Risk-Based Passive Fire-Protection Optimization

Enrique Munoz-Garcia, MMI Engineering Limited

Summary
Passive fire protection (PFP) has been used in the oil and gas industry for many years as a method to avoid/delay global collapse of offshore installations. However, location of PFP has normally been based on simplistic assumptions, standards, guidance, and methods that do not always consider the real response of the structure to fire. The resulting PFP schemes can be conservative, leading to unnecessary cost to the operator in terms of application and maintenance costs. More importantly, there is the potential for the PFP scheme to be insufficient for the actual fire hazards, which will increase the level of risk to the personnel onboard.

Fire-induced progressive collapse is a function of the level of redundancy of a structure; it is for this reason that redundancy analyses have sometimes been used as a simplistic method to calculate the level of PFP required. However, this method does not take into account the size of the fire threat against which the PFP is designed and could lead to less-than-conservative results because it considers removing only one member of the structure at a time, without considering reduction in the strength of the surrounding members as they are also being heated by the fire.

Performance-based fire-collapse analysis provides an understanding of the response of the individual members, as well as the entire structural system, to fire. Understanding the failure mechanisms, susceptibility to progressive collapse of the structure, and key members that must remain in place during an accident situation allows for the optimization of the PFP scheme, protecting only the required members while allowing for local failure of redundant members.

The present paper provides a comparison between the different methods, and provides case studies that have resulted in optimum PFP schemes linked to design fires on the basis of acceptable risk levels.

Introduction
Hydrocarbon fires on offshore installations are extremely hazardous, involving large heat loads, which can have serious consequences for health, safety, and the surrounding environment. Ever since the 1988 Piper Alpha accident (Cullen 1990), the offshore industry has made increasing efforts to ensure the safety of both personnel and assets. More recently, the 2010 Deepwater Horizon (BP 2010) accident highlighted the importance of providing an adequate level of protection to offshore installations against accidental fire events.

PFP has been used in the oil and gas industry for many years as a method to avoid/delay global collapse of offshore installations. However, the location of PFP has normally been based on simplistic assumptions, standards, guidance, and methods that do not always consider the real response of the structure to fire. The resulting PFP schemes can be conservative, leading to unnecessary cost to the operator in terms of application and maintenance costs. More importantly, there is the potential for the PFP scheme to be insufficient for the actual fire hazards, which will increase the level of risk to personnel.

The recent Fire and Blast Information Group (FABIG) Technical Note (TN) 11 (2009) has set out a methodology to perform a detailed fire-risk assessment to calculate the design accidental loads (DAL) that can be applied to a fire zone within an oil and gas installation. The calculation of the DAL within each fire zone is achieved by performing a risk-based approach, which takes into account the probability of a fire event on the basis of the cumulative frequency of each possible event. The DAL is then selected on the basis of risk-acceptance criteria.

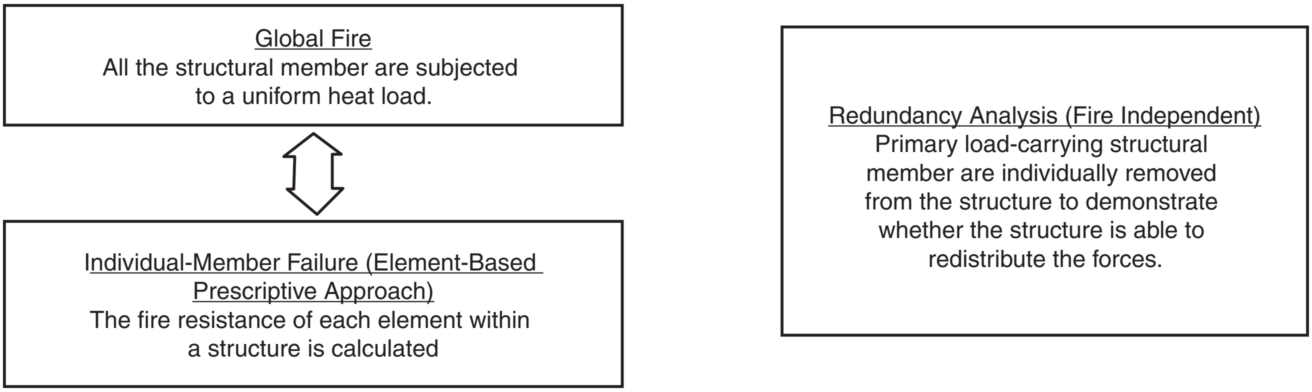
FABIG TN 6 (2001) and 11 (2009) also provide a methodology to calculate the response of the structure subject to the calculated DAL. The effects of the DAL on a topside structure are calculated by performing a coupled heat-transfer analysis that uses the magnitude and distribution of the heat fluxes calculated in the fire-risk assessment as an input. The output of the thermal analysis is the temperature distribution with time for each of the structural members. A structural analysis is then performed to calculate the response of the global structural system. This analysis combines the gravity loads with the thermal loads, and provides an understanding of the failure mechanism and withstand time of the protected and unprotected structure for a given design fire.

The methodology outlined in the preceding paragraphs requires the use of specialized software packages, such as 3D computational fluid dynamics (CFD) and nonlinear finite-element analysis (FEA), which require a high degree of expertise and, consequently, are thought to be more expensive than other simplified methodologies.

These simplified methodologies can be divided into two main groups: Assessment of element capacity to fire loading and assessment of the redundancy of a structural system. The first group calculates the temperature required for an individual structural member to fail; the second group measures the level of redundancy of a structural system by removing individual members from the structure to measure their influence on the structural integrity of the entire system. Both methods avoid the use of a specific fire hazard. The present paper compares the results obtained from these simplified methods and highlights some of the pitfalls that can occur when using these methods.

Traditional Simplified-Analysis Strategies To Calculate the Required PFP Scheme
There are two main types of simplified analyses that can be used to calculate the fire protection required in a structure. Both simplified approaches are intended to be independent of the fire threat. **Fig. 1**

This paper (SPE 166573) was accepted for presentation at the SPE Offshore Europe Oil and Gas Conference and Exhibition, Aberdeen, UK, 3–6 September 2013, and revised for publication. Original manuscript received for review 6 June 2013. Revised manuscript received for review 28 August 2013. Paper peer approved 18 September 2013.



(a) Individual-element structural fire-resistance design

(b) Measurement of the redundancy of the structure

Fig. 1—Traditional simplified methods to design PFP.

presents a summary of the traditional simplified methods to design the PFP scheme.

Global-Fire/Individual-Member Failure. The traditional approach for specifying fire protection used to concentrate unduly on the most severe fire-loading requirements in an attempt to define the required PFP. This fire hazard was then applied to all steelwork within a topside module, which resulted in the PFP being overspecified to meet this extreme fire-loading condition.

Application of a global fire that engulfs the entire structural system results in the heat up of all of the individual members simultaneously. In real terms, this represents analyzing the individual fire resistance of each of the members forming part of a structural system. Redistribution of the loads can therefore be neglected as all the members lose their strength simultaneously, removing the redundancy of the system. Within this approach, we can find the following two types of analyses:

1. Heating up the entire structure
2. Individual-element heatup

The critical core temperatures (CCTs) and the collapse times calculated with these two different approaches result in very similar values because both methods essentially analyze the capacity of each individual member.

Redundancy Analysis. Recent advances in computational power have made it feasible to perform multiple analyses of a structural system to measure its level of robustness. A redundancy analysis can be a good demonstration of robustness and consists of the removal of one or more load-carrying members from a structural system to determine the critical members required in avoiding global progressive collapse of the structure. The analysis is then repeated until all the load-carrying members are assessed. The members identified as being critical to preventing collapse are then protected with PFP.

Typical offshore topside structures have a large degree of redundancy because the structure is designed to resist a variety of load combinations, such as construction, load out, transportation, and lifting, in addition to normal and extreme operations. The design and configuration to resist all of these conditions produces very redundant structural systems that can survive the loss of a single load-carrying member when subject to operational loads.

However, it must be noted that this could give a result that is not conservative for the reason that this method does not take into account the size of the fire threat against which the PFP should be designed. This method considers removing only one or more members of the structure at a time, without considering reduction in the strength of the surrounding members as they are also being heated by the fire. Because no specific fire hazard is defined, it is not easy to predict the size and extent of the fire and, consequently, the number of members being engulfed by the fire.

Risk-Based PFP Design

Scenario-based design requires a more-detailed consideration of fire characteristics such as size, type, heat-flux intensity, and duration, and consideration of which structural members are affected for that particular scenario.

Combining these features permits a far more rational design of the PFP scheme. For example, scenario-based design may show that while the initial fire is very severe, the fire could reduce rapidly in magnitude as a result of emergency shutdown and depressurization, thus removing the heat load before structural failure can occur.

The risk-based approach consists of two parts: Fire-risk assessment and fire-induced progressive-collapse analysis of the structure (presented in **Fig. 2**). This approach has been defined in the FABIG TN 11 (2009) methodology.

Fire-Risk Assessment. FABIG TN 11 (2009) describes the approach for establishing the DAL fire on the basis of a fire-risk analysis. “During the Fire Risk Assessment, the representative cases are screened via an initial fire risk analysis where the leak frequencies, ignition probabilities and inventories are combined to determine the cases with the highest risk. These representative cases are further considered in the consequence assessment involving detailed fire load modelling with CFD. The fire risk analysis is subsequently performed based on the consequence results and the fire frequencies.

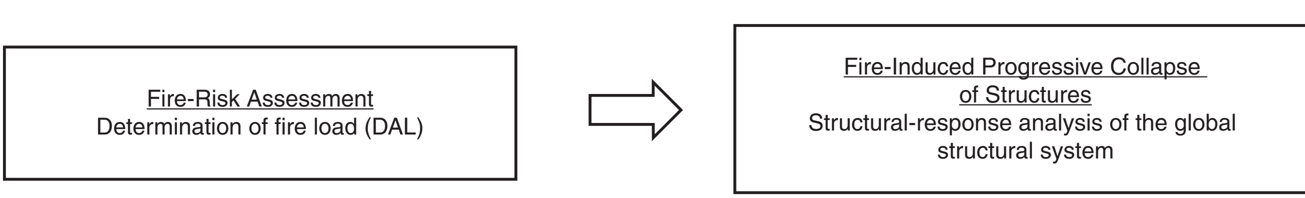


Fig. 2—Risk-based design of PFP.

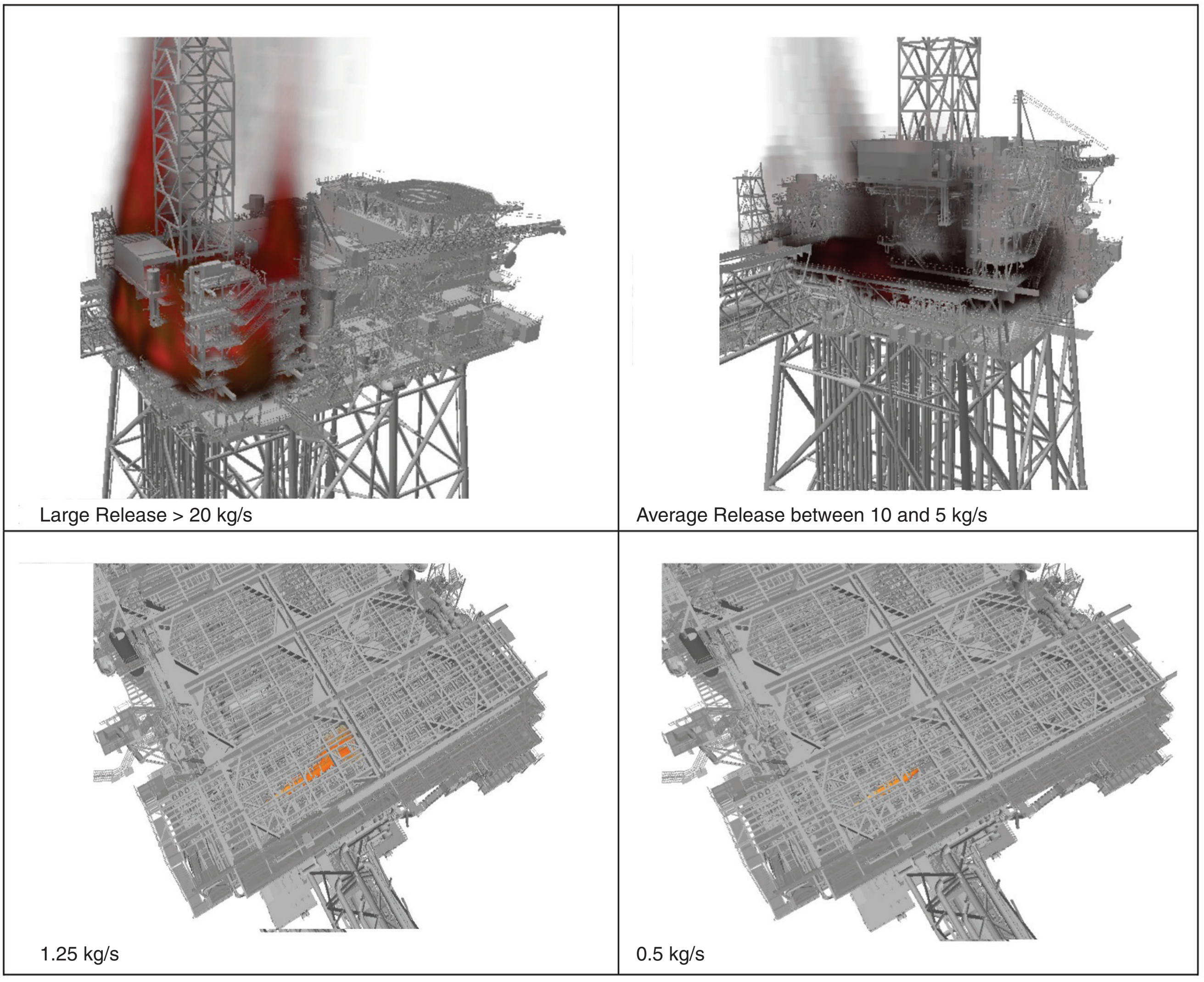


Fig. 3—Jet fires and release rates

The output from the fire risk analysis is the fire exceedance plot which is used to assess the DAL fire scenario and load. The risk acceptance criterion (RAC) is then applied to determine the DAL fire which is used to assess whether mitigating measures such as improvements to the Emergency Shut Down (ESD) and blow-down system are required."

Realistic Transients Fire. Because of the nature of fires, neither heating nor cooling will occur simultaneously in all parts of the structure. This implies that stresses and material strengths may be increasing in some areas but decreasing in others at any time during a fire event (Wang et al. 2012). **Fig. 3** presents a CFD example of the transient nature of a jet fire on an offshore platform. A typical jet fire will generally start with a larger release rate at the beginning of the event; the size of the fire reducing as the pressure reduces. The speed of the reduction may be increased if isolation and blowdown are initiated, such as in the event of confirmed fire detection.

Another characteristic from transient fires that can also be seen in Fig. 3 is the level of interaction between the fire and the structure as a function of release rate. Larger release rates cause fire spread around the structure because the jet fires impinge large obstructions such as walls, pipelines, and vessels, which disperses the fire within the fire zone. Smaller release rates will be more concentrated around smaller areas, reducing the areas of influence of the fire.

The CFD results also highlight that characterizing fires by use of phenomenological models will ignore the interaction of the fire with the module structure unless an estimate of the potential flame spread is made.

Structural-Response Analysis. Performance-based, nonlinear structural-fire-collapse analysis provides an understanding of the response of individual members, as well as the entire structural system, to fire. Understanding the failure mechanisms, susceptibility to progressive collapse of the structure, and the key members that must remain in place during an accidental situation provides the scope for optimization of the PFP scheme by protecting only the key load-carrying structural members while allowing for local failure of redundant members.

A rational approach to fire-safety assessment is to relate functional requirements (such as prevention of spreading heat and smoke and safe evacuation and rescue) to fire resistance, considering both local and global stability of structures. In a performance-based design, the structural fire engineer needs to first understand the level of performance that is expected. At the beginning of the performance-based analysis and design of an oil and gas installation, the fire engineer and the operator should both agree on the project scope and purpose of the PFP—for example, is the PFP to support evacuation or asset protection? It is the role of both safety and structural engineers to define and prioritize the performance

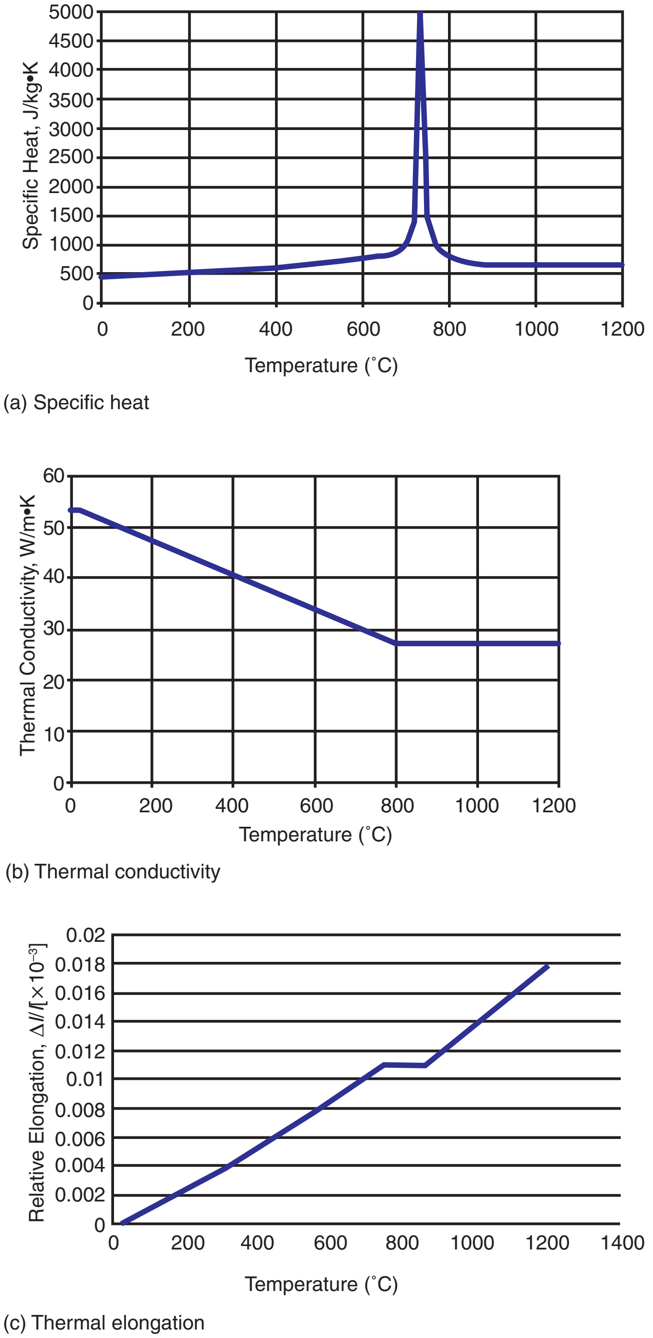


Fig. 4—Thermal properties of carbon steel: (a) specific heat, (b) thermal conductivity, and (c) thermal elongation.

criteria that must be met, and the fire safety goals and objectives pertaining to the PFP design intent.

The process for performance-based design would involve the following steps:

1. Identify goals and design objectives.
2. Establish appropriate performance criteria to meet the design intent of the PFP.
3. Evaluate the structural response to the calculated DAL scenarios.
4. Ensure robustness of the design, and the reliability and durability of the protection systems.

Fire-Induced Progressive Collapse. As a result of the introduction of performance-based approaches to design, it is now possible for designers to treat fire in the same manner as any other form of load. However, for this to happen, it must be possible for designers to predict with confidence how a structure will respond to fire. Considerable research and effort have been dedicated in recent years to providing the knowledge needed for this, and significant progress has been made.

The structural behavior in fire in all but the simplest cases is much more complex than analysis based solely on loss of material strength because of heating (Wang et al. 2012). High temperatures affect the mechanical properties of the structural materials, resulting in changes to the linearity, strength, modulus, and defined yield point of the material. If this is added to the fact that a real fire travels in space and time, then this means that not only the stresses within a heated structure change with time, but also the structure's strength changes, and all this must be considered during analysis. A final consequence of the heating induced by a fire is the thermal expansion. Large stresses can result if this expansion is restrained. These new stresses should be taken into account in a global model to avoid failure of the structure caused by an unforeseen failure mechanism. A global analysis should be able to account for material nonlinearity, geometric nonlinearity, and time and temperature varying strength.

Nonlinear Material Modeling. *Nonlinear Material Modeling of Steel.* Material properties of steel should be defined to perform the thermal- and structural-response analysis of steel structures because of fire. API RP 2FB (2006) and BS EN 1993-1-2:2005 (BSI 2005) provide the thermal and mechanical properties necessary to perform a nonlinear structural-response analysis under fire loads.

Thermal Material Properties of Steel. The required thermal material properties of steel are: coefficient of thermal elongation, specific heat capacity, thermal conductivity, density (for calculating "thermal" inertia), and surface emissivity. Specific heat capacity, thermal conductivity, and the coefficient of thermal elongation vary at different temperatures both for carbon steel and for stainless steel; this can be modeled according to BS EN 1993-1-2:2005, as can be seen in **Fig. 4**.

Mechanical Properties of Steel. In general, the strength and stiffness of steel with increasing temperature is decreased. Therefore, for structural-response analysis because of fire, the temperature-dependent mechanical properties should be considered.

Elevated-temperature material-property data found in BS EN 1993-1-2:2005 are based on both transient-state (nonisothermal) and steady-state (isothermal) tests, derived from extensive testing and research conducted by numerous establishments. The variation of these reduction factors with temperature is illustrated in **Fig. 5.** It can be seen that carbon steel begins to lose strength at temperatures greater than 400°C. The Young's modulus begins to change at lower temperatures (100°C).

Nonlinear Material Modeling of PFP. The PFP coating materials most commonly used in the oil and gas industry can be categorized into two main types: Epoxy intumescent and cementitious. Epoxy PFP undergoes chemical and physical changes when exposed to fire, while cementitious PFP does not react.

Epoxy PFP is widely used offshore for structural members, external decks and roofs, underside decks, equipment enclosures, pipe work, and risers. A chemical reaction takes place and the material starts to expand when exposed to fire. How much it expands varies between products, and it can expand to many times its original thickness. The expansion provides an insulating char, which protects the substrate. As a result of the increase in volume, the density of the material decreases. Predicting the response of PFP can be very difficult and is different for each proprietary PFP product. Evaluating the exact response of intumescent materials is currently the subject of much research, and results are outside of the scope of this paper.

On the other hand, cementitious PFP maintains the steel surface temperature at 100°C because trapped water is turned to steam. The endothermic reaction of this change-of-phase process in the water provides insulation until all the water is evaporated. Once the hydrates are spent, the temperature on the unexposed side of an endothermic fire barrier tends to rise rapidly.

Simplification of the actual response of both PFP materials can be made using, for example, the methodology provided in BS EN 1993-1-2:2005 to evaluate the temperature buildup of structural members insulated in PFP on the basis of constant thermal properties.

Risk-Based PFP-Optimization Procedure

The fire-load response analysis is based on a general calculation method that uses CFD to calculate the heat-flux fields on the topside caused by specific fires within each fire zone, followed by nonlinear FEA, which considers the structural system as a whole. This approach allows a realistic simulation of the response of structures exposed to fire. The general calculation method consists of separate CFD thermal- and structural-response analyses:

- CFD analysis: Specific jet or pool fires are simulated within the considered fire zones; the results from these analyses are the heat-flux fields produced by steady-state fires with specified constant release rates. This leads to the production of a DAL fire to be used within subsequent analyses, as representative of the likely fires to which the platform will be subjected.
- Thermal-response analysis: The thermal-response analysis determines the heatup of the structure. The inputs to this analysis are the heat-flux fields associated with the DAL that are calculated during the CFD analysis. The calculated temperature history for each individual structural member is subsequently entered into the structural-response analysis.
- Structural-response analysis: The structural analysis determines the response of the structure subjected to a combination of dead, live, and fire loads. The structural analysis traces failure of structural components, force redistribution within the structural system and global and local collapse, and establishes the deformations of the structure during the fire. Subsequently, it can be determined if the structure meets the relevant acceptance criteria, and whether PFP is required to help it achieve this.

Failure-Screening Procedure. The dimensioning fire, characterized by heat-flux contours, is positioned at a number of locations throughout the fire area to cater for the possible range of release source locations and orientations. This process ensures that multiple leak locations are considered, thus accounting for variability in the location of the fire. This is achieved by running a series of independent thermal-response analyses for each fire location and release. Each thermal analysis is then followed by a mechanical-response analysis.

PFP-Optimization Procedure. The optimization of any PFP to be applied identifies the critical structural components that need to remain intact during the identified fire scenarios to withstand the structural loads for a required period of time so that the acceptance criteria are met. The flow chart shown in **Fig. 6** shows the assessment procedure for determining the optimum structural-protection scheme.

Robustness in the Context of Fire. The prevention of disproportionate or progressive structural collapse is provided by structural robustness. The formal definition of robustness is defined in NA to BS EN 1991-1-7:2008-12-31 (BSI 2008) as “the ability of a structure to withstand events like fire, explosions, impact or the consequence of human error without being damaged to an extent disproportionate to the original cause.” This is an active research topic, and there is still no definitive methodology of providing means of achieving adequate robustness for structures in fire.

There are few strategies to increase the redundancy of a structure to enable it to resist accidental loading, such as:

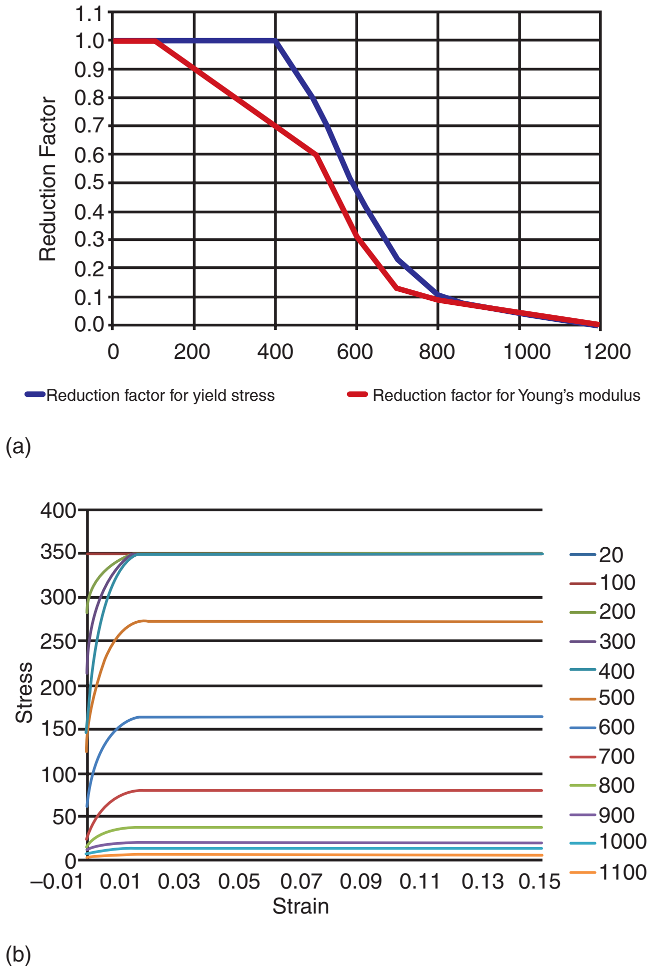


Fig. 5—(a) Reduction factors for carbon steel at elevated temperatures; (b) stress/strain relationships for carbon steel at elevated temperatures.

- Enhance redundancy; provide alternative load paths.
- Key elements designed to sustain notional accidental load.

In the case of a fire design, the protected structure should be able to withstand the additional loads generated by the load redistribution because of the load shedding of the failed, unprotected members. The procedure presented in Fig. 6 allows the designer to identify if the proposed PFP is located correctly on members that can sustain the redistribution of all the loads and prevent the structure from reaching a global-collapse state. If collapse is detected in any members within the PFP scheme, then additional PFP should be added to the surrounding members until the structure is able to withstand the full endurance period required.

Comparison of the Different Methods to Calculate the PFP Scheme

To demonstrate the aspects discussed in this paper, a sensitivity analysis was performed using specialized software tools—fire and heat-transfer simulator (FAHTS) (USFOS Reality Engineering 2011) and Ultimate Strength of Framed Offshore Structures (USFOS Reality Engineering 2012)—which have the capabilities to evaluate the survivability of offshore structures from fire loading. It is possible within USFOS to import Kameleon FireEx (KFX) 3D CFD (ComputIT 2013) results directly, allowing coupling of the CFD and FEA to model and assess the collapse mechanism.

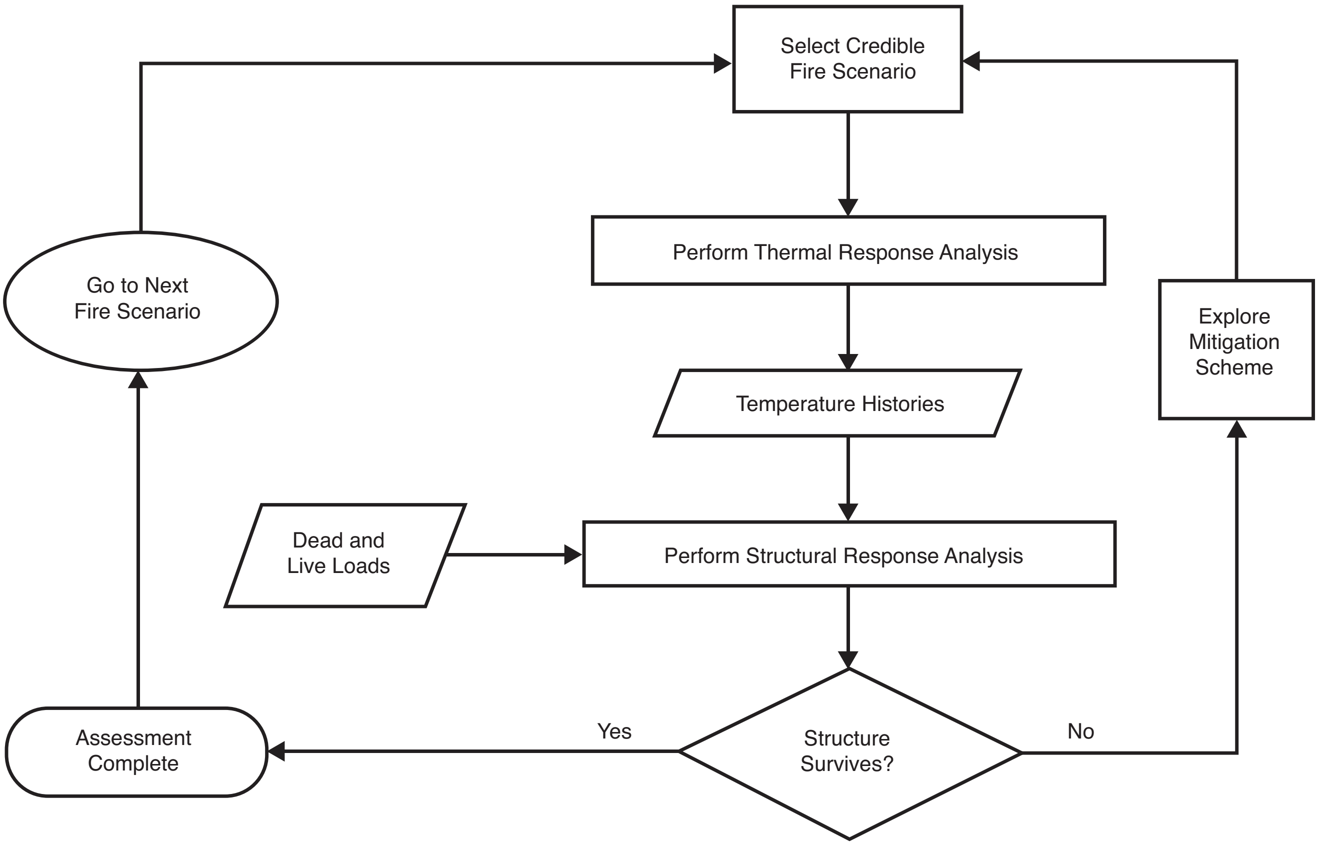


Fig. 6—Assessment procedure for determining an optimum PFP scheme.

The model selected for the assessment is representative of a typical, integrated module design. Offshore modules are normally highly redundant as a result of the large number of load combinations that are considered during their design. The module analyzed is presented in **Fig. 7.**

The module was subject to three assessments as follows:

- Global fire
- Redundancy analysis
- Risk-based PFP optimization

Global Fire. The fire scenario considered was a fully engulfing fire that heated all of the steel work in the modules. The extent of the fire is shown in Fig. 8. The only fire scenario considered was an all-engulfing high-momentum jet fire with a heat flux of 250 kW/m^2, which corresponded to the lower thermal-radiation values for a jet fire in accordance with recommendations provided in the FABIG TN 11 (2009). This fire was applied constantly for a period of 60 minutes.

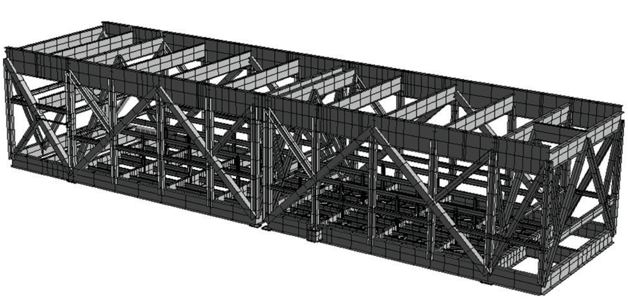


Fig. 7—Typical offshore module analyzed using the different methods to calculate PFP.

As can be seen in **Fig. 8**, the global fire results in the onset of overall failure of the structure in less than 10 minutes of exposure to the global fire. The engulfing fire produces a global failure of the primary structure with no redistribution being possible because of simultaneous failure of all the members. Consequently, the resulting PFP scheme protects most of the primary structure.

Redundancy-Analysis Method. A redundancy analysis was performed for the same structure. Traditional redundancy analyses consist of removing one or more members of the primary structure followed by a static or dynamic analysis. The purpose of this analysis is to investigate if the structure can withstand losing a member without triggering disproportionate collapse of the structure.

For this sensitivity study, a single column or primary vertical brace was removed one at a time to represent the loss of a single structural member as a result of a localized jet fire impinging any single member only. This is shown in **Fig. 9.**

The results demonstrated that the modules possess sufficient robustness to withstand losing one member without escalation of failure caused by the inherent robustness of normal offshore modules. As a consequence, it was concluded that no PFP is required for these modules.

This result emphasizes how, by making the assumption that only one member is affected by a fire, this approach could result in very little, if any, PFP being required, and consequently resulting in a nonconservative conclusion to the need for PFP.

It also highlights that without an understanding of the fire threats, no assumptions can be made on the number of structural members that must be removed simultaneously (i.e., removing a single member makes the tacit assumption that the jet/pool fire is small enough to impinge only one structural member at a time).

Risk-Based PFP Optimization. The final analysis consisted of calculating the most probable design fire on the basis of the meth-

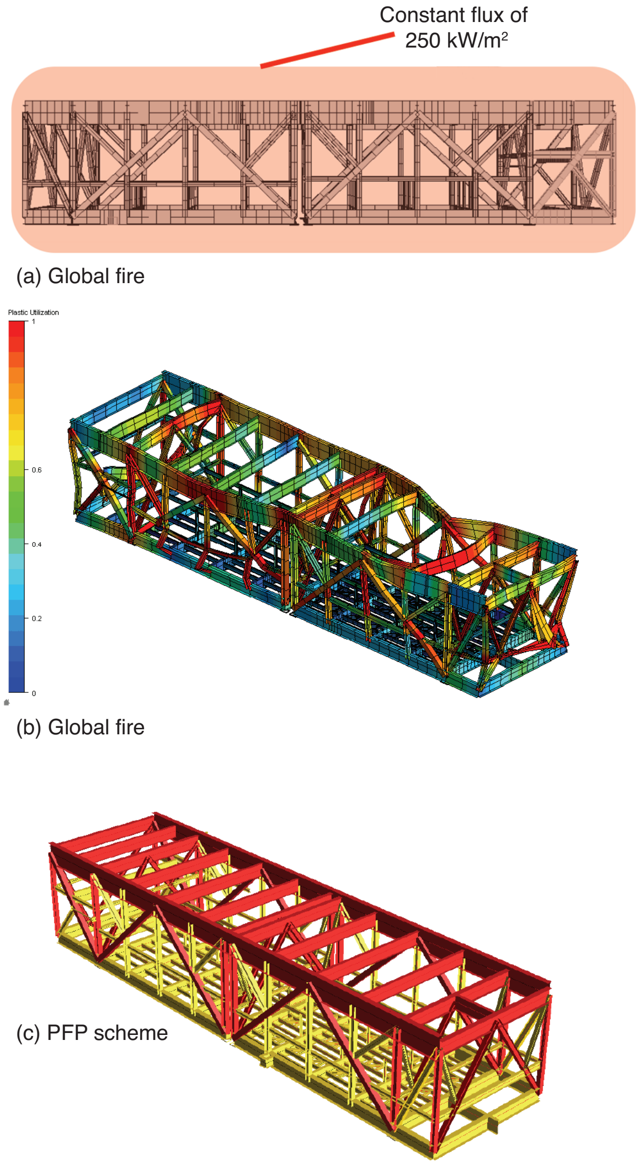


Fig. 8—PFP scheme from global-fire method.

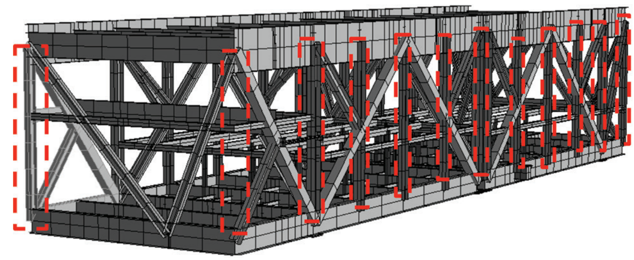


Fig. 9—Redundancy-analysis method.

odology provided in the FABIG TN 11 (2009). For the example module, the resulting design fire was a transient jet fire with an initial release rate of approximately 8 kg/s and a subsequently decaying release rate, with time, as isolation and blowdown started to have an effect.

The transient fire was represented using the results from fires as a result of a limited number (in this case, three) of steady-state release rates modeled with CFD analysis, as shown in **Fig. 10b.** The 3D heat-flux results from the KFX CFD (ComputIT 2013) analysis were then stepped through the heat-transfer-analysis model to calculate the heatup of the structure. The heat-transfer analysis was followed by a structural analysis taking after the process described in the Risk-Based PFP-Optimization Procedure section. The fire was moved around the module to investigate if any disproportionate failure could be started anywhere in the modules impinged by the DAL.

Because the design fire was quite localized and short in duration (Fig. 10c), the resulting PFP scheme was only concentrated on the primary girders supporting the primary structure above the module (Fig. 10d). This analysis also confirmed that the redundancy in the vertical members allowed for single members to be damaged without the onset of global failure in the primary structure.

Cost/Benefits Comparison. From this example, it can be seen that a risk-based approach to optimizing the PFP has the potential to reduce the costs of the PFP significantly in terms of material costs, reduced application costs, and subsequent ongoing maintenance, while providing a scheme that reduces risks to a level that is as low as reasonably practicable. The scheme becomes highly cost effective as a risk-reduction measure. **Table 1** summarizes the PFP surface areas resulting from each approach.

It can be seen that using the risk-based approach reduced the PFP required to meet the performance requirements by 92%. The redundancy methodology resulted in no PFP being required; however, this example has demonstrated that the redundancy approach would have resulted in a nonconservative PFP scheme, which would not adequately consider the fire threat. Previous experience has demonstrated that applying the risk-based PFP optimization can yield reductions in material applications ranging from 50 to 90%, depending on factors such as risk-acceptance criteria (typically ranging in frequencies between 10–4 and 10–5/year), structural usage (how heavily loaded is the structure), structural robustness, and type of fire (i.e., pool or jet fires).

Risk-based PFP optimization has been demonstrated to be very efficient in terms of reducing the initial installation cost, reducing the PFP weight, and reducing the ongoing maintenance requirement.

Discussion and Conclusions

From the results in the preceding paragraphs, the following can be concluded.

Global Engulfing Fire-Load/Individual-Member Capacity. The global analysis represents a quick analysis method to calculate the fire capacity of individual members. Using this method has the following advantages:

- It is possible to calculate the CCT that produces the onset of failure for a specified heat flux or external temperature.
- The time to reach the CCT can also be calculated for each member.
- No specific fire hazard is defined.

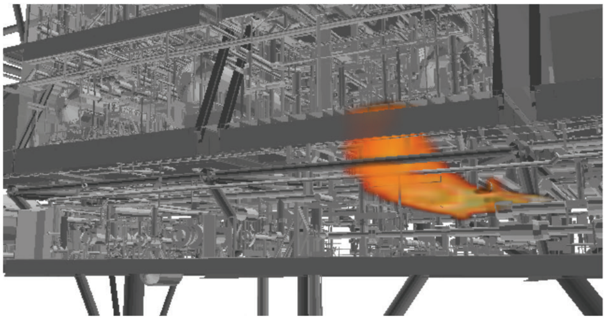
However, using this method has the following limitations:

- No load redistribution or redundancy of the structure is taken into account.
- No assessment of the robustness of the structural system can be made.
- PFP schemes are expected to be overconservative.

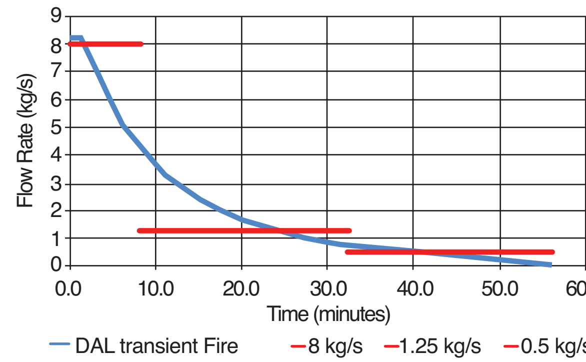
Redundancy Analysis. The following conclusions can be made when a redundancy analysis is performed on an offshore topside structure to calculate the PFP required.

Advantages:

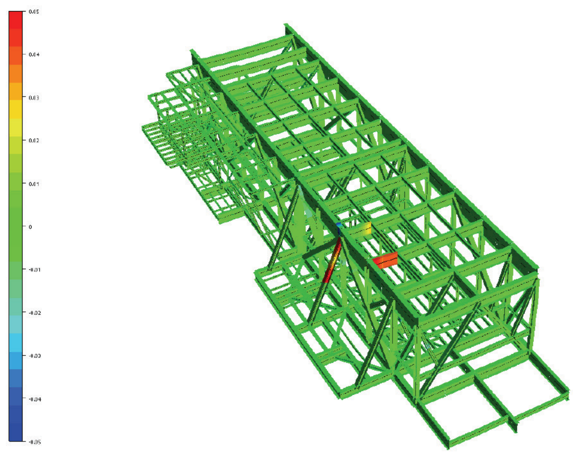
- Load redistribution can be taken into account and measured.
- This analysis produces an understanding of the failure mechanisms expected for a small fire (i.e. impinging an individual member).
- No specific fire hazard is required.



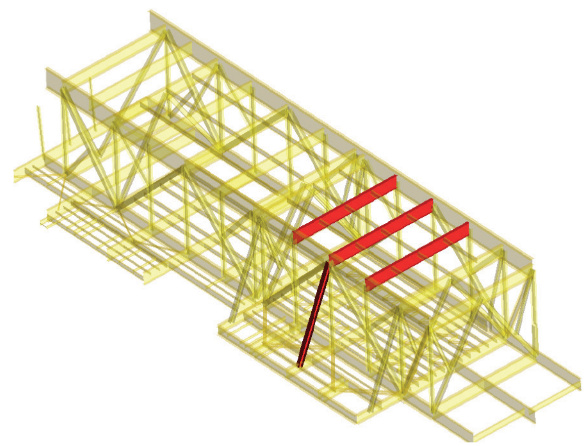
(a) CFD modeling of DAL fire



(b) 10^{-4} DAL Fire



(c) Localized structural damage because of small size of the 10^{-4} DAL fire



(d) PFP scheme

Fig. 10—PFP scheme from global-fire method.

Limitations:

- There is no understanding of the actual size of the fire threat.
- The PFP scheme produced from a redundancy analysis that removes a single member at a time is likely to demonstrate that little or no PFP is needed because offshore platform topsides are highly redundant.
- The removal of two, three, or even more members at the same time might be required to represent a real fire; however, without knowing the size of the design fire, it is difficult to predict the number of members that must be removed simultaneously.

Risk-Based PFP Optimization. The results from the sensitivity analysis using the risk-based PFP-optimization process demonstrate that it generates a cost-effective level of PFP protection appropriate for the DAL. It reduces the chances of severely underestimating the required PFP, as would be predicted when using a redundancy-analysis approach, and it reduces the chance of significantly overestimating the amount of PFP, as would be predicted when using the global-fire method. **Table 2** provides a summary comparison between the methodologies discussed in this study.

TABLE 1—COMPARISON OF SURFACE AREA FOR EACH PFP SCHEME

Approach	PFP Surface Area (m^2)
Global-fire/individual-member failure	2061
Redundancy analysis	0
Risk-based PFP optimization	156

Final Remarks. The risk-based methodology evaluates the amount of PFP required for a given risk-acceptance level. This paper has intended to demonstrate that using this methodology increases the level of certainty about the level of protection provided to the structural system, and provides a framework to demonstrate that a robust process has been followed. Although this methodology requires a higher degree of expertise in risk assessment and structural analysis, and the use of specialized software packages (such as 3D CFD and nonlinear FEA) can result in a higher analysis cost, the resulting PFP scheme is likely to yield major savings in capital expenditure and operation expenditure by reducing the material required to meet the performance requirements.

References

API RP 2FB, Recommended Practice for the Design of Offshore Facilities against Fire and Blast Loading. 2006. Washington, DC: API.

BP. 2010. *Deepwater Horizon* Accident Investigation Report. Internal Report, BP, London (8 September 2010), http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/incident_response/STAGING/local_assets/downloads_pdfs/Deepwater_Horizon_Accident_Investigation_Report.pdf.

BS EN 1993-1-2:2005 Eurocode 3. Design of steel structures. General rules. Structural fire design. 2005. London: British Standards Institution (BSI).

TABLE 2—COMPARISON BETWEEN METHODOLOGIES				
Methodology	Fire Threats Included in the PFP Design?	Redundancy of the Structure Assessed	Remarks	Size of the Resulting PFP Scheme
Global-fire/individual-member failure	No	No	No understanding of the most probable fire load and structural redundancy	Large PFP scheme expected
Redundancy analysis	No	Yes	Redundancy of the structure assessed but not linked back to a specific fire load; consequently, it could result in a nonconservative PFP scheme.	Because of inherent redundancy of most offshore production platforms, the resulting PFP scheme is normally small and underpredicted.
Risk-based PFP optimization	Yes	Yes	Design fire linked to risk-acceptance criteria. The transient nature of the fire in terms of space and time included in the analysis to capture the coupled thermal/structural response.	PFP scheme is linked to risk-acceptance criteria. PFP can be designed in terms of asset protection or evacuation purposes,, as required

ComputIT. 2013. KFX® (Kameleon FireEx), http://www.computit.no/en/Products_+_services/KFX/.

Cullen, W.D. 1990. *The Public Inquiry Into the Piper Alpha Disaster,* Vol. 1310. London: Command Papers, H.M.S.O./Great Britain Department of Energy.

FABIG. 2001. Design Guide for Steel at Elevated Temperatures and High Strain Rates. FABIG Technical Note 6, Steel Construction Institute (SCI), Ascot, UK http://app.knovel.com/web/toc.v/cid:kpDGSETHS1/viewerType:toc/?kpromoter=legacy.

FABIG. 2009. Fire Loading and Structural Response. FABIG Technical Note 11, Steel Construction Institute (SCI), Ascot, UK http://app.knovel.com/web/toc.v/cid:kpFLSRFAB6/viewerType:toc/?kpromoter=legacy.

NA to BS EN 1991-1-7:2008-12-31, National Annex to Eurocode 1. Actions on structures—Accidental actions. 2008. London: British Standards Institution (BSI).

USFOS Reality Engineering. 2011. Fahts—Fire And Heat Transfer Simulations for Performance Based Fire Design (Ver. 637), http://usfos.no/.

USFOS Reality Engineering. 2012. Ultimate Strength of Framed Offshore Structures (Ver. 8-6a), http://usfos.no/.

Wang, Y., Burgess, I., Wald, F. et al. 2012. *Performance-Based Fire Engineering of Structures.* Boca Raton, Florida: CRC Press.

Enrique Munoz-Garcia is a principal consultant in MMI Engineering's Aberdeen office, where he is heavily involved in structural fire collapse, PFP-optimization analyses, blast assessment, and design for oil and gas installations. He has more than 13 years of experience in structural engineering, with experience in the offshore oil-and-gas industry, research, and within the civil and structural building industry. Munoz-Garcia's areas of technical interest are structural integrity and extreme loading effects on structures, especially in relation to fire and explosion hazards, together with detailed structural analysis and design of strengthening and protecting solutions. He holds a BS degree in civil engineering from the National Autonomous University of Mexico and a PhD degree in structural engineering from the University of Sheffield in the UK (his research topic was the structural integrity of steel connections subjected to dynamic transient loadings).