Delta \cdot \rho Y_i \overrightarrow{u} = \Delta \cdot \rho D_i \Delta Y_i + W_i \tag{4}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h \overrightarrow{u} = \frac{Dp}{Dt} - \nabla \cdot \overrightarrow{q_r} + \Delta \cdot k \nabla T + \sum_L \nabla \cdot h_i \rho D_i \nabla Y_i + \overrightarrow{u} \Delta p \tag{5}$$

Gas state equation:

$$\nu = \rho TR \sum_{i} \frac{Y_i}{M_i} \tag{6}$$

where ρ is density (in kg/m³); \vec{u} is velocity vector, m/s; p is pressure, Pa; h is total enthalpy, J/kg; T is temperature, K; Y_i is the mass concentration of component i; D_i is the diffusion coefficient of component i, m²/s; W_i is the chemical reaction rate of component i, kg/(m³ s); M_i is the molecular weight of component i, kg/mol; R is the molar gas constant, J/(mol. K); $\vec{q_r}$ is fire heat radiation, W/m²; q is the combustion reaction heat, J/mol; k is the thermal conductivity, W/(m·K); g is the gravity acceleration, m/s²; t is the simulation time, s; τ_{ij} is the viscous stress tensor, Pa. The contribution of those existing equations and numerical procedures comes from the commercial software FDS, the same as in Section 4.1.

The flame of liquid hydrocarbons in the pool on the ocean platform can quickly spread to the entire oil pool, so the ignition process is very short. Thus, it isn't necessary to consider the ignition process, only to study the characteristics of the formation of flame.

3.2. FDS Model and Results of Pool Fire

Fire simulation is based on a real situation to simulate a virtual fire scene. The heat of combustion for liquefied petroleum gas transfers mainly in the form of heat radiation which produces a large number of CO and CO₂, resulting in a certain area of casualties and equipment damage and a large number of people's death by suffocation.

Figure 6 depicts the instantaneous temperature contours of a mid-longitudinal section of a pool fire. It was obtained through the post-processing function of the FDS software. The pool fire creates a thermal vortex at the bottom of the combustion and the small eddy draws air into the center of the flame and continues to rise as the flame rises. At the height of a small diameter of the oil pool, the small eddy begins flow separation with the fire plume and gradually disappears at a turbulent fire plume. At the height of the half diameter of the oil pool, it can be clearly seen that the flame has shrunk into a neck, which is known as the pool fire flame neck-in phenomenon. Most of the combustion will be completed in the area between where the flame neck-in phenomenon occurs and in front of a certain separation point at the height of 1–2 pool oil diameters. At the same time, a new heat vortex will be formed on the combustion surface. Due to the pulsation characteristics of the fire, it will cause the periodic generation and shedding of a thermal vortex. It is important to note that the FPSO has coamings limiting the size of pools of leaked oil. The problem with gas is not a pool fire, but a jet fire, due to the pressure of the gas inside the pipes.



Figure 6. Instantaneous temperature contours of pool fire.

3.2.1. Flame Shapes of Pool Fire

The CAD model of the entire FPSO offshore platform structure is shown in Figure 5. The simulation of a pool fire for 600 s of combustion is created by FDS. Different parameters according to the characteristics of a pool fire have been set to obtain the influence degree of different parameters on the pool fire. The fuel of the oil pool is assumed to be heptane. The pressure is assumed to be the atmospheric pressure, the ambient air density is 1.258 kg/m³, and the leakage is continuous leakage. The distribution of the whole temperature field and the flow field of the fire is unstable, but this instability is limited. The beating of the flame is going up and down at a certain amplitude, and when the fire falls into a pattern, we can choose the fire at a certain moment as the research object. The open environment condition: the temperature is 20 °C; the air pressure is 101 kPa; the wind speeds are 0 m/s, 1.5 m/s, and 3 m/s, respectively. In this paper, we only study a part of this platform and simplify it into an FDS model as shown in Figure 7.



Figure 7. The simplified model in FDS.

Figures 8–10 depict the flame shapes under different wind speeds. The flame shapes are obtained through the software Smokeview. Under the action of each single wind speed, the four instantaneous shapes of the fire development process have been selected and compared at the moment of 2 s and 10 s, and 100 s and 400 s during the fire development process. It can be found from Figures 8–10 that the flame will tilt; the greater the wind speed, the greater the tilt angle of the flame. When the wind blows, the flame is subjected to the wind force W_f along the wind direction, as the flame has buoyancy F at the same time, so the combined action of the two forces causes the flame to tilt. It can also be found that the fire spreads quickly, reaching a prosperous period of fire development at 10 s, which shows that the burning speed of a pool fire is very quick. Thus, at the beginning of the fire, personnel should be evacuated without delay. When the fuel is leaking while it is burning, the burning area will become larger and significant heat will be released. As the flame spreading direction is unknown, it can also cause more damage, especially in the vicinity of the oil pool which hasn't burnt up. Once the fire spreads, it is more difficult to keep the fire under control. It will cause inestimable damage to the surrounding equipment and buildings.

Under the action of the wind, the flame deviates from the center of the flame and then returns to the center; this is due to the return force of the flame itself which can cause the flame to become out-of-center and then return back to the central position. The interaction



of wind force and return force causes the flame to tilt significantly, destroying the symmetry of the pool fire performance, and increasing the complexity of the research.

Figure 8. Flame shapes under the wind speed of 0 m/s.



Figure 9. Flame shapes under the wind speed of 1.5 m/s.



Figure 10. Flame shapes under the wind speed of 3 m/s.

3.2.2. Temperature Field of Pool Fire

The temperature field of the flame under different wind speeds is shown in Figure 11. Observing Figure 11, it can be seen that with the increase in wind speed, there is an inclination angle of the flame when it has been in a stable state. In addition, the distribution of temperature is tilted with the inclination of the flame; the wind can change the temperature distribution of the flame area and will also change the temperature distribution of the deck



area so that the high-temperature distribution of the deck is mainly concentrated in the area downwind.

Figure 11. Temperature field of XZ plan, Y = 8 m: (a) wind speed = 0 m/s; (b) wind speed = 1.5 m/s; (c) wind speed = 3 m/s.

Under different wind speeds, when the wind speed reaches 3 m/s, the temperature of the flame can be reduced. It can be found from the temperature contours that the maximum temperature of 0 m/s and 1.5 m/s is 1000 °C, and when the wind speed reaches 3 m/s, the maximum temperature is 870 °C. Excessive wind speed will accelerate the heat exchange between the flame and air and as the speed of cold air blowing in from the outside increases, the flame temperature will be dispersed in time; therefore, when the wind speed is too high, sometimes it will not increase the temperature, but will reduce the flame temperature. The wind can bring oxygen to the flame and cause the fuel to burn more intensely and cause a more complete release of heat. The wind can also promote the heat exchange between the flame and the air, which causes the thermal vaporization of the fuel gas diffusion to become faster and the combustion to release more heat. However, with the increase in wind speed, the flame temperature will decline. This is because when the wind is too powerful it brings in cold air more quickly, causing the exchange rate of hot air and cold air to accelerate, and as a result, the temperature loss of the oil pool is intensified and the heat convection is also increased.

3.2.3. Heat Radiation of Pool Fire

Many scholars have conducted significant research on heat conduction and heat convection in fire research, however, during the development and spread of fire, heat radiation can cause other no-fire areas to catch flame and expand the fire. Offshore platform fires belong to open environment fires; the pool fire in the open environment causes the most serious casualties and equipment damage. The overturning of the platform is mainly reflected in the intensity of the heat radiation flux of the fire; the radiation heat flux is the heat radiation energy per unit area per unit time. The offshore platform is the base of marine production and operation and is also the infrastructure of offshore oil exploitation. The study on the radiation field of the pool fire has instructive significance for the measures of marine fire and the means of escape.

To obtain the size of radiation heat flux, different monitoring points are chosen for detection, the oil pool center (X = 7 m, Y = 7 m) is set up as the monitoring center, the 18 points along the X axis with an equal distance (1 m) of the oil pool are chosen as the detecting points, and the measured height is 1.65 m (assuming that the height of the person is 1.65 m). The locations of different points are shown in Figure 12.



Figure 12. Top view of detecting points.

As there is usually wind at sea, we discuss the radiation heat flux under different wind speeds. Because of the large fluctuation of the radiation heat flux, the average values of different wind speeds have been compared. The average radiation heat flux of different detecting points is shown in the figure below: the 0 point is the center of the oil pool, the right side of the pool is positive, and the left side of the pool is negative.

As shown in Figure 13, with the observation of the changes in the radiation heat flux of each detecting point, it can be found that when the wind speed is 0, the maximum heat flux is in the oil pool center. When the wind speed is 1.5 m/s, the maximum radiation heat flux is under the downwind direction with a distance of 3 m from the oil pool center. When wind speed is 3 m/s, the maximum radiation heat flux is under the downwind direction with a distance of 5 m from the oil pool center. This is because under the action of wind a large amount of heat moves in downwind, resulting in the radiation heat flux of the downwind area being higher than that of the upwind area, which also leads to the increase in the risk of the downwind direction with the increase from 0 m/s to 3 m/s of the wind speed is 0, the radiation heat flux also increases. It is also found that when the wind speed is 0, the radiation heat flux curve is symmetric with respect to the center of the pool.



Figure 13. The average radiation heat flux of different detecting points under different wind speeds.

4. Structural Response and Mechanism of Platform under Pool Fire

4.1. Simulation Principle of ABAQUS

The main component of the offshore platform is steel, and in the study of the fire risk of the offshore platform, the research of the thermal performance and mechanical properties of the steel structure at high temperatures is also an important part.

In order to better reflect the influence of the pool fire on the structural response of the platform structure, based on the FDS software to calculate the various conditions of

the structure temperature field and the environmental temperature field, the structural response analysis of offshore platforms is made using ABAQUS software, which obtains the structural deformation distribution and stress distribution of specific pool fire conditions for offshore platform structures.

ABAQUS can be used for the analysis of non-coupling heat transfer, sequential coupled thermal stress analysis, fully coupled thermal stress analysis, and thermal analysis. The stress and strain field in the process of sequential coupling thermal analysis is determined by the temperature field, but the temperature field is not affected by the stress and strain field; compared with the sequential coupling analysis, the heat transfer analysis and stress analysis are carried out at the same time in fully coupled thermal stress analysis. The study of this paper is the structural response of offshore platform structures under a pool fire, and the temperature field is obtained by FDS software, so we adopt the sequential coupled thermal stress analysis method for the simulation of the structural response and mechanism of the offshore platform structure on the FPSO. Under the action of fire, the elastic modulus and yield strength of the steel will decrease sharply at high temperatures and the bearing capacity of the platform structure will change. Based on the ABAQUS software, this paper analyzes the structural response under high temperature; firstly, the simply supported beam under high temperature is analyzed and compared with the experiment to prove the validity of the research method. Then, the structural response of the two decks of the offshore platform is analyzed.

When ABAQUS is used to create the sequential coupled thermal stress analysis, the heat transfer parameters must be set reasonably to ensure the accuracy of the temperature distribution in each position and time step. The basic theory of ABAQUS thermal stress analysis is based on the Fourier heat conduction law and the law of conservation of energy.

The energy conservation equation and the specific temperature distribution are solved by the following equations in ABAQUS.

$$\rho_s c\theta = W - I_q \tag{7}$$

where ρ_s is the density of the steel structure, *c* is the specific heat of the steel structure, θ is the temperature rate of change, *W* is the external heat, and I_q is the internal heat.

The unit area heat balance equation based on the Fourier heat conduction law in ABAQUS is shown in Equation (8).

$$Q = -\lambda \cdot gradT \cdot F \tag{8}$$

where Q is the heat flux per unit area, λ is the thermal conductivity, *gradT* is the temperature gradient vector, and F is the heating area of the steel structure. Equation (8) can also be expressed as a heat conduction differential equation just as the following.

$$\rho_s c \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left(\lambda_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left(\lambda_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left(\lambda_z \frac{\partial T}{\partial z} \right) - q_v = 0 \tag{9}$$

T is the temperature of the steel at *t* time and is the coefficient of thermal conductivity of steel, *x*, *y*, *z* are the coordinates of the structure, and q_v is the heat generated by the heat source inside the steel structure.

The steel of the platform used in this paper is Q235 steel, a homogeneous steel, meaning $\lambda_x = \lambda_y = \lambda_z = \lambda$, $q_v=0$, so the Equation (9) can be simplified to the following equation.

$$\rho c \frac{\partial T}{\partial t} - \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = 0$$
(10)

After the pool fire, the temperature change of the offshore platform structure is related to the fire time. Therefore, the transient heat conduction analysis step in ABAQUS is used to simulate the heat transfer process. In addition, the ambient air temperature change curve of the structure is obtained by FDS; therefore, the heat transfer analysis can be carried out directly in ABAQUS by the heat flow between the air and the surface of the structure, so as to obtain the temperature field in ABAQUS.

When heat conduction occurs, the structure itself has the temperature difference between *T* (*x*, *y*, *z*). The temperature difference can cause the expansion of the structure, the expansion coefficient is α_T . The physical equation of the structure due to thermal expansion is as below.

$$\begin{cases} \varepsilon_{xx} = \frac{1}{E} \left[\sigma_{xx} - u(\sigma_{yy} + \sigma_{zz}) \right] + \alpha_T \Delta T \\ \varepsilon_{yy} = \frac{1}{E} \left[\sigma_{yy} - u(\sigma_{xx} + \sigma_{zz}) \right] + \alpha_T \Delta T \\ \varepsilon_{zz} = \frac{1}{E} \left[\sigma_{zz} - u(\sigma_{xx} + \sigma_{yy}) \right] + \alpha_T \Delta T \\ \gamma_{xy} = \frac{1}{G} \tau_{xy}, \gamma_{yz} = \frac{1}{G} \tau_{yz}, \gamma_{xz} = \frac{1}{G} \tau_{xz} \end{cases}$$
(11)

4.2. ABAQUS Model and Results of Pool Fire

As it is impossible to simulate the real ocean environment by computer, the following assumptions are made. (1) The temperature of the marine environment is 20 °C and the temperature of all the structures is also at a temperature of 20 °C. (2) The strength of the joints of all the components is the same as that of the welded parts. (3) For the shell element, the temperature gradient along the shell thickness is not considered. (4) The shell element should be used for a thin structure, the temperature of the upper surface of the shell is equal to that of the lower surface of the shell, and the temperature on the surface of the shell is to be considered, but not in the direction of thickness.

4.2.1. Experimental Verification

Before making the structural response analysis, the validity of the ABAQUS method should be verified. Because of the great fire experiment cost, therefore, we can verify the correctness of the ABAQUS method with the experiment results of Southeast University by Shuping Cong et al. In the experiment, Q235 I steel beam was mainly used (it is assumed to be the ideal type, one end is sliding hinged and the other end is hinged–fixed). The beam is placed in the oil-fired furnace to be heated by the constant load, whose value is 10 kN/m. The span of the beam is 4.2 m, the height of the web is 250 mm, and the thickness is 6 mm; the width of the flange plate is 125 mm, and the thickness of the flange plate is 9 mm. The beam loading and the loading temperature curve of the beam are shown in Figures 14 and 15, respectively.

According to the experimental temperature curve, a steel beam model was built with ABAQUS. In order to maintain the consistency between the experimental model and the finite element model, the dimensions of the model are the same as that of the I-beam used in the experiment, as is the fixed form. The finite element model is established with the shell element. The first step is to create the temperature load on the beam, the second step is to apply the uniform load on the upper panel of the I-beam, and the third step is to submit the calculation.

As shown in Figure 16, it can be seen from the simulation that the displacement of the middle position of the beam is larger, which is similar to the deformation of the experimental component, which also has the largest displacement change in the middle position.

According to the finite element model and the experimental data, we can make a comparison of the maximum displacement values of the beam center position of the two methods. The results obtained by the two methods are in excellent agreement.



Figure 14. Schematic diagram of beam loading.



Figure 15. Loading temperature curves versus time.



Figure 16. The comparison between the simulation and the experiment.

Figure 17 shows that the maximum displacement of the middle position of the steel structure increases linearly with the increase in temperature when the temperature is less than 600 °C. However, when the temperature is higher than 600 °C, the displacement changes rapidly, and then the displacement variable changes exponentially with the increase in temperature. Figure 18 shows that the displacement of steel structure members is small and smooth when the time is less than 2700 s; with time, the mutation of the displacement variation occurs at 2700 s and the displacement increases sharply, which indicates that the fire resistance time of the steel structure is 2700 s.



Figure 17. Displacement-temperature curve.





It can be concluded that the finite element method can be applied to the coupling analysis of a fire temperature structure by comparison with the experimental results.

4.2.2. Finite Element Model of Offshore Platform Frame Structure

The superstructure model of offshore platform size is $20 \text{ m} \times 14 \text{ m} \times 6 \text{ m}$, including two deck structures. In order to maintain the continuity and effectiveness of numerical simulation, this simplified model is consistent with that of the fire simulation. Although the model is simplified, the most basic structural framework is retained. The vertical and horizontal support beams of each deck are Q235 steel I-beam shape, as shown in Figure 19. The height is 6 m, the material support column for Q235 steel. In order to reduce the calculation time, considering that the secondary beam is far less than the support effect of the main girder, we only set up the main girder of the deck without modeling the secondary beam.



Figure 19. Model in ABAQUS.

The analytical parameters of heat transfer (surface radiation) and interaction (surface film condition) in relation to fire heat transfer are defined in the interaction module. Before setting the conditions of thermal convection and heat radiation, the rising temperature curve of the steel frame structure must be obtained by FDS software. First of all, the upper and lower two decks should be numbered, as shown in Figure 20; then, the temperature variation curves of the corresponding observation nodes are obtained by FDS software; in order to make the results as accurate as possible, the temperature of each node in the target area is selected and then the average value is obtained, which is used for the temperature change curves of the two layers of the steel frame.

According to the observed values, 48 kinds of temperature amplitude curves are established in ABAQUS, and then the parameters of heat convection and heat radiation are defined in the Interaction module. The surface film condition is chosen to define the convection condition in the constraint condition and the convective heat transfer coefficient is 1500. It should be noted that the temperature curve must correspond to the corresponding heating area. Then the surface radiation is chosen to define the radiation condition in the constraint condition. The parameter selection method is similar to the convection condition, and the thermal radiation coefficient is 0.5.

T1	T4	Τ7	T10	T13	T16	T19	T22
T2	T5	Т8	T11	T14	T17	T20	T23
Т3	Т6	Т9	T12	T15	T18	T21	T24

Figure 20. The observation area of the deck.

To create and define the boundary conditions in the load module, the boundary conditions of the platform column are defined as fully fixed, and the initial temperature is set as 20 °C. When the heat transfer analysis is completed, it is necessary to add the mechanical boundary conditions, and the weight of the mechanical equipment on the deck is applied to the upper deck in an equivalent gravity load. After referring to the specific platform weight distribution and calculation, 8 times the equivalent gravity load is applied to the weight of the equipment, the temperature of the ABAQUS is then used as the predefined field of structural analysis, and the ABAQUS model is used to calculate the stress and displacement of the steel frame structure.

Due to using the shell element, the grid partition is quadrilateral mesh; as it is a sequential coupling analysis, the element unit type of heat transfer analysis is not the same as that of the structural analysis. Among them, the element unit type used in heat transfer analysis is Heat Transfer and the element unit type used in structural analysis is Shell.

4.2.3. Structural Response Analysis of Steel Frame Structures

Here, the structural response of the structural frame is studied when the oil pool size is 2 m \times 2 m. In order to more accurately reflect the integrity of the pool fire combustion process for frame structure strength of offshore platform steel, the total simulation time is set to be 20,000 s so that it can make sure the transfer process is thorough and closer to the actual situation.

Figure 21 shows the stress and deformation of the structure at different times. As can be seen from Figure 21, the stress and deformation of the structure increase with the time of the fire; the region with the largest deformation after heating occurs in the middle T8 and T9 area, which is the first coverage area of the pool fire combustion. The maximum deformation occurs at the bottom of the third beam. In addition, the steel frame structure begins to suffer an obvious collapse phenomenon after the fire has been burning for 8000 s; the steel in the middle part of the upper deck is broken and the other transverse members extend to both sides. During the fire, the mechanical behavior of the steel is nonlinear. Although the steel itself will not burn, its properties will change greatly at high temperatures. When the temperature is 400, the yield strength will drop to the average at room temperature. When the temperature is 600 °C, the yield strength and elastic modulus drop to one-fifth of the room temperature, and the bearing capacity has been basically lost. According to Figure 11, the temperature of the platform in the fire can reach 600–1000 °C, and the bearing capacity of steel greatly changes. During the whole combustion, the stress of steel changes and redistributes all the time. The joint position is the weak link of the steel frame in fire resistance, especially the stress concentration at the root of the beam flange

at the junction of the beam and column, which has a great impact on the fire resistance bearing capacity of the beam.

The maximum deformation can be found in the middle parts of the upper deck, which are the weakest ones in the structure. The results show that the deformation at different times after heating can be increased with the increase in time, and the maximum deformation is the area covered by the pool fire. Other parts will have different levels of deformation, just as shown in Figure 22.



Figure 21. Cont.



Figure 21. Stress and deformation at different time: (**a**) 1000 s; (**b**) 5000 s; (**c**) 8000 s; (**d**) 10,000 s; (**e**) 12,000 s; (**f**) 15,000 s; (**g**) 18,000 s; (**h**) 20,000 s.

T1	T4	T7	T10	T13	T16	T19	T22
			Coi	llapse Are	a		
T2	T5	(T8	711	T14	n 1 T17	T20	T23
			\square				
				Beam 2			
T3	T6	Т9	T12	T15	T18	T21	T24

Figure 22. Model in ABAQUS.

5. Conclusions

In this paper, the structural response analysis of the offshore platform structure is made using the finite element method, and a risk assessment method based on the quantitative analysis of a pool fire caused by liquid leakage is proposed. This study demonstrates the following:

(1) A pool fire is a common type of offshore platform fire and the consequences are incalculable. Under different wind speeds, when the wind speed is lower than 1.5 m/s, with the increase in wind speed steel structure temperature increases; but when the wind speed is 3 m/s, the temperature of the steel structure is lower than that of 1.5 m/s and 0 m/s. Although different wind speeds can lead to different temperatures of the same part and the difference of the highest temperature of the whole steel structure, the temperature change trend of a steel structure caused by a pool fire is basically the same. Under the

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action of the outside wind, the amount of heat moves along with the wind direction, which leads to higher thermal radiation in the downwind direction and an increase in the risk for the downwind area.

(2) When the pool fire occurs, the temperature of the steel members of the platform gradually increases under the action of the fire. When it has been under the action of the fire for 1000 s, although the steel structure has serious buckling, the integrity of the platform is maintained well. When it is 5000 s, the steel members at the top of the pool fire flame will have a large deformation; with the increase in the fire time, the deformation of the platform becomes more serious, causing platform structure failure and overturning. The FPSO has complete fire protection systems, such as a fire water system, foam system, water sprinkler system, and lifeboat. The aim of these safety systems and the protection of structural elements subject to large fires ensures enough time to evacuate people before any critical structural collapse. According to the calculation results, unless the structure collapses significantly in a short time, 1000 s is enough time to ensure the evacuation of personnel to a safe area.

(3) FDS is based on the solution of the linear grid. The accuracy of the simulation calculation of rectangular objects is very high, so in the establishment of the rules of the offshore platform model, the calculation accuracy will be high. However, the FDS software is not a universal simulation software of fire, the modeling and meshing are not flexible, and the solution is simple. In this study, the mechanical calculation data of the structural response were obtained after the completion of the fire simulation. The fire simulation and structural response simulation were conducted separately. This caused some delay. In future steps, we hope to couple a fire simulation and structural response simulation, so that the process of structural failure and deformation occurs at the same time as a fire occurs. This requires some linkage of the software.

Author Contributions: Conceptualization, D.Z. and B.Z.; methodology, K.Z.; software, D.Z.; validation, D.Z. and K.Z.; investigation, D.Z.; resources, D.Z.; data curation, D.Z.; writing—original draft preparation, D.Z.; writing—review and editing, B.Z.; visualization, B.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Program for Scientific Research Start-up Funds of Guangdong Ocean University, grant number 060302072101, and the Zhanjiang Marine Youth Talent Project-Comparative Study and Optimization of Horizontal Lifting of Subsea Pipeline, grant number 2021E5011.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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