ONE-WAY VERSUS TWO-WAY FLUID-STRUCTURE INTERACTION

Analyses of Offshore Installations in Fires

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For safety studies of structural systems in fires, the effects of time-varying geometry and material properties due to changes in temperatures should be taken into account in fluid-structure interaction (FSI) analysis. In the industry, the so-called one-way FSI analysis is often adopted for the purpose of simplicity and convenience, whereby the fire loads are defined as a first step, and are then applied in the structural response analysis in the next step. On the other hand, the so-called two-way FSI analysis is often adopted when a more refined analysis is required where both the fire load definition and structural response analysis are carried out simultaneously. The benefits of the two-way FSI analysis method include that the effects of time-varying geometry and material properties can be accounted for. The objective of the present study is to examine the impacts of the application of the two-way FSI analysis method in association with nonlinear structural response in fire by making a comparison with the results of the one-way FSI analysis of offshore structures in jet and pool fires. The two-way FSI analysis method applied in the present study is a rather simplified technique whereby the one-way FSI analyses are repeated at a small time interval determined in advance. In this method, geometry and material properties are redefined at every incremental time step, and both CFD (computational fluid dynamics) and NLFEA (nonlinear finite element analysis) are performed at the corresponding time step. It is concluded that the traditional one-way FSI analysis method is not always practicable, and thus it is recommended to apply the two-way FSI analysis method for more refined safety studies.

Abbreviations

API: American Petroleum Institute
CFD: Computational Fluid Dynamics
EN: European Standard
FABIG: Fire and Blast Information Group
FE: Finite Element
FEA: Finite Element Analysis
FEM: Finite Element Method
FSI: Fluid-Structure Interaction
HSE: Health and Safety Executive
KOSORI: The Korea Ship and Offshore Research Institute
NLFEM: Nonlinear Finite Element Method
NORSOK: Norwegian Standard
OGP: International Association of Oil & Gas Producers
PNU: Pusan National University
UKOOA: United Kingdom Offshore Operators Association

Nomenclature

Δt = Time increment for two-way FSI analysis
$E_{a,\theta}$ = Slope of the linear elastic range
l = Length of structure at 20°C
Δl = Temperature induced elongation
$\varepsilon_{p,\theta}$ = Strain at the proportional limit
$\varepsilon_{t,\theta}$ = Limiting strain for yield stress
$\varepsilon_{u,\theta}$ = Ultimate strain
$\varepsilon_{Y,\theta}$ = Yield strain
σ = Stress
$\sigma_{p,\theta}$ = Proportional limit
$\sigma_{Y,\theta}$ = Effective yield stress

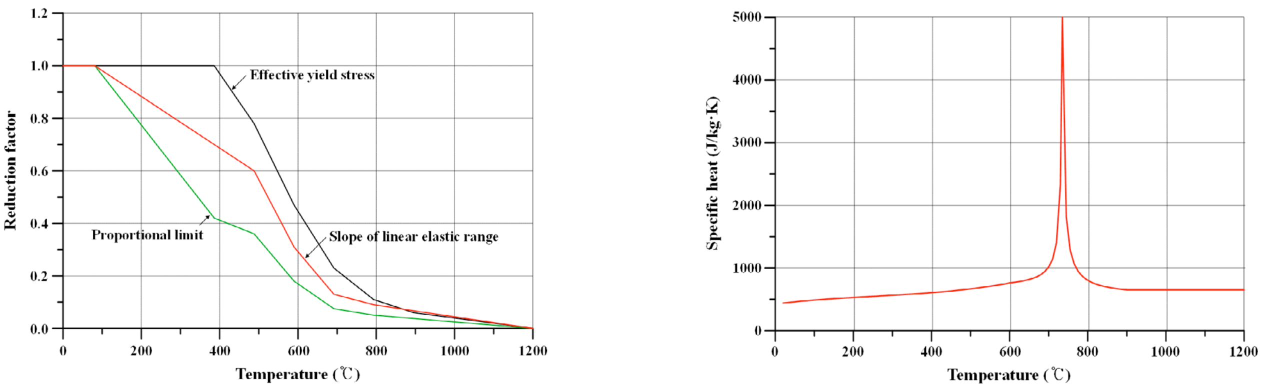
1 Introduction

Oil and gas are important sources of energy, produced mainly in demanding oceanic and industrial environments with significant fire and explosion hazards. The topsides of offshore platforms are the most likely structures to be exposed to hazards such as hydrocarbon fire and/or explosion. A number of major accidents involving the topsides of offshore installations have been reported, such as the Piper Alpha accident of July 1988 in the North Sea and the Deepwater Horizon accident of April 2010 in the Gulf of Mexico, as shown in Figure 1 (Vinnem 2007, USCG 2011).

Following the Piper Alpha accident, greater attention was focused on the structural design of offshore rigs to counter the threat of fires and determine the means of minimising damage from accidents. The Deepwater Horizon accident reconfirmed the importance of structural design against hydrocarbon fires.

Structural design and safety assessment both require the identification of the characteristic actions and action effects. In fires, the thermal characteristics of steel are the main factors affecting structural integrity. At temperatures above 400°C the mechanical properties of steel significantly decrease, as shown in Figure 2(a) which represents a non-continuous segment plot based on the definition of Eurocode (EN 2005). Also, the specific heat of steel varies with temperature, as shown in Figure 2(b). The heat from fire flows relatively 'rapidly' in steel, which is a good heat conductor compared to other materials, e.g. concrete. Thus, fire can lead to the collapse of steel structures, and the severity of fire loads usually requires the application of passive fire protection for critical structural elements. As such, the change in material property characteristics should be considered when analysing the structural response when subjected to fire loads.

Figure 1 The Piper Alpha (left) and Deepwater Horizon (right) accidents



(a) Mechanical properties of steel with temperature

(b) Specific heat of steel with temperature

Figure 2 Examples of the change in material properties according to temperature (EN 2005)

Within the industry, simplified methods are usually applied for assessing the structural response of offshore installations to fire, according to the structural designer's and/or engineer's convenience (UKOOA and HSE 2003, API 2006, EN 2005, NORSOK 2008). Some of the ways in which such analyses may be simplified include the following:

- Simplification of load: idealized fire loads;
- Simplification of structure: 1-dimensional structure;
- Simplification of procedure: numerical calculation.

Conventional fire safety design approaches are essentially composed of a series of regulations, standards and procedures. As a result, conventional approaches need to be supplemented by integrated fire safety design approaches that are in principle based on performance. Integrated fire safety design requires taking advantage of fire computational fluid dynamics (CFD) simulations (Paik et al. 2010) and nonlinear structural response analyses (Guedes Soares et al. 1998, Shetty et al. 1998; Guedes Soares and Teixeira 2000, Skallerund and Amdahl 2002, Paik and Thayamballi, 2007).

The action characteristics of hydrocarbon fires can be modelled using CFD, which is recognized as one of the most powerful modelling approaches currently available. CFD makes it possible to model fire using first principles through solving the basic conservation equations of mass, energy, and momentum whilst using accurate 3D topological models of structures. This CFD modelling approach has successfully solved various fire safety problems (Novozhilov 2001).

In addition, the action effects of fire on structures can be characterized by the nonlinear finite element method (NLFEM). Therefore, more refined methods for CFD modelling and NLFEM simulations will help improve the prediction of the fire risk associated with offshore installations. These numerical computations need to be validated in advance with full or large-scale prototype testing.

The aims of this study are to perform a fluid-structure interaction (FSI) analysis of structures on offshore platforms through one-way and two-way analyses, and to compare the results of these analyses. The study involves the following related procedures.

1. Literature review: to review the relevant regulations on structural assessment in relation to fires;
2. Suggestion of an advanced procedure: to introduce an advanced procedure for the nonlinear structural analysis of fire load vulnerability;
3. Fluid-structure interaction analysis: to investigate the characteristics of nonlinear structural response to fire in association with the interactions between fire loads and time-varying geometry and material properties, and;
4. Comparison of the results: to compare the results of analytic procedures and the effects of using different time increments in two-way analyses as a means for identifying the most suitable time increments.

2 Industry practices for fire safety assessment

API (2006) suggests a procedure for risk-based fire design of structures as shown in Figure 3. It applies a qualitative and deterministic approach with a risk matrix.

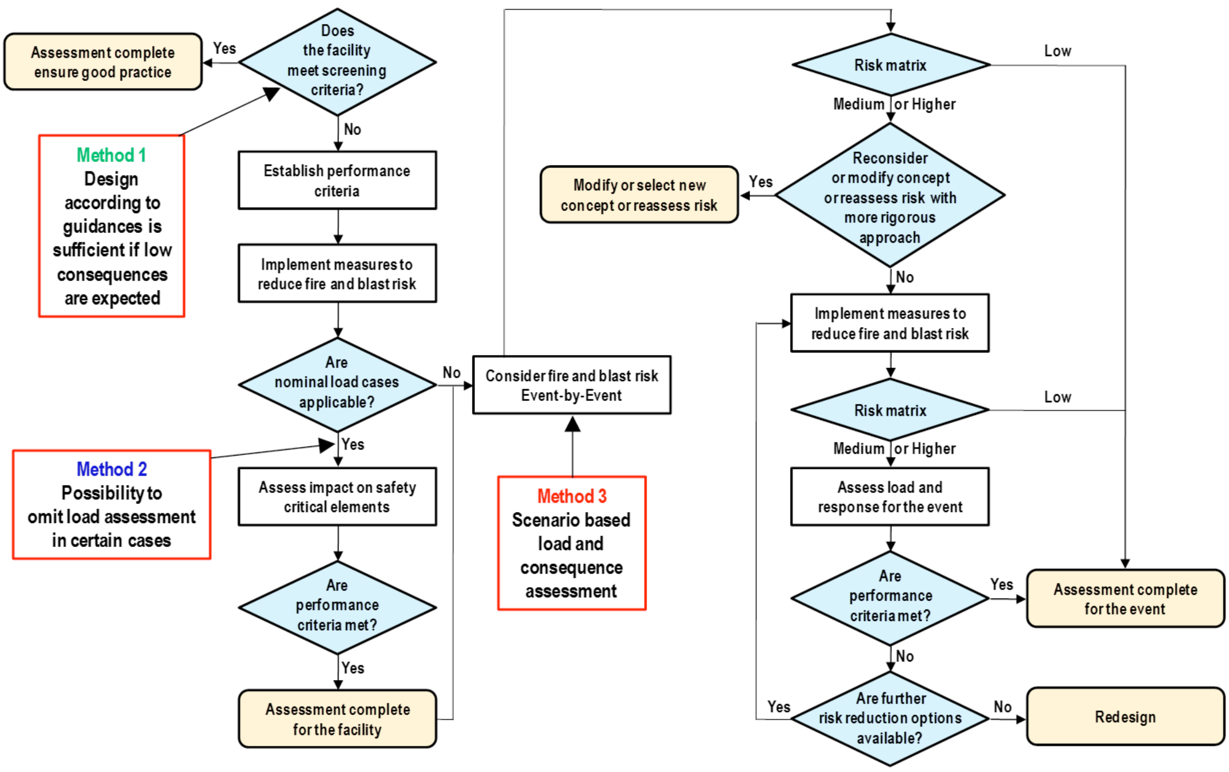


Figure 3 American Petroleum Institute procedure for risk-based fire design (API 2006)

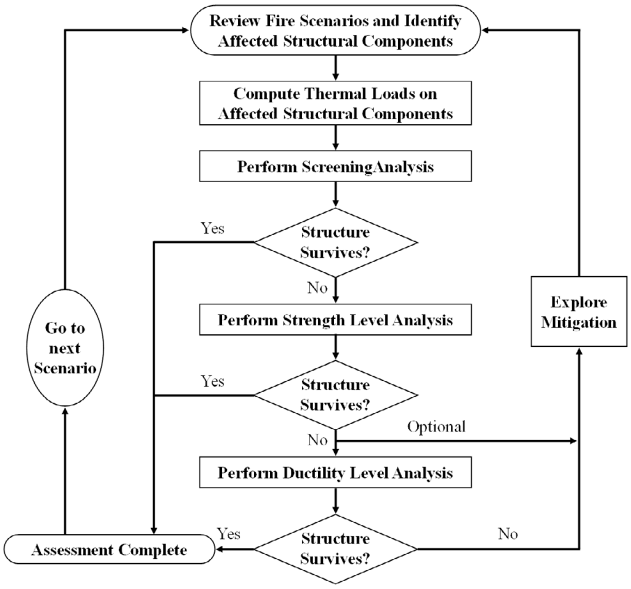


Figure 4 Process for structural assessment against fire, as proposed by API (2006)

It provides a recommended practice for the design of offshore facilities against fire and blast loading. Figure 4 presents a procedure for structural assessment of vulnerability to fire loads. This procedure provides simple calculation methods for defining the fire loads of pool and jet fires, and for determining the resulting steel temperatures. In conducting structural assessments, three types of methods are suggested (API 2006):

- Zone (or screening) method;
- Strength level method;
- Ductility level method.

The Eurocode 3 (EN 2005) is the most frequently used and referred to set of standards for industrial structures. EN (2005) provides guidelines for the basic design structural fire hazard assessment, including sets of requirements, design capacities, properties of materials and verification methods. One of the most useful guidelines in EN (2005) concerns the material modelling of carbon steel and stainless steel in relation to temperature increase.

Figure 5 shows an example of a stress-strain relationship for carbon steel at elevated temperatures. The curve changes according to the metal's properties at specific temperatures. The key parameters of the stress-strain relationship shown in Figure 5 include the effective yield stress, the proportional limit and the slope of the linear elastic range. Further information on these parameters is given in the Eurocode 3 (EN 2005).

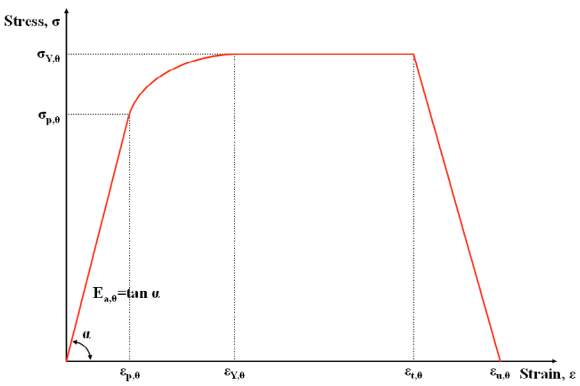


Figure 5 Stress-strain relationship for carbon steel at elevated temperatures (EN 2005)

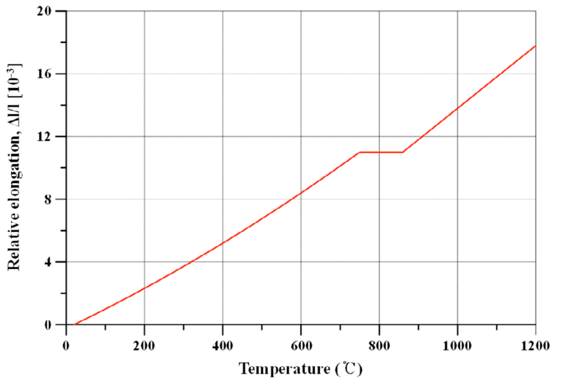


Figure 6 Relative thermal elongation of carbon steel as a function of temperature

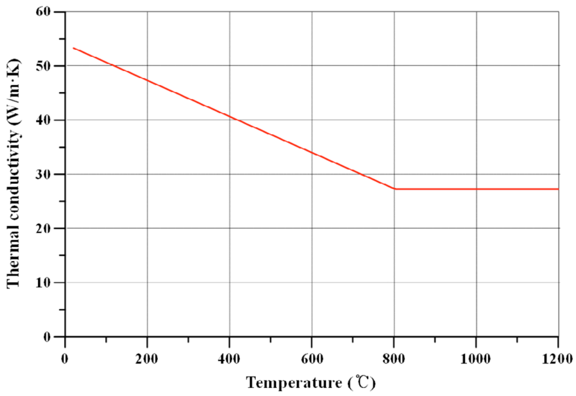


Figure 7 Thermal conductivity of carbon steel as a function of temperature

EN (2005) also provides thermal properties such as the thermal elongation, specific heat, and thermal conductivity for carbon steels and stainless steels. Figures 2, 6 and 7 show material properties, relative thermal elongation, specific heat, and thermal conductivity of carbon steel as a function of temperature, respectively (EN 2005). For structural design against fire loads, two assessment methods for structural design are recommended, as follows:

- Simple calculation method;
- Advanced calculation method.

The Fire and Blast Information Group (FABIG) Technical Note 3 (FABIG 1995) introduces the use of ultimate strength-testing techniques for fire resistant design of offshore structures. This set of guidelines provides methods for calculating thermal loads and structural response under various fire loads as follows:

- Calculation of thermal loads and response, including the intensity, duration, and variability with time and space of the fire;
- Calculation of structural response under fire loads;
- Prediction of structural failure under fire loads;

- Provision of mechanical properties at elevated temperatures for grade 43A steel;
- Application of methods to structures.

Further guidance, FABIG Technical Note 6, concerns the design of steel to resist fire, explosion and impact loads. This document, published by FABIG (2001), gives guidance based on available data concerning the effects of elevated temperatures and about the high-strain rate material properties for high-strength steels that are used specifically for offshore structures. The contents included in this document are as follows (FABIG 2001):

- Design basis for both fire and explosion;
- Methods to measure material properties at elevated temperatures.

FABIG (2001) presents a carbon steel model based on extensive transient-state and steady-state tests conducted by Eurocode 3.

The Korea Ship and Offshore Research Institute (KOSORI) at Pusan National University suggested a procedure for the quantitative fire risk assessment and management for offshore installations using a probabilistic approach as shown in Figure 8 (Paik at el. 2013).

In the procedure, risk is defined as a product of frequency and consequence. Thus, the main task is to accurately calculate the frequency and consequences of specific events within the framework of risk assessment and management. The identification of the action and action effects of fire is required to design and assess the structure.

NORSOK (2008) recommends the application of standardised values of heat flux (as presented in Table 1) for structural analysis under fire loads, unless a specific fire analysis is performed. These suggested values are uniformly distributed on the target structures. NORSOK N-001 (NORSOK 2004b) briefly describes the standards for structural design based on the tolerable limits for accidental damage under conditions such as fire, explosion, collision or dropped objects.

	JET FIRE (kW/m²)		POOL FIRE (kW/m²)
	LEAK RATE < 2kg/s	LEAK RATE > 2kg/s	
Local peak heat load	250	350	150
Global average heat load	0	100	100

Table 1 Heat flux values for structural analysis (NORSOK 2008)

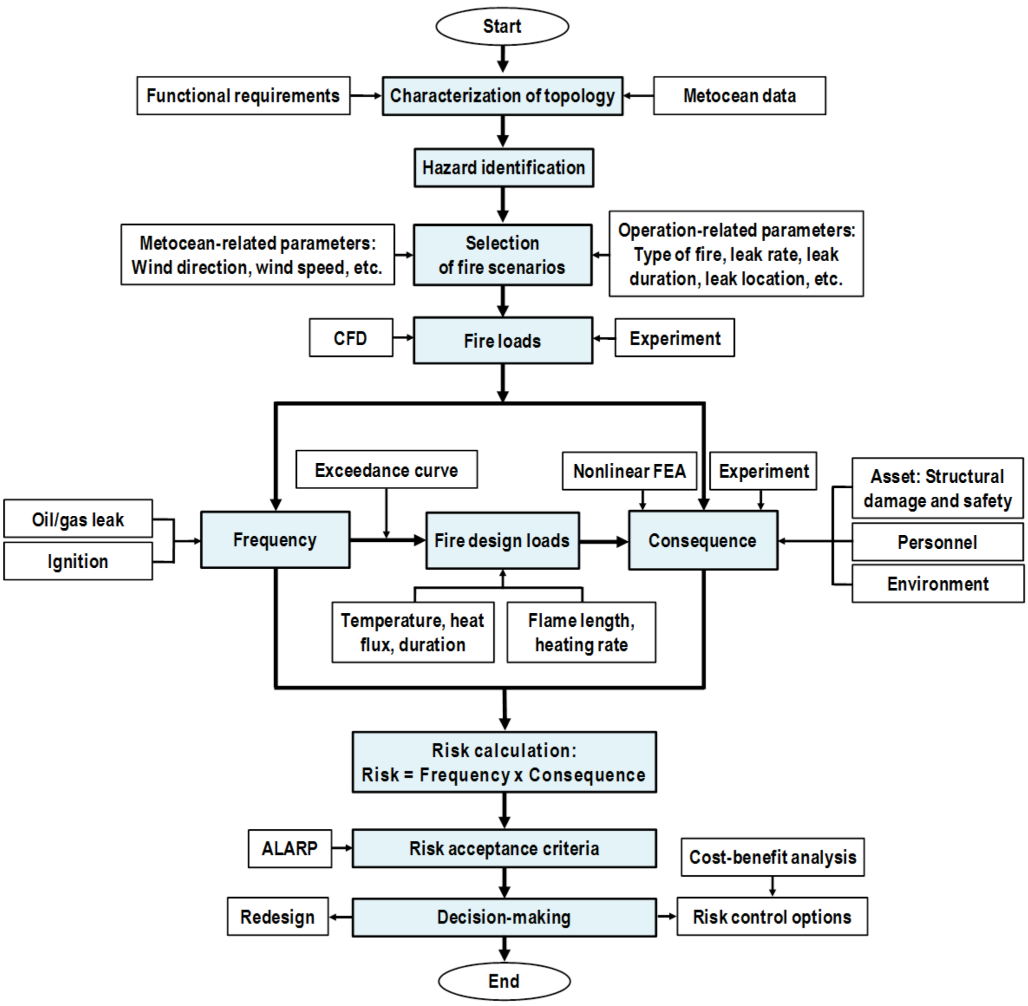


Figure 8 The procedure for quantitative risk assessment and management for offshore installations in fires (Paik et al. 2013)

TEMPERATURE (°C)	STRUCTURE	CRITERIA
550-620	Structural steel onshore	Temperature at which fully stressed carbon steel loses its design margin of safety
427	LPG tanks (France and Italy)	Based on the pressure relief valve setting
400	Structural steel offshore	Temperature at which the yield stress is reduced to the minimum allowable strength under operating loading conditions
300	LPG tanks (UK and Germany)	Integrity of LPG vessel is not compromised at temperatures up to 300°C for 90 minutes
200	Structural aluminium offshore	Temperature at which the yield stess is reduced to the minumum allowable strength under operating loading conditions
180	Unexposed face of a division/boundary	Maximum allowable temperature at only one point of the unexposed face in a furnace test
140	Unexposed face of a division/boundary	Maximum allowable average temperature of the unexposed face in a furnace test
40	Surface of safety related control panel	Maximum temperature at which the control system will continue to function

Table 3 Commonly used critical temperatures, as indicated by UKOOA and HSE (2003)

Another standard, NORSOK N-004 suggests a method for structural steel design (NORSOK 2004a). This method is largely based on Eurocode 3. NORSOK N-004 presents standards for determining the extent of structural analysis necessary for determining fire loads. This standard also offers methods for the assessment of fire load effects and mechanical response. The issues covered include the following:

- Target structures for structural analysis;
- Methods for fire load effect assessment.

NORSOK N-004 explains that an assessment of ultimate strength is not needed if the maximum steel temperature is below 400°C, but the deformation criteria may have to be checked for impairment of the main safety functions (NORSOK 2004a).

OGP 434-15 (OGP 2010) summarises expected times to failure for the evaluation of offshore platforms in terms of their capacity to withstand accidents, including fires, explosions or missiles. This set of guidelines summarises the typical failure times for the various items composing platforms and related structures, as shown in Table 2. The specific details of projected failure times are noted in the text of OGP 434-15 (OGP 2010).

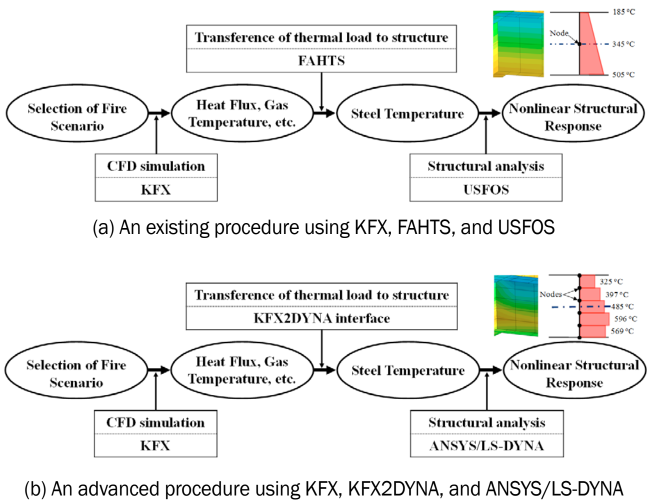


Figure 9 Procedures for the one-way method for nonlinear structural response analysis in fires (Paik et al. 2010)

OGP 434-15 also provides the most commonly used critical temperature standards for various components and vessels. These temperature standards are largely based on UKOOA and HSE (2003), and are summarised in Table 3.

OGP 434-15 (OGP 2010) suggests that fire load limits should be derived through applying structural vulnerability assessments that consider the following fire related factors:

- The fire scenario or design fire;
- The heat-flow characteristics from the fire to the plant/structure;
- The behaviour and material properties of the plant/structure at elevated temperatures;
- The properties of the fire protection systems.

FIRE SCENARIO	FAILURE	TIME TO FAILURE
Flame with heat flux of 250kW/m² impinging onto a pipe support with no fire protection	Excessive deformation of pipe supports leading to loss of tightness and potential rupture	< 5 min
Flame with heat flux of 250kW/m² impinging onto a connector of flange (clamp or bolted) with no fire protection	Hub connector or flange (clamp or bolted), loss of tightness	< 5 min
Flame with heat flux of 250kW/m² impinging onto a valve with no fire protection	Valve, loss of tightness	< 10 min
Flame with heat flux of 250kW/m² impinging onto a safety valve with no fire protection	Safety valve, opens at a pressure lower than the setting pressure	< 10 min
Flame with heat flux of 250kW/m² impinging onto a bursting disc device with no fire protection	Bursting disc, pone at a pressure lower than the setting pressure or is destroyed	< 10 min

Table 2 Examples of times to failure of pipework, vessels, equipment and other structures affected by fire (OGP 2010)

This set of guidelines strongly recommends the definition of actual fire scenarios and design fluxes, which are usually characterised in terms of the following variables with respect to time (OGP 2010):

- Heat release rates;
- Toxic-species production rates;
- Smoke production rates;
- Fire sizes, including flame lengths;
- Fire durations.

OGP 434-15 recommends the use of detailed design loads for pool and jet fires to enable more accurate calculation of radiative and convective heat transfers (OGP 2010). These standards refer to the characteristics of pool and jet fires as indicated by UKOOA and HSE (2003) and by NORSOK (2008).

The UKOOA and HSE (2003) suggest the critical temperatures for carrying out structural assessments without detailed structural analysis. Table 3 shows the most commonly used critical temperatures, as summarised by UKOOA and HSE (2003). It also provides data on the characteristics of various types of fires. These data can be used in structural analysis.

3 Procedure for nonlinear structural response analysis in fire

In order to conduct FSI analysis of structures subjected to fire loads, several computational tools and applied methods are needed.

Figure 9 illustrates the procedures for a one-way method for analysing the nonlinear structural response of offshore installations subjected to fires. An existing procedure shown in Figure 9(a) uses KFX for CFD simulation, FAHTS for estimating the transfer of thermal loads from KFX to structures in FEM, and USFOS for the nonlinear structural analysis. Figure 9(b) shows an advanced procedure that adopts KFX, KFX2DYNA and ANSYS/LS-DYNA.

For nonlinear structural response analysis with a two-way method, it is necessary to consider the time-varying geometry and material properties. Figure 10 illustrates a scheme for two-way FSI analysis. The structural response assessment becomes more accurate with the use of smaller time increments in the two-way analysis, and this process requires the use of an adequate time increment (Δt). If the time increment is the same as the total simulation time, then the process is a one-way FSI analysis.

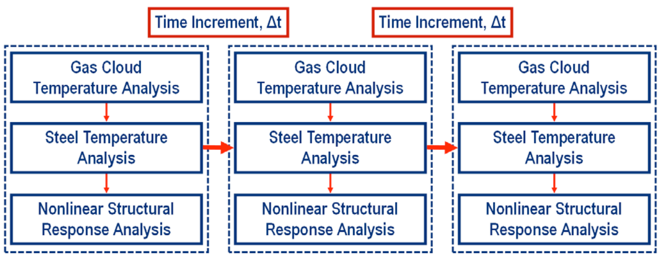


Figure 10 Scheme for two-way FSI analysis, with a time increment of *Δt*

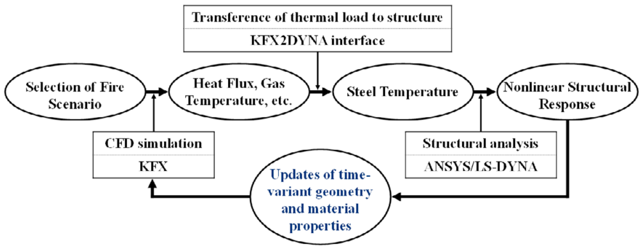


Figure 11 Procedure for the two-way method for nonlinear structural response analysis in fires

Figure 11 shows the procedure for a two-way FSI analysis of nonlinear structural response to fire, which is the proposed procedure in this study. Whereas in the one-way method, the structural response analysis is performed following the completion of the CFD simulation, in a two-way analysis, the FEA is conducted after partial completion of the CFD simulation. The procedure involves the following steps:

- Fire CFD simulation with time increment (which can be set as 0.1s, 1s, or another increment);
- Heat transfer analysis and nonlinear FEA, using results from CFD simulation until the first time increment;
- Fire CFD simulation, using updated geometry results from FEA until the second time increment;
- Heat transfer analysis and nonlinear FEA, using results from CFD simulation until the second time increment;
- Repetition of CFD simulation, FEA and update of geometry.

3.1 *Fire CFD simulations*

The aim of fire CFD simulation is to characterise the gas cloud temperatures and heat fluxes that are time- and space-dependent. The fire load is physically correlated to the elevated temperatures and heat fluxes in the gas cloud as obtained by fire CFD simulation. Both the radiation and the convection associated with fire play key roles in terms of characterising fire loads. A commonly adopted tool for fire CFD simulations in both procedures is the KFX (2017) code, which is a three-dimensional transient finite volume CFD program.

3.2 *Transfer of thermal loads to structures*

3.2.1 Existing procedure (KFX-FAHTS-USFOS)

The FAHTS code is useful for performing heat transfer analyses based on the results of KFX simulations, which are automatically read in terms of gas cloud temperatures and heat fluxes (FAHTS 2013). FAHTS has full access to the detailed results of KFX simulations within the whole calculation domain.

The FAHTS code takes both radiation and convection into account. For every shell element in FAHTS, an advanced ray tracing is performed, based on the discrete transfer radiation method (Lockwood and Shah 1981). Figure 12 shows a schematic representation of a steel temperature distribution obtained by heat transfer analysis using either the KFX2DYNA or the FAHTS with shell elements.

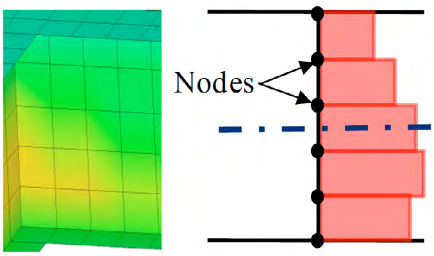


Figure 12 Schematic distribution of steel temperatures, calculated by heat transfer analysis using either the KFX2DYNA or the FAHTS with shell element models

3.2.2 Advanced procedure (KFX-KFX2DYNA-ANSYS/LS-DYNA)

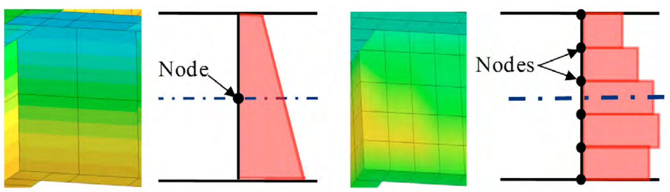
The advanced procedure uses a computer program known as KFX2DYNA (2017) to automatically read the results of KFX simulations, which are directly exported to ANSYS/LS-DYNA to perform the heat transfer analysis.

KFX2DYNA has access to all of the KFX results obtained from the commercial version of the KFX code, including the results for gas cloud temperature, soot concentration visibility, gas velocity and radiation. However, this information is limited to readings from the monitoring points, unlike the FAHTS, which can access the entire calculation domain. Therefore, KFX2DYNA interpolates the related information at the nearest monitoring points before exporting it to LS-DYNA for the heat transfer analysis. LS-DYNA uses plate-shell elements to model the structures, and takes both radiation and convection into account, as for FAHTS.

3.3 Structural response analysis

3.3.1 Existing procedure (KFX-FAHTS-USFOS)

In the existing procedure, the results of the FAHTS heat transfer analysis are exported to USFOS (2013) for the nonlinear structural response analysis. However, as FAHTS uses shell element models and USFOS uses beam element models, some approximation must be made to convert the shell element models into beam element models before loading the steel temperatures. Such steel temperatures should be loaded at the end nodes of the beam elements, as illustrated in Figure 13(a).



(a) USFOS with beam elements (b) ANSYS/LS-DYNA with shell elements

Figure 13 Application for the determination of steel temperatures by heat transfer analysis

3.3.2 Advanced procedure (KFX-KFX2DYNA-ANSYS/LS-DYNA)

The nonlinear structural response analysis is performed using ANSYS/LS-DYNA (2017) with the shell element models used for the heat transfer analysis. The process for defining the steel temperatures is illustrated in Figure 12. This approach is beneficial because no changes are required for the analytical models as indicated in Figure 13(b).

Furthermore, using the ANSYS/LS-DYNA code is beneficial because it allows structures with complex geometry (e.g. structures involving combinations of beam members and plated panels) to be more precisely modelled using shell elements.

4 Applied Example: Test I-girder in Furnace

The nonlinear structural response of an I-girder made of mild steel (yield stress: 235 MPa, Young's modulus: 205.8 GPa) in a furnace was investigated by Cong et al. (2005), and the model derived from this test has been used to validate other procedures. The test results, in terms of the steel temperatures transferred from the gas cloud temperatures and the structural response, are compared to the results of the two procedures described previously. Even if the CFD simulations are not validated, it is sufficient to compare the results of the two procedures in a one-way FSI analysis, and then select the best procedure for use in further analysis.

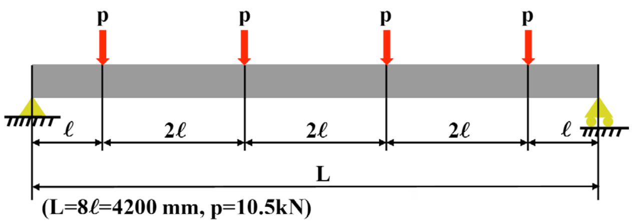


Figure 14 Target I-girder for FSI analysis

Figure 14 shows the applied loads in the experimental test and the FE analysis. Figure 15 presents the finite element models for the structural analysis. In USFOS, beam elements are applied because this is strongly recommended for structural analysis (USFOS 2013). Plate-shell elements are used in ANSYS/LS-DYNA (2017). In addition, beam elements are applied in ANSYS/LS-DYNA for the sake of comparison.

In the heat transfer analysis, the emissivity of gas and steel, and the heat conductivity of the steel affect the calculation of steel temperatures. These measurements should be obtained from experimental tests, because the coefficients are dependent on factors such as the specific material, roughness and geometry.

(a) USFOS with beam element (b) ANSYS/LS-DYNA with beam elements (c) LS-DYNA with plate-shell elements

Figure 15 Finite element models for the structural analysis

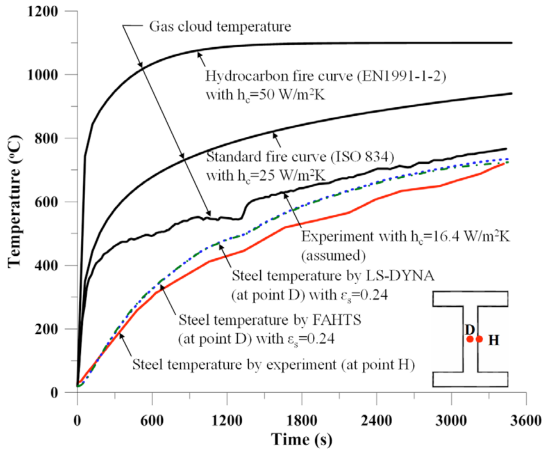


Figure 16 Comparison of steel temperature at the mid-section of beam

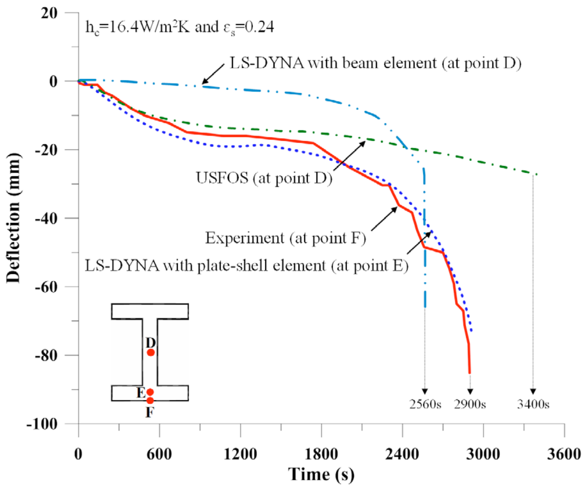


Figure 17 Comparison of structural response at the mid-section of the beam

Figures 16 and 17 compare the results of the heat transfer analyses and the structural analyses for the two procedures, which are also compared to the results from the experimental test. In this study, the values of 0.24 for the emissivity of steel, and 16.4 for the heat conductivity are applied. Even though the results of the heat transfer analysis are almost the same, the nonlinear structural response of the I-girder in the furnace according to the different procedures are quite different. Such difference in results appears because beam elements cannot be used for a realistic response in structural analysis, and shell elements are applied in both of the heat transfer analyses.

It can be seen from the figures that the advanced procedure (which consists of KFX, KFX2DYNA and ANSYS/LS-DYNA with plate-shell elements) provides better agreement with the experimental test results than the existing procedure. Therefore, in additional one- and two-way FSI analyses, the advanced procedure is applied for the CFD simulation, heat transfer analysis and nonlinear FEA.

Figure 18 illustrates the deformed shapes of the I-girder following the test and the FE analysis. The deformed shape as measured by ANSYS/LS-DYNA with plate-shell elements shows detailed deformation such as tripping whereas the beam element models only shows simple deformation.

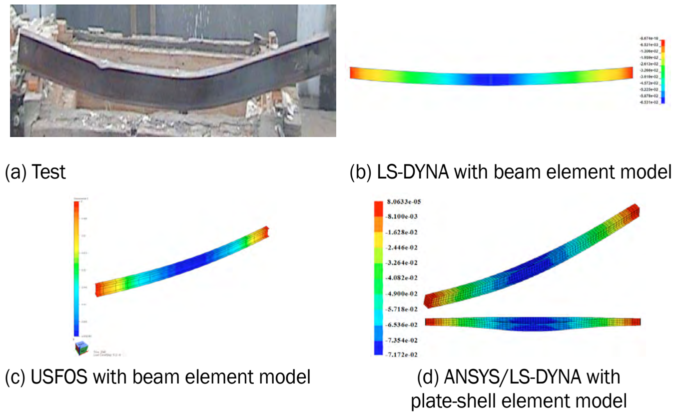


Figure 18 Deformed shapes of the I-girder

5 Applied Example: I-girder in Jet Fire

5.1 Target structure

The advanced procedure with plate-shell elements in ANSYS/LS-DYNA is applied for the nonlinear structural analysis.

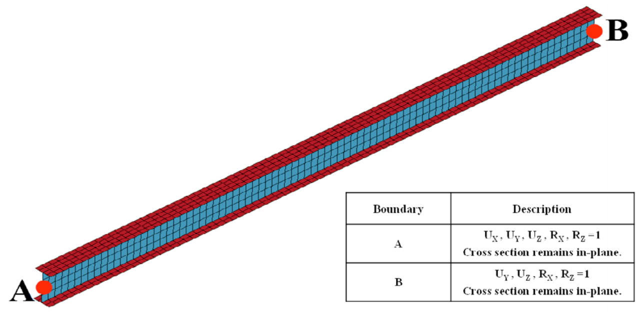


Figure 19 Finite element model with plate-shell elements in ANSYS/LS-DYNA and boundary conditions

The I-girder described in Section 4 is used as a target structure for a two-way FSI analysis under jet fire conditions. Figure 19 shows a finite element model with plate-shell elements in ANSYS/LS-DYNA, together with the applied boundary conditions for performing the nonlinear structural analysis of the I-girder subjected to a jet fire.

5.2 FSI analysis of I-girder subjected to jet fire

5.2.1 KFX simulation for I-girder in jet fire

For the fire simulation using KFX, it is necessary to select a jet fire scenario. In this study, a jet fire with a leak rate of 0.04 kg/s and a duration of 3600 s is applied as follows:

- Leak rate: 0.04 kg/s;
- Leak hole size: 30 mm;
- Leak duration: 3600 s;
- Leak direction: +Z;
- Leak position in X direction: 2.1 m;
- Leak position in Y direction: 0.0 m;
- Leak position in Z direction: -1.0 m;

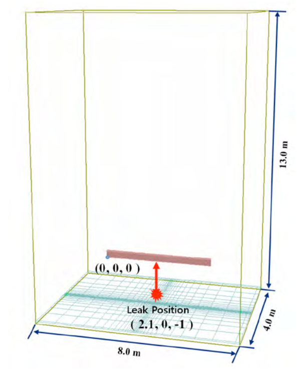


Figure 20 Extent of computational domain for the fire CFD simulation in KFX

Figure 20 shows the extent of the computational domain for the fire CFD simulations and the position of the leak in KFX. In the cases of jet and pool fires, the fire loads, including temperature and heat flux, tend to move upwards. Therefore, the extent of the fire in the Z-direction is larger than in the other directions. Figure 21 illustrates the positions of the monitoring points (and sections) at nine locations along the beam. The fire loads for heat transfer analysis are obtained at these points/sections. Similar monitoring points are also set in FEA for investigation of the structural response.

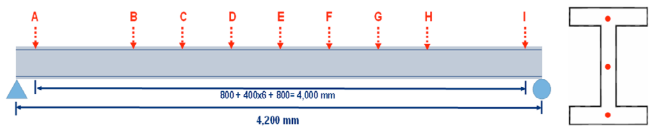


Figure 21 Location of sections and monitoring points for derivation of fire loads

5.2.2 Transfer of thermal loads to structure

For the heat transfer analysis, the changes in specific heat and thermal conductivity of the material are considered, depending on the temperatures, as shown in Figures 2(b) and 7. Analyses are performed at every time increment to define the transferred thermal loads.

In addition, it is necessary to define the time increment (Δt) for the two-way FSI. In this study, four time increments are considered for investigating the effects of different time increments. The time increments are determined to be 60, 30, 15, 10, and 10+α (min), as follows:

- Case I: 3600 s;
- Case II: 1800 s;
- Case III: 900 s;
- Case IV: 600 s;
- Case V: 600 s until 2400 s, and 400 s from 2400 s to 3600 s.

Case I, with a time increment of 3600 s, can be treated as equal to a one-way FSI analysis, because its total simulation time is 3600s.

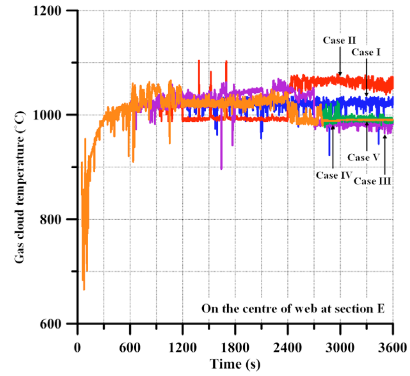
5.2.3 Structural analysis

The modelling technique validated with the experiment by Cong et al. (2005) is applied to the structural analysis under jet fire conditions from the CFD simulation.

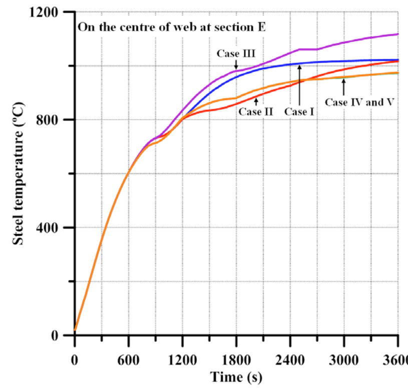
5.3 Results of Analysis

Figure 22 shows representative results of the FSI analyses, including the CFD simulations, heat transfer analyses and the nonlinear FEA on the centre of the web at section E, which is the mid-section presented in Figure 21.

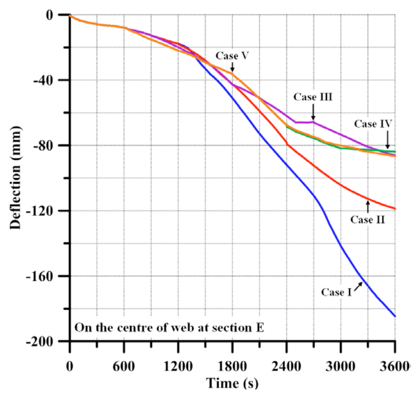
Figure 22(a) presents the gas cloud temperature-time histories in the KFX fire CFD simulation, according to different time increments. The figure shows that gas cloud temperatures decrease with decreases in time increment (Δt). This results from the fact that the temperature at the heat source is lower than that at the end of the flame. Figure 22(b) provides the steel temperature-time histories from the heat transfer analysis, and Figure 22(c) shows the nonlinear structural response, which indicates the deflection at the centre of the I-girder versus the time histories from ANSYS/LS-DYNA nonlinear FEA, according to



(a) Gas cloud temperature-time histories from the CFD simulation



(b) Steel temperature-time histories from the heat transfer analysis



(c) Deflection-time histories from the nonlinear FEA

Figure 22 Results of FSI analysis considering jet fire scenario

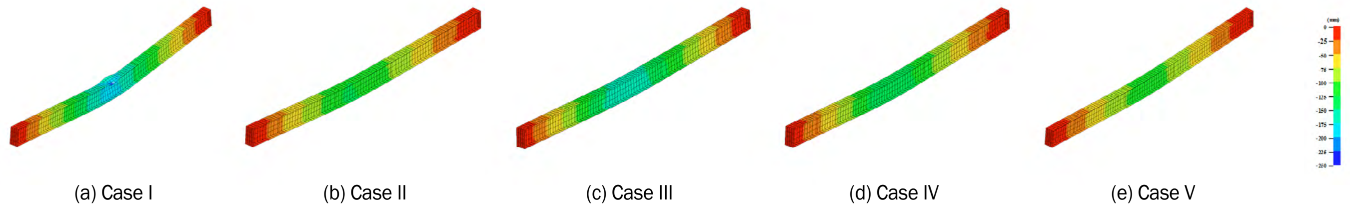


Figure 23 Deformed shape, as obtained from nonlinear structural analysis at 3600 s

changes in the time increments. In Figure 22, it seems that there are large differences in structural response according to the time increments. These differences signify that the two-way FSI analyses should be performed with finer and finer time increments as the temperature increases.

Figure 23 shows the maximum structural response, which are deflections at 3600 s, according to the time increments of the two-way FSI analysis, in order to decide on themost suitable time increment. In this study, the time increments of 15 min. (Case III) or 15+α min. (Case V) are considered to be the most suitable time increments for FSI analysis of the I-girder subjected to jet fire. Specifically, finer time increments should be applied as the structure losses its strength with higher steel temperatures. Figure 24 shows the deformed shapes as predicted by the nonlinear structural analysis of the I-girder in jet fire at 3600 s.

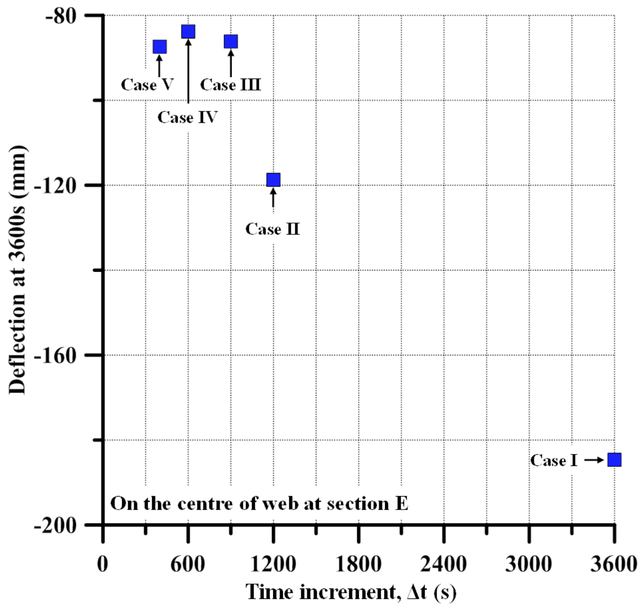


Figure 24 Maximum deflection versus time increments in the FSI analysis considering the jet fire

6 Applied Example: Pool Fire on Topside Structure

6.1 Target structure

As with the FSI analysis of the I-girder, FSI analysis is also applied for investigating the effects of a pool fire on an offshore topside structure.

A hypothetical topside module of an offshore platform at the Hadong campus of the Korea Ship and Offshore Research Institute (KOSORI) at Pusan National University (PNU) is used as a target structure for examining the effects of pool fire conditions. Figure 25 shows the topside structure of this KOSORI test facility, with its layout and principal dimensions.

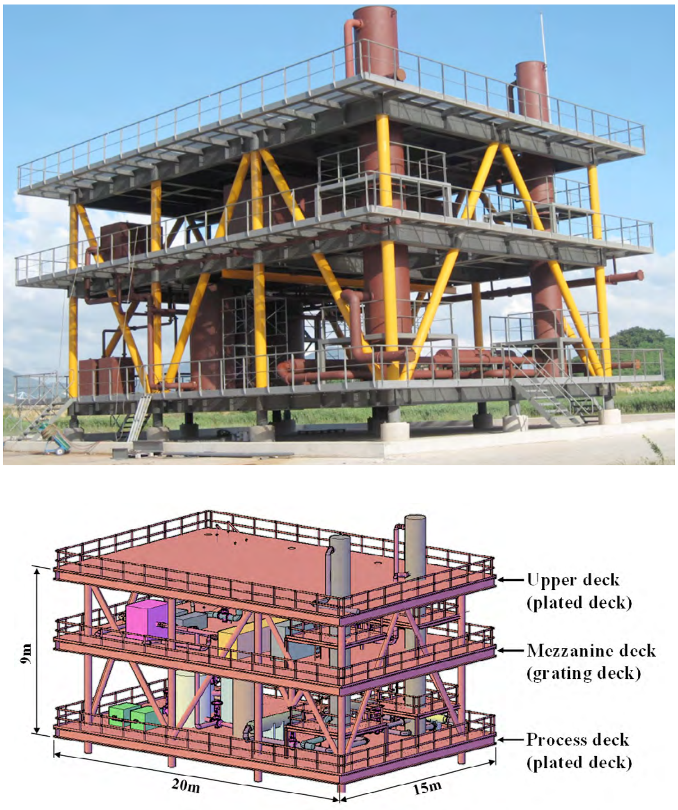


Figure 25 Layout and principal dimensions of a target structure for FSI analysis of the topside module on an offshore installation subjected to a pool fire

6.2 FSI analysis of topside structure subjected to pool fire

6.2.1 KFX simulation of topside structure in pool fire

Figure 26 shows the target structure from a KFX CFD simulation, and the location of the diesel pool fire. The diameter of the pool is 2.097 m, its depth is 1 m, and the detailed scenario of the pool fire is as follows:

- Oil: Diesel ($C_{12}H_{26}$);
- Leak amount (burner volume): 3.454 m^3;

- Oil specific weigh: 28.5 kg;
- Leak position of centre of pool in the X direction: 4.3 m;
- Leak position of centre of pool in the Y direction: 4.8 m;
- Leak position of centre of pool in the Z direction: 3.7 m;
- Total simulation time: 1800 s.

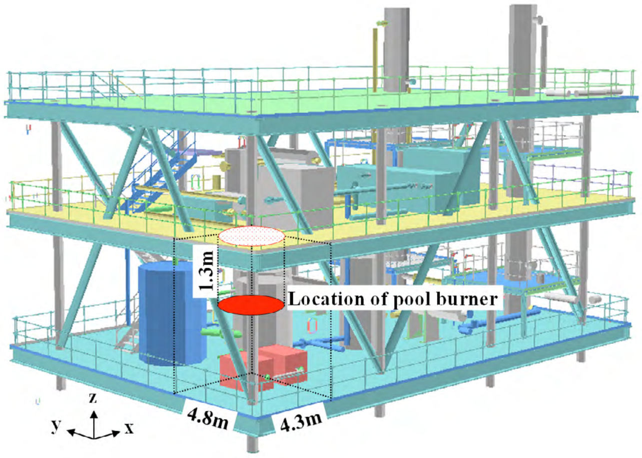


Figure 26 Model of the target structure for KFX CFD simulation and location of the pool fire

In the case of the jet fire, a fire duration is set based on the time needed for escape. In the case of the pool fire, however, it is the total amount of fuel that is defined, and the fire duration is automatically determined by the time required to burn all the fuel.

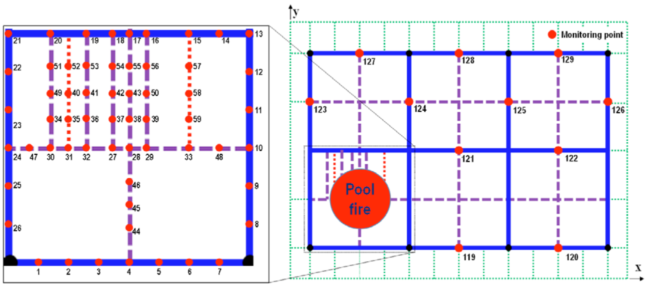


Figure 27 Location of monitoring points on the mezzanine deck to obtain fire loads, transferred loads and structural response

Figure 27 shows the monitoring points on the mezzanine deck for obtaining not only the fire loads (such as temperature and heat flux in KFX), but also the transferred loads (steel temperature in KFX2DYNA) and the structural response (deflection in ANSYS/LS-DYNA). Above the location of the pool burner, additional monitoring points are located at the upper/lower flange and the centre of the web.

6.2.2 Transfer of thermal loads to structure

The method for the transfer of thermal loads to the structure is same as that used in the heat transfer analysis of the I-girder in the jet fire, except for the time increments.

Four time increments are considered, and their effects are tested as in the FSI analysis of the I-girder. These time increments are 30, 15, 10, and 5 (min), as follows:

- Case I: 1800 s;
- Case II: 900 s;
- Case III: 600 s;
- Case IV: 300 s.

6.2.3 Structural analysis

In the structural analysis of the topside structure, the extent of the analysis is limited to the mezzanine deck as the pool fire only affects structures above and around the pool. Figure 28 shows the extent of the structural model, which consists of the mezzanine deck and its columns in ANSYS/LS-DYNA.

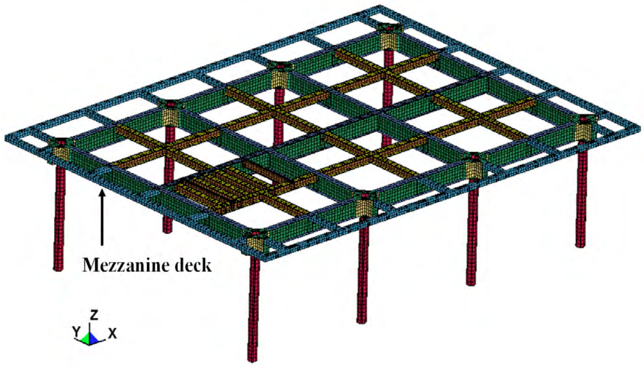


Figure 28 Extent of structural analysis model for nonlinear FEA

Figures 29 and 30 and Table 4 present the detailed layout and the dimensions of the structural members at the mezzanine deck. All of the structural members are made of mild steel, with a yield stress of 235 MPa and a Young's modulus of 205,800 MPa. An elastic perfectly

	$h_w \times t_w + b_f \times t_f$ (mm)
Primary frame	700 × 13 + 300 × 24
Secondary frame	300 × 10 + 300 × 15
Tertiary frame	300 × 6.5 + 150 × 9
Rectangular frame	200 × 10 + 200 × 10

Table 4 Dimensions of frames

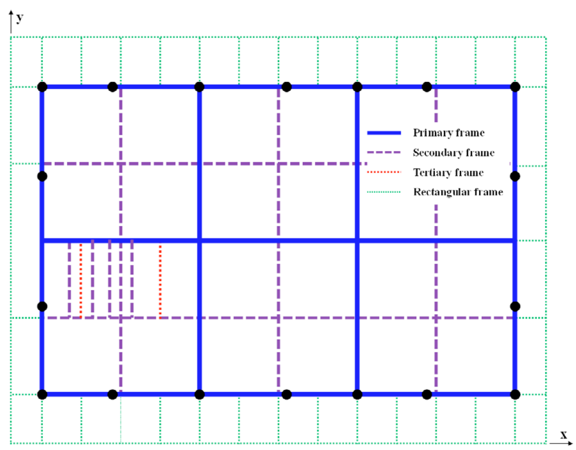
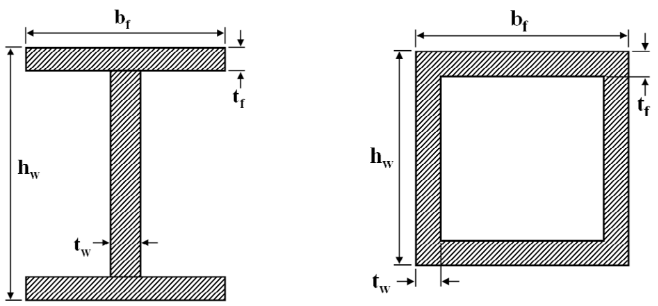


Figure 29 Detailed layout of structural members at the mezzanine deck



(a) Primary, secondary and tertiary frames

(b) Rectangular frame

Figure 30 Geometric properties of the frames

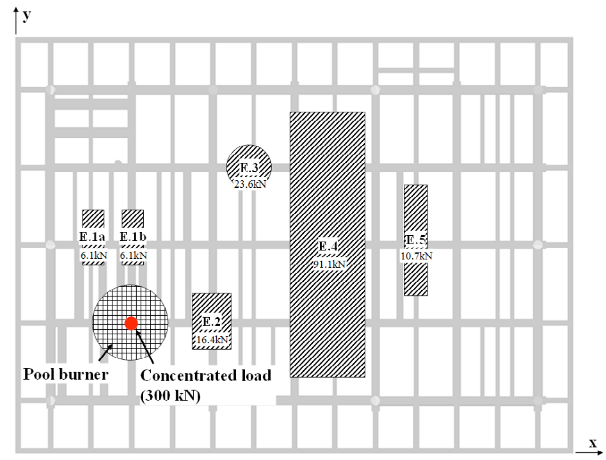


Figure 31 Location of equipment on the mezzanine deck

plastic material model is applied, and the changes in material properties (as presented in Figures 2(a) and 6) are considered.

With regard to loading conditions, five types of equipment items are located on the mezzanine deck, as shown in Figure 31. In addition, a concentrated load of 300 kN is applied at the centre of the pool. More details of the structural members, layout and equipment are described in a paper by Kim (2016).

Topside structures on floating offshore facilities are generally fixed on support members on the deck of the hull side, as shown in Figure 32. There is however no rotational restriction. As such, a fixed condition with three displacements is applied at the bottom of the main columns. Figure 33 shows the boundary conditions applied to the structural analysis, which is considered a part of the FSI analysis in this study.

6.3 Results of Analysis

Figure 34 shows the results of the FSI analysis considering the pool fire scenario, including the CFD simulations, the heat transfer analyses and the nonlinear FEA at monitoring point 28, which is above the centre of the pool burner, as shown in Figure 27.

Figure 34(a) shows the gas cloud temperature-time histories from KFX fire CFD simulation, according to different time increments.

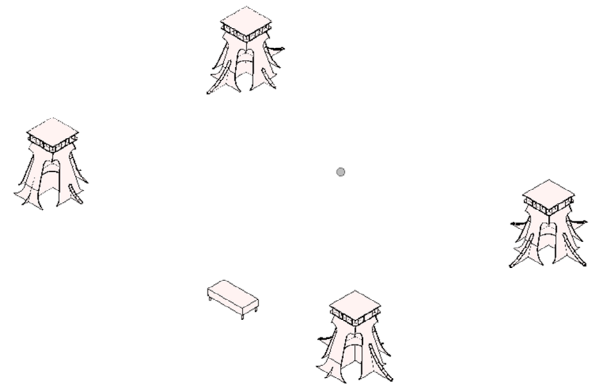


Figure 32 Example of support members on the hull side of a floating installation, to retain the position of the topside module

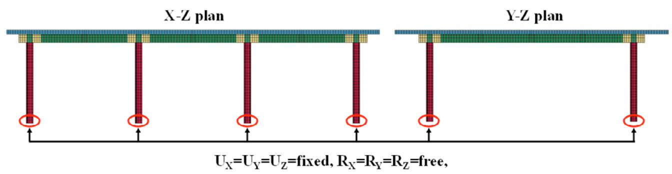


Figure 33 Applied boundary conditions for structural analysis

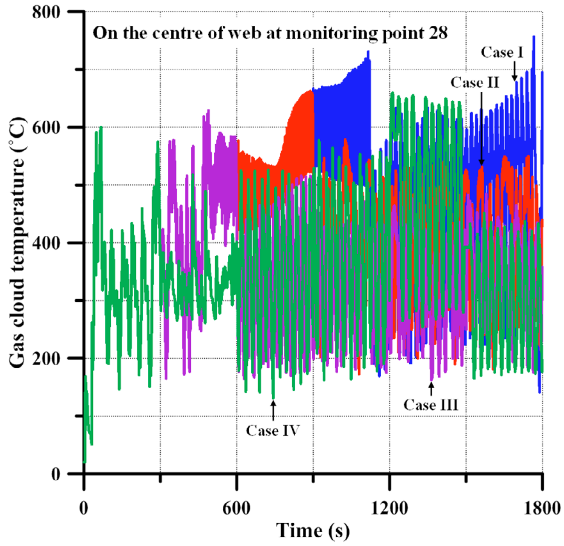
In the case of the FSI analysis of a pool fire, there are large differences in gas cloud temperatures for different time increments because the temperatures generated by the pool fire vary significantly according to the distance from the pool. Therefore, a case with finer time increments in FSI analysis leads to lower gas cloud temperatures with lower deflections.

Figure 34(b) provides the steel temperature-time histories at monitoring point 28 from the heat transfer analysis, and Figure 34(c) shows the structural response, which indicates the deflection at point 28 (centre of the web) versus the time histories predicted by the ANSYS/LS-DYNA nonlinear FEA, according to the four selected time increments.

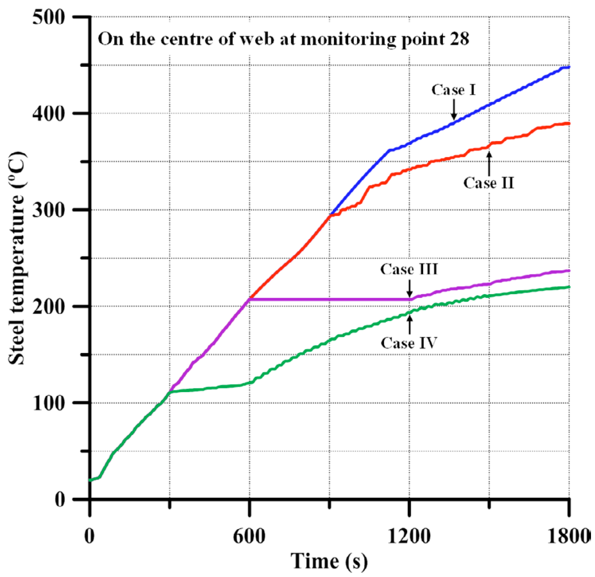
In Figure 34(c), major differences in terms of deflections can be seen for the various cases due to the different time increments (which lead to different gas and steel temperatures). These differences show that the two-way FSI analysis should be performed with finer and finer time increments, as for the FSI analysis considering jet fire.

Figure 35 illustrates the deflections at 1800 s versus the time increments of two-way FSI analysis for deciding the most adequate time increment. In this study, time increments of 5 min are considered as the most suitable time increments for the FSI analysis of the structure subjected to a pool fire. However, additional analysis with finer time increments should be considered as the strength of the structure decreases.

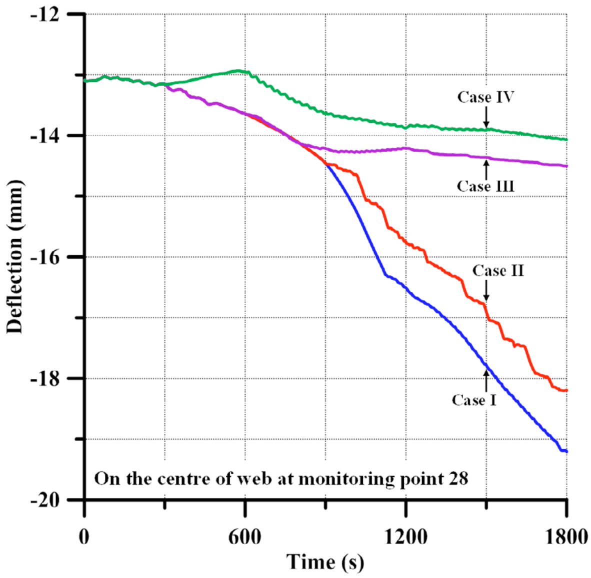
Figure 36 shows the deformed shapes of the topside structure following the completion of all the simulations.



(a) Gas cloud temperature-time histories from the CFD simulation



(b) Steel temperature-time histories from the heat transfer analysis



(c) Deflection-time histories from the nonlinear FEA

Figure 34 Results of FSI analysis considering pool fire scenario

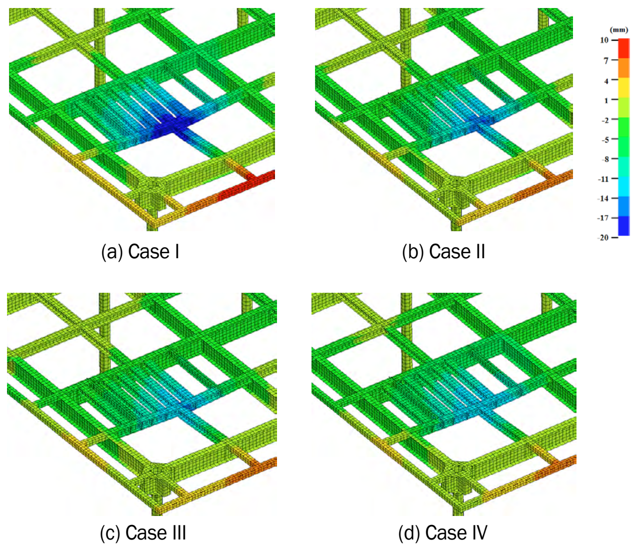


Figure 35 Deformed shape according to nonlinear structural analysis at 1800 s

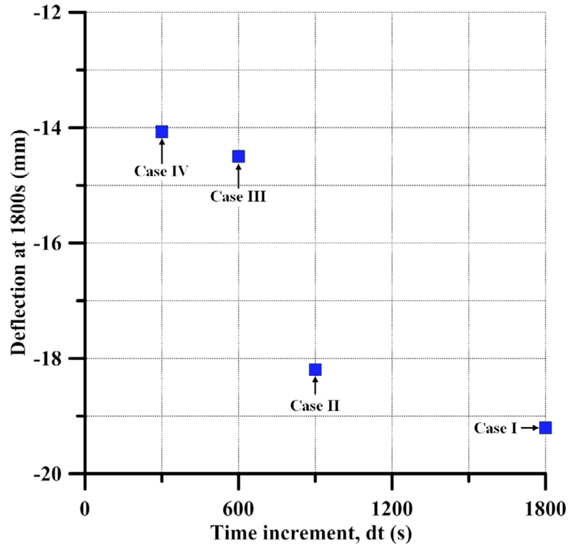


Figure 36 Maximum deflection versus time increment of FSI analysis considering pool fire scenario

7 Conclusions

The objectives of this study were to investigate the interactions between the fire loads, time-varying geometry and material properties in fire. Based on the results, the following conclusions and further studies can be drawn.

1. Existing guidelines and industry practices for fire safety assessment are primarily based on a deterministic approach using the one-way FSI analysis method;
2. Some guidelines (e.g. the EN code) specify a simulation-based approach, but they still use the one-way method;
3. Some industry practices (e.g. API) specify procedures for risk assessment and management, but these procedures are based on a qualitative rather than a quantitative approach. It is obvious that a quantitative approach is much better than a qualitative approach;

4. The one-way method is sufficient for structures with uniform fire loading conditions, as in a furnace, where the interaction effects between fire loads, time-varying geometry and material properties can be neglected;
5. For non-uniform fire load cases, however, the two-way method should be applied to account for the various interaction effects;
6. For a smaller and simpler structure, e.g. the I-girder in a jet fire considered in the present study, the time increment can be 15 min for the two-way method analysis;
7. For a larger and more complex structure, e.g. the topside structure subjected to a pool fire considered in the present study, the time increment can be 5 min for the two-way method analysis;
8. The one-way method analysis tends to overestimate structural consequences (e.g. with larger deformation predictions) compared to the two-way method analysis. This may be due to the fact that the changes of the time varying geometry and material properties are not accounted for in the one-way method;
9. As the structural consequences become more severe with time, the differences between the one-way versus two-way methods become more significant.

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