PERFORMANCE BASED DESIGN OF OFFSHORE STRUCTURES EXPOSED TO FIRE

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Abstract. Fires and explosions are continuous threats on offshore oil installations. It is required that the structures are able to withstand the actual fires for a certain time, for example the time needed to evacuate personnel, etc. (typically 1 to 2 hour).

Specific requirements regarding strength and passive fire protection were introduced several decades ago, long before advanced computational tools were available. The guidelines and the practice therefore had to be based on simplified descriptions of the complex physical problems. The fires, the temperatures in the structure and the structural integrity were schematically and conservatively described.

Over the past decades, the knowledge about fires, material behaviour and structural performance at elevated temperatures has increased substantially. In addition, specialized computer tools have become available, and direct computer costs have dropped to almost zero.

The industrial practices and the guidelines/recommendations formed in the early days of “the Norwegian oil history” are still used in many engineering communities. Today we know that these recommendations and practices were based partly on “myths” about the reality. One myth is for example the assumption that steel structures fail if the temperature exceeds “the critical” 400 °C. Another myth is the assumption that steel is a good heat conductor. These two myths combined have formed an industrial practice on how to protect structural components using passive fire protection (PFP).

Experience over the past 10 years shows that roughly speaking 2/3 of the passive fire protection applied according to “normal” procedures is surplus. The surplus PFP is often located on those parts of the structures, which are most difficult to access, and hence become expensive to protect.

By using Performance Based Design based on today’s available knowledge and tools, substantial costs are saved without reducing the safety. The result is cheaper and more maintenance friendly structures.
1 INTRODUCTION

Fires and explosions are continuous threats on offshore oil installations. It is required that the structures are able to withstand the actual fires for a certain time, for example the time needed to evacuate personnel safely with good margins, (typically 1 - 2 hours). Other requirements could for example be that the structural integrity should be maintained until the fire is extinguished, (either active using deluge etc or when all fuel is consumed).

![Figure 1: Extreme events sometimes happen. Offshore Egypt in 2004 (left) and WTC in 2001 (right)](image)

Different acceptance criteria exist with respect to the structural performance after the accidental fire:

- The structure shall not be damaged and should be possible to use without major replacements and repair after the fire.
- The structure could be damaged, and will be completely renewed after the fire.

The first alternative is often used in connection with onshore buildings, (especially for high-rise buildings). The costs and consequences of a complete collapse of one or more floors are enormous. The amount of flammable materials within buildings is limited, and the fire compartment temperatures caused by combustion of building materials, furniture, paper etc normally does not exceed 800ºC. There are therefore good reasons and also less costly to define strict acceptance criteria for building structures.

For offshore oil installations, the situation is different. The amount of fuel could be “unlimited”, the fire temperatures are generally higher (1000-1300ºC) and the cost of the structure itself is limited compared with the equipment and process units inside the platform. A major accidental fire will most likely result in renewal of platform modules or the entire platform. Re-use of the steel structures exposed to fire is therefore normally not an issue for oil- and gas installations.

Oil installations are normally equipped with a series of means in order to limit the consequences of an accidental leak and fire: Gas detectors, Deluge, Emergency shutdown valves (ESV), de-pressurisation systems, etc. However, it is required that the structural
integrity should be maintained without the deluge system, (which could be “knocked out” due to explosion etc).

The structural integrity assessment therefore is focusing on securing escape routes and evacuation in general and to avoid fracture of pressurized hydrocarbon pipes and vessels, which could lead to escalation of the fire.

In summary: Small fires shall not develop into huge accidents, and it should be possible to evacuate the platform safely.

2 EXISTING PRACTICE

When the “Norwegian Oil Age” started in the early 70’s, requirements and guidelines within all disciplines including safety were established, (see Table 1). At that time, computers and computational tools were unavailable for most engineers. Linear finite element method for structural analysis had just been introduced, but their use was costly and had many limitations. Nevertheless, the Finite Element Method was selected for the structural analysis of the offshore platforms, and the design for environmental loads was based on functional requirements, (performance based design).

Corresponding computational tools for analysis of the complex fire process and structural response were not available. The guidelines within fire safety and the practice therefore had to be based on simplified descriptions of the complex physical phenomena. The fires, the temperature rise in the structure and the structural integrity were modelled in a simplified and conservative way. The safety discipline methodology was, and still is today, based on prescriptive regulation based design methods and not on numerical simulation techniques.

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<th>Event</th>
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<td>Linear Finite Element for Structural Analysis becomes available</td>
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<td>Guidelines and Recommendations are established</td>
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<td>Industrial Practices are formed</td>
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<td>Numerical Simulation of Fire using CFD technique becomes available</td>
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<td>Simulation of the complete accident (Fire, temperature, Collapse) is possible</td>
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<td>The Safety discipline is based on performance based methods</td>
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Table 1: Development of Methodology and Practice within Structural Integrity Assessment.
In this format the fires are typically specified as constant heat fluxes, (for example 200 kW/m$^2$ lasting for 1 or 2 hours), and the heat flux is assumed to expose all surfaces with same intensity. Such simplification implies that the roofs and the floors within a fire compartment are assumed exposed to the same heat flux, (see Figure 2).

![Figure 2: Commonly used simplification of a fire: 200 kW/m$^2$ exposing all surfaces equally](image)

The temperature development within the structural component cross sections is based on a model consisting of the cross section area and the perimeter, (the so called Hp/A ratio). It is assumed that all surfaces of a cross section receive the same heat flux, and that all parts of the cross section have the same temperature. A small Hp/A number means small exposed surface compared with the cross sectional area (for example thick wall pipe), while thin walled open profiles get high Hp/A ratios.

For the I-profile show in Figure 3, the constant heat flux (typically 200 kW/ m$^2$), is assumed to expose the profile equally from all sides, and the total heat energy heats up a mass without dimension, (mass point). The fact that the flanges are thicker than web and will be heated substantially slower than the web cannot be described using the Hp/A ratio. In addition, the heat fluxes are never exposing all surfaces equally. In consequence, the Hp/A ratio technique seldom describes the reality accurately.

![Figure 3: Simplification of the Cross section temperature calculation based on Hp/A ratio.](image)
Personnel within the safety discipline have normally their educational background from process- and petroleum technology. The safety personnel seldom have the knowledge needed to evaluate the performance of structures exposed to increasing temperatures. Therefore, the structural performance was not selected as acceptance criteria for structures exposed to fire. Instead, simple steel temperature threshold values were introduced, and the most commonly used threshold value is the 400ºC value, (this temperature is often mentioned as the “critical temperature” for steel within the safety community).

Redundancy of the structural system is of great importance for the safety. A redundant structure is able to handle substantial loss of component strength before global instabilities occur. Structural redundancy cannot be measured in terms of temperatures.

3 NEW INSIGHT IN COMPLEX PROBLEMS

3.1 Fire

Figure 4 describes a fire schematically. Any fire is dependent on combustible material and access to oxygen. The heating from the fire results in a relatively fast upwards gas flow, and a correspondingly flow of cold air at the lower parts. The heating within a fire compartment is therefore seldom uniform: Floor and lower parts of the compartment are normally less heated than the ceiling and upper parts. The assumption of equal heat flux on all surfaces within a fire compartment is purely hypothetical and does not correspond with the reality.

![Figure 4: Schematic description of a fire.](image)

During the 80’s the computers became faster and more available, and development of advanced numerical simulation tools were initiated. By the end of the 80’s, it was possible to simulate fires, (the combustion process), using CFD (Computational Fluid Dynamics) techniques. Researchers have been working continuously with the understanding of the fundamental physics involved in the combustion process both in the laboratories and theoretically. Today it is possible to simulate highly complex scenarios with high precision.
Figure 5 describes some snapshots from simulations of two Fire-on-Sea accidents using the CFD tool KAMELEON FireEx (KFX). The impact from wind speed- and direction, fuel release rate and the geometrical boundaries are possible to evaluate numerically. Information about radiation fluxes, gas temperatures and speed, spread of smoke and toxic gases etc are computed accurately everywhere in the fire domain. It is possible to measure the benefit from different shut down and depressurization systems as well as the impact from deluge or water spray on the extent and duration of the different fires under different environmental conditions and/or ventilation conditions etc.

3.2 Heat Transfer

Non linear transient heat transfer is modelled and computed easily using the Finite Element technique. The technique is able to describe “all” physical effects involved in the heat energy- transfer and -balance for arbitrarily shaped geometries. Typical effects which are accounted for in a fire simulation are: Temperature dependent material properties, (conductivity, heat capacity and emissivity), radiation exchange between structural components and heat flux varying in time and space. Further, the effect of insulation may also be calculated. In order to avoid numerical difficulties, the so called equivalent heat transfer coefficient method is recommended.

In order to demonstrate the importance of describing the physics correctly, two examples are simulated (utilizing the specialized tool FAHTS). A pipe with diameter 1m is exposed to a parallel heat flux of 200 kW/m², see Figure 6. Only the left side of the cross section is receiving the heat flux, and due to the curvature of the cross section, the flux intensity normal to the pipe surface reduces along the circumferential of the cross section. Surfaces, which are parallel with the radiation beams or are facing away from the radiation receive no heat flux at all.
The temperature rise in the pipe on the exposed side (to the left) and the unexposed side (to the right) is presented as a function of time in the plots.

Figure 6 is used to demonstrate the contribution from heat conduction only. No radiation energy exchange is accounted for in this example. As seen from the plot, the temperature rises to 1100º C on the exposed side, while the unexposed side hardly experience any temperature rise at all. After 2 hours, the temperature has increased to approx 70º C.

In Figure 7 it is demonstrated the importance of including the radiation effects in the heat energy balance. The radiation is proportional with $T^4$, (T is Kelvin temperatures), and when the exposed side reaches temperatures of ~6-800ºC, the transfer of heat energy to the cold side becomes substantial. In this case, which describes the reality more accurately, the unexposed side is heated up to ~600ºC within 2 hours. Because the exposed side radiates energy to the colder, unexposed side, the peak temperature of this side stabilizes at approx 950ºC.

The examples illustrates that steel is a poor heat conductor, and that radiation between surfaces with visible contact dominates the heat transfer in the temperature domain of interest with respect to structural failure (~600-900ºC).

Figure 6: 200 kW/m² radiation. Heat transfer by conduction only.

Figure 7: 200 kW/m² radiation. Heat transfer by conduction, but also accounting for internal radiation.
3.3 Mechanical Response

Within structural analysis, tools for describing the non linear behaviour, (material yielding, instabilities and collapse), of structures exposed to extreme actions became available in the late 80’s. These tools are based on non linear finite element techniques and make it possible to describe the behaviour and performance of structures for increasing temperatures. Using non linear structural analysis tools, the redundancy of structural systems are possible to measure. This gives the engineers valuable information on how to enhance the safety of structures exposed to extreme events like accidental fire. Figure 8 illustrates the fire “footprint” on the underside of a floater (left) and the corresponding mechanical response utilizing the tool USFOS.

Materials degrade for increasing temperatures, and Figure 9 describes the degradation curve defined in today’s Eurocode. The figure also indicates the “old” degradation curve, which was the assumed performance in the 70’s and 80’s. According to the old curve, the performance of steel at for example 600°C was assumed reduced to 20% while the steel in reality has approx 50% of the initial strength when strains in the range of 2% are accepted.

![Figure 8: Temperature on Underside of Deck (left) and Local Yielding (right)](image)

![Figure 9: Material Degradation for Steel vs. temperature at 2% strain. (“Effective Yield Stress”)](image)
4 EXAMPLES

Some of the physical effects discussed above are demonstrated in connection with relevant details on offshore oil structures. The simulations are verified in laboratory, see references /1/ to /7/.

4.1 Member Connections

Normally, the main steel in fire exposed areas is thermal insulated using passive fire protection, PFP. Based on the assumption that steel conducts heat energy effectively, the industry has introduced a practice to thermal insulate also the attached member a certain length (the so called coat back length). Today, this length is set to 400-600mm. Figure 10 illustrates the case without coat back at all (to the left), the case with only 100mm coatback, and the typical today’s practice (450mm). All images are taken after 1 hour exposure of a HC fire, (200 kW/m²).

As seen from the image to the left, the unprotected secondary steel has little influence on the cross section temperature of the main steel. Only local heating on the web is observed, and local softening of the web has minor impact on the capacity performance of the main girder, (refer to cut-outs for ventilation, which is widely accepted).

The main effect of leaving out the coat back insulation on the secondary steel is connected to deflection of the main girder, (due to non uniform heating of the cross section).

![Figure 10: Temperature after 1 hour. No coatback (left), 100mm coatback (mid) and 450mm (right)](image)

4.2 Access to welds for inspection

For structures exposed to cyclic loading, like FPSO and floaters, fatigue is a design issue. Welds have to be inspected regularly, and if the components are to be covered with PFP, you have to options: 1: Remove/replace for each inspection or 2: Use a factor of 10 for the fatigue life design. Option 1 complicates the inspection, while option 2 causes use of more coarse components which means additional weight.

In many cases, the consequences of leaving an opening in the PFP for inspection are limited. Connections are often located in less fire exposed zones within the fire...
compartment (at floor level, in back eddies close to walls etc). Figure 11 demonstrates the effect of leaving a 100mm opening in the PFP for a T-joint, which is exposed to a radiation heat flux of ~150 kWm\(^2\), (image to the left). The temperature in the connection rises locally to approx. 500ºC after 1 hour, which means a moderate reduction of capacity.

The example demonstrates that it is possible to design maintenance friendly fire protection solutions by utilising today’s available knowledge and tools.

4.3 Insulation of Floors

Insulation of floors and beam over sides are not wanted of practical reasons, (“speed bumps” over every girder, wear due to traffic etc.). In Figure 12, (to the left), the green surfaces indicate the areas with PFP, while the red surfaces are unprotected. Only the girders are protected, and no coat back is applied on the plates. The image in the middle shows the temperature field after 1 hour exposure of a standard HC fire from under side. As seen from the image, the upper flange temperature is approx 600º while the temperature of the lower flange is approx 350ºC. The image to the right shows the temperature after 1 hour for an assumed fire from the upper side with an intensity of 100 kW/m\(^2\). Again it is seen that the temperature levels are not very high, and that the capacity is little influenced. However, the gradients could cause upheaval deformations, which have to be accounted for in the design of pipe supports, etc.
4.4 Penetration of Fire Wall

If an unprotected pipe line is penetrating a fire wall, it is normal to insulate the $\frac{1}{2}$ m of the pipe adjacent to the wall in order to avoid heat to “flow” through the fire wall. Experience from the North Sea shows that such “wrapping up” of pipelines could cause corrosion, which is hard to observe, and could eventually cause leakage of hydrocarbon.

The real benefit or need for such “coatback insulation” could be discussed, and Figure 13 demonstrates the consequences of penetrating a fire wall. The unprotected pipes are exposed to 200kW/m² radiation on one side of the 100 mm wall, while the room on the cold side of the wall holds a temperature of 20º C. The image in the middle shows the temperature field after 1 hour constant fire exposure. The plot to the right shows that the temperature at the pipe surface behind the wall is rising relatively slow, and after 60 min, the temperature is still relatively low, (approx 120º C). This beneficial effect is due to the poor heat conduction capability of steel.

![Figure 13: Penetration through 100mm wall. No Coat Back. Temperatures on warm and cold side.](image-url)
5 PERFORMANCE BASED DESIGN

The new insight in the complex accidental fire problems opens for more precise safety solutions. With access to reliable simulation tools it is possible to base the structural safety solutions on functional requirements in lieu of prescriptive rules. The documentation will then follow the same principles as used for structural analysis in general.

Experience over the past 10 years shows that there are great potentials for saving passive fire protection by using performance based design. A rule of thumb experience has shown that approximately 2/3 of the PFP applied on North Sea platforms designed according to the prescriptive, regulations is surplus. For a medium size platform, this surplus PFP could represent a weight in the order of 100 tonnes and a fabrication cost of 3-10 mill US$. In addition, the reduced amount of PFP implies corresponding lower maintenance costs during platforms lifetime.

Performance based design based on realistic analysis of the governing physical phenomena ensures, on the contrary, that the PFP is only applied on the extent needed and one those locations which are essential for the load-carrying.

Figure 14: Typical situation for many North Sea Installations
6 CONCLUSIONS

Substantial improvements within numerical simulation technique make it possible to simulate the complex physics in connection with accidental fires. “Myths” about steel and structural performance during fire have resulted in an industrial practice which often is overly conservative.

Experience over the past decade shows that 2/3 of the passive fire protection, PFP applied according to “normal” procedures is surplus.

By using Performance Based Design based and today’s available knowledge and tools, substantial costs are saved without reducing the safety. The result is a cheaper and more maintenance friendly structure.

REFERENCES


