NON-LINEAR ASSESSMENT OF OFFSHORE STRUCTURES EXPOSED TO FIRE

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This paper outlines structural analysis procedure performed to evaluate structural capacity in the event of fire as the effort to minimize weight increased by Passive Fire Protection (PFP). Fire is one of the Design Accidental Loading (DAL) to be considered to ensure the integrity of safety critical elements. DALs are determined as the load caused by an accidental event with re-occurring frequency of once per 10,000 years.

The main objective is to ensure that the primary structures can withstand the fire specified in DAL, with deformation but not collapse. The structural integrity shall be maintained to prevent further damage escalation to critical equipment. The Ductility Level Analysis method was used in accordance with API-RP-2FB, a progressive non-linear collapse analysis that allows redistribution of structural load from failed members and can indicate collapse of the structure after no further load distribution is possible. Temperature-time history loading of steel members, during the fire scenario is analyzed in combination with operating loads. The changes of steel thermal properties over the time, degradation of steel strength and stiffness are also considered in analysis. FAHTS software is used to simulate the heat transfer for each member, which afterward evaluated in non-linear collapse analysis by USFOS. The acceptance criteria are defined by critical strain of 10% for S420 and 15% for S355 steel material as the limit for material rupture.

The fire scenario consists of large jet fire (350 kW/m^2) with duration of 1.1 minute and continued by small jet fire (250 kW/m^2) with duration of 2.3 minute. The jet fire is directed on to some selected critical members i.e primary deck leg, deck beam. A pool fire scenario with radius of 3 m is also considered on selected critical area in order to maximize the potential effect of the heat loads. Live load is taken as 75% of maximum values in analysis. The analysis results indicate maximum temperature of 1700 ^{o}C are reached on structural members. No global collapse of structure recorded in any of the fire scenario. No material rapture occurred as the plastic strain for all fire scenario was below 10%. It was concluded that topside has sufficient structural integrity to survive the fire scenario without PFP.

Significant weight and cost reduction can be achieved through advanced technique and proper analysis tool to simulate the complex accidental fire and non-linear structural behavior. The 'normal' procedures on assumption that steel structures fail when the temperature exceeds 400 ^{o}C and need PFP can be optimized using this analysis approach. Application of PFP comes with a hazard 'Corrosion Under Fireproofing', which in many cases are located in area difficult to access and expensive to inspect or repair.

Keywords: Accidental Fire; Non-Linear; Offshore Structures; Passive Fire Proofing.

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1 Introduction

API RP 2FB *'Recommended Practice for the Design of Offshore Facilities Against Fire and Blast Loading*' recommends three type of assessment methods for structures exposed to fire:

- Zone (or Screening) method
  The current 'normal' assessment used by the industry that is based on the assumption or a '*myth*' that steel member cannot survive the critical 400 degree Celsius.
- Strength Level Method (Elastic Analysis)
  A conventional linear elastic analysis, the reduced stiffness and yield stress of member should be used in the analysis depending on the maximum temperature attained by the structural member for the duration of the fire
- Ductility Level Method (Non-Linear Analysis).
  A progressive collapse analysis which allows redistribution of structural load from failed members and can indicate collapse of the structure after no further load distribution is possible

The structures are expected to withstand the fire for 60 minutes for personnel evacuation as required in Fire Risk Assessment. The structural integrity shall be maintained to prevent further damage escalation to critical equipment.

Passive Fire Protection (PFP) is commonly used as one of mitigations to provide protection to offshore structures to minimize the Likelihood of Failure and to reduce risk level.

2 Ductility Level Method

2.1 *Heat Load*

The heat on structural steel members are gained due to radiation, convection and conduction resulting from pool fires or jet fire. Conduction may usually be ignored for members that are directly subject to thermal loading.

Temperature-time history loading of steel members, during the fire scenario is analyzed in combination with operating loads. The changes of steel thermal properties over the time, degradation of steel strength and stiffness are also considered in analysis.

The thermal loads are calculated using the Stefan-Boltzmann law from the heat flux. The fire loads are applied in form of temperature profile and time histories. The ambient heats is transferred into structures, which will lead to structural internal loads. To convert the ambient heat into the structural loads, FAHTS (Fire and Heat Transfer Simulations) software is utilized, which afterward evaluated in non-linear collapse analysis by USFOS.

2.2 *Material Properties*

The steel properties will be varied at elevated temperature. In particular, the yield strength and elasticity modulus shall be modified taking into account steel temperature, for which API RP 2FB will be referred. Poisson ratio for steel remains constant at 0.3 up to the melting point.

2.3 *Thermal Properties*

Thermal properties of steel refer to Table C.11.1-1 of API RP 2FB and shown in **Table 2-1** below. These are nominal thermal properties for structural steel between room temperature and 600°C, utilized to compute the fire load because of radiation, convection and conduction.

Table 2-1 Nominal Thermal Properties of Steel Ref. [0]

Steel Type	Specific Heat (J/kg °C)	Thermal Conductivity (W/m °C)	Emissivity	Coefficient of Linear Expansion (/ °C)
ASTM A36 A633 Gr. C or D	520	46 – 65	0.75 – 0.90	14 x 10-6
Stainless Steel	533	14 – 20	0.75	18 x 10-6

A variation of thermal conductivity and specific heat of carbon steel is to be accounted for based on **Figure 2-1** and **Figure 2-2** as referred to (OTI 92 604)

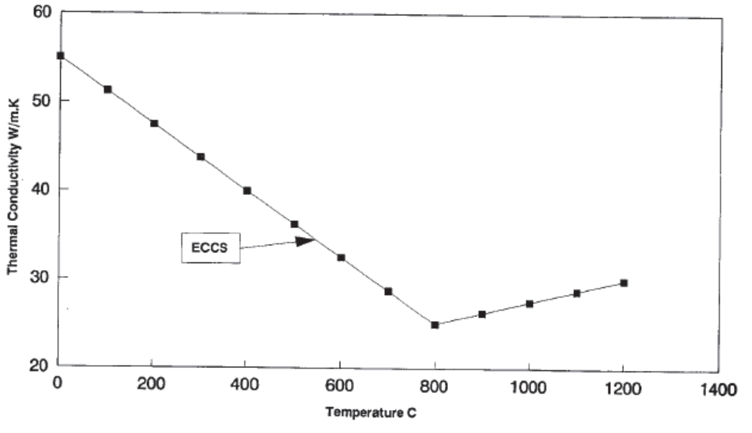

Figure 2-1 Variation of Thermal Conductivity of Low Carbon Steel with Temperature (OTI 92 604)

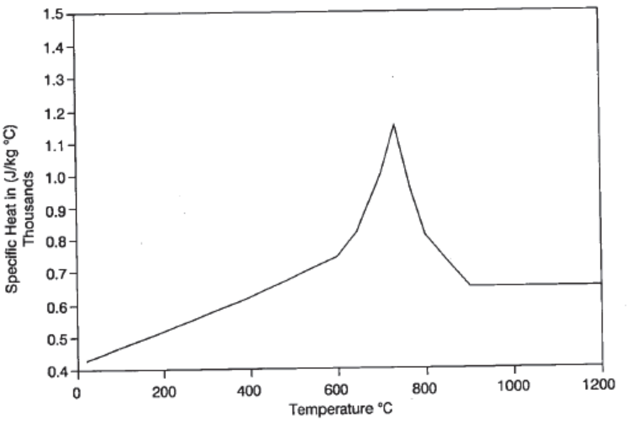

Figure 2-2 Variation of Specific Heat of Carbon Steel with Temperature (OTI 92 604)

2.4 *Mechanical Properties*

The reduction in Young's Modulus and Yield Stress due to temperature elevation as referred to API RP 2FB for strain of 2% is shown in Table 2-2 and Figure 2-3 below. Poisson’s ratio for steel remains constant at 0.3 until melting point

Table 2-2 Young's Modulus and Yield Stress Reduction Factor (API RP 2FB)

Steel Temperature		Young's Modulus Reduction Factor	Yield Stress Reduction Factor at Strain of 2%
(°C)	(°F)		
20	68	1.000	1.000
100	212	0.991	1.000
200	392	0.961	1.000
300	572	0.916	1.000
400	752	0.826	0.971
500	932	0.617	0.776
600	1112	0.173	0.474
700	1292	0.130	0.232
800	1472	0.090	0.115
900	1652	0.0675	0.062
1000	1832	0.0450	0.0446
1100	2012	0.0225	0.0297
1200	2192	0.0000	0.0149

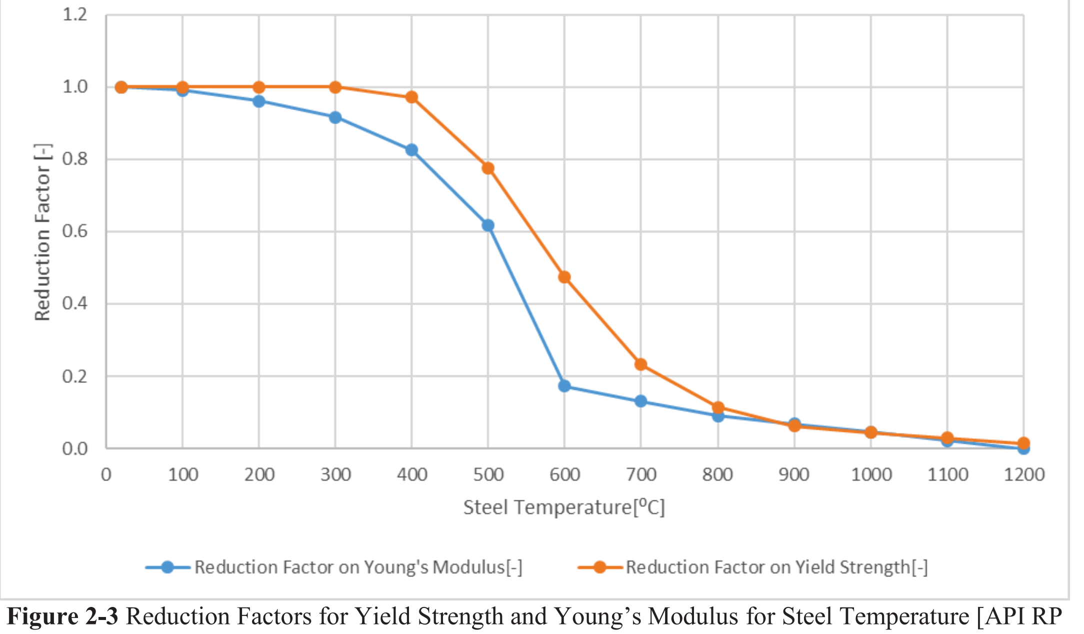

Figure 2-3 Reduction Factors for Yield Strength and Young's Modulus for Steel Temperature [API RP 2FB, for strain of 2%]

2.5 *Acceptance Criteria*

The topsides structure may sustain permanent deformation and substantial damage due to steel yielding and failure under the fire thermal loading but global collapse should not occur during the DAL duration. Strain limit is used to judge material rupture. According to Eurocode 3 Part 1-

2 initiation of material rupture of normal carbon steel at elevated temperatures occurs at strain level of 10% for S420 and 15% for S355. According to the results, the relevant mitigation including PFP options will be developed and optimized.

3 Case Study

A Process Platform topside supported by 6-Legged jacket structures consist of four deck level with dry weight of 16,500 MT in North Sea is exposed to fire in accordance with Fire Risk Assessment (FRA). Fire is one of the Design Accidental Loading (DAL) to be considered to ensure the integrity of safety critical elements. DALs are determined as the load caused by an accidental event with re-occurring frequency of once per 10,000 years.

3.1 *Fire Scenario*

The following jet fire scenario is considered:

- Large jet fire on process area Level 3 with duration of 1.1 minute
- Small jet fire on process area Level 3 with duration of 2.3 minute in continuation after large jet fire. The jet fire time history is shown in **Figure 3-1**.
- Leak size of 36 mm pointed in 6 direction of North, South, East, West, Up and Down
- Release height to be 1 m above level 3
- The jet fire length is 53 m with flame width 9.0 m in accordance with FRA.
- The jet fire is directed onto some selected critical deck legs, flare boom support and deck beam.
- A pool fire with radius of 3 m is also considered on selected critical area in order to maximize the potential effect of the heat loads.
- Live load is taken as 75% of maximum values

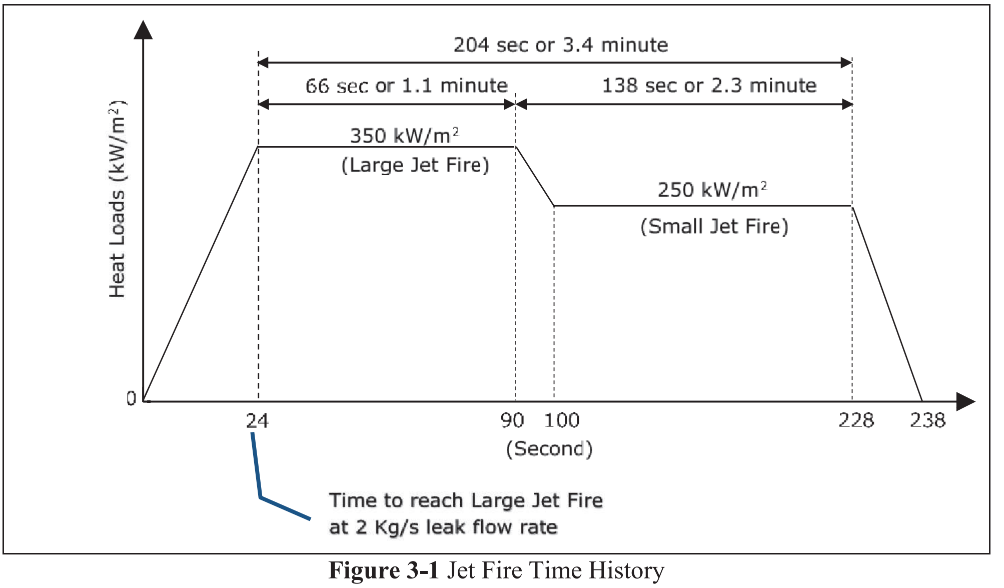

Figure 3-1 Jet Fire Time History

3.2 *Analysis Results*

The following figures show the results of fire and heat transfer simulation (FAHTS) analysis for one of cases with jet fire directed on deck leg A4. The temperature-time curve in **Figure 3-3** shows the maximum temperature experienced by steel members during the event. The maximum temperature recorded is 1700 °C reached for one of case for pool fire on Deck Leg C3 at Level 3.

These temperature results are further used by USFOS for non-linear structural response analysis to observe the behavior/performance and redundancy of the structure in increasing temperature during fire.

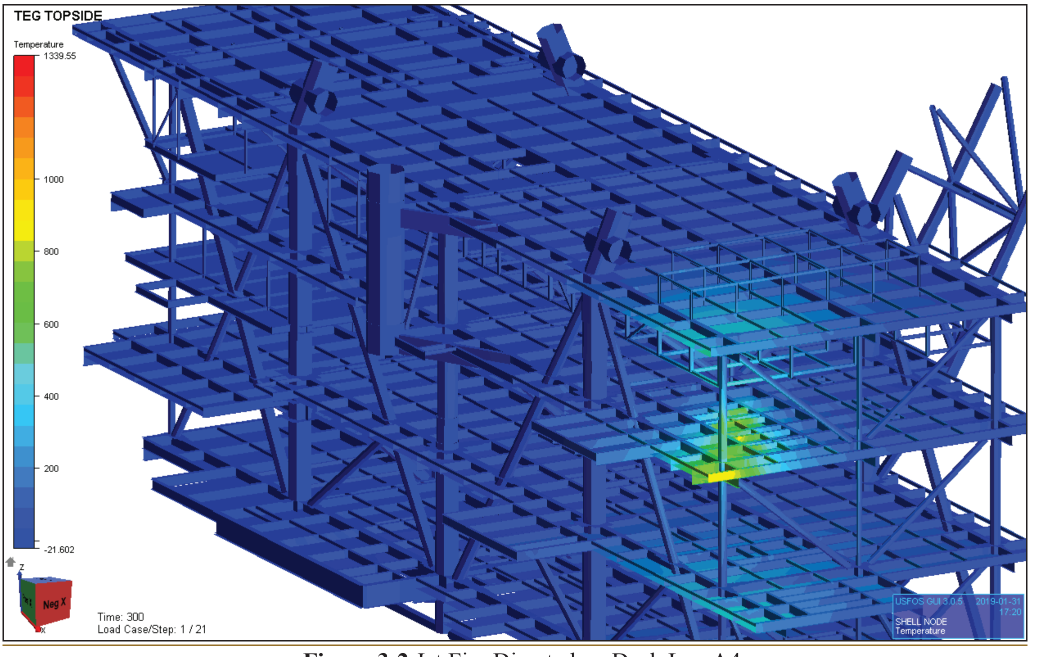

Figure 3-2 Jet Fire Directed on Deck Leg A4

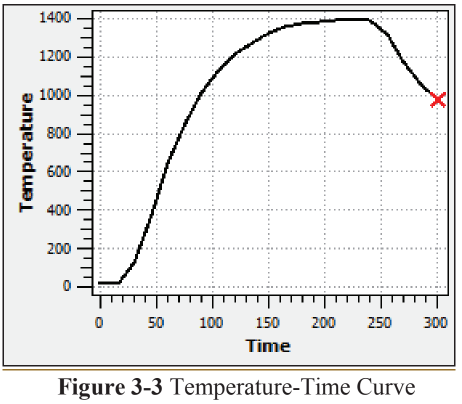

Figure 3-3 Temperature-Time Curve
(Temperature in °C; Time in seconds)

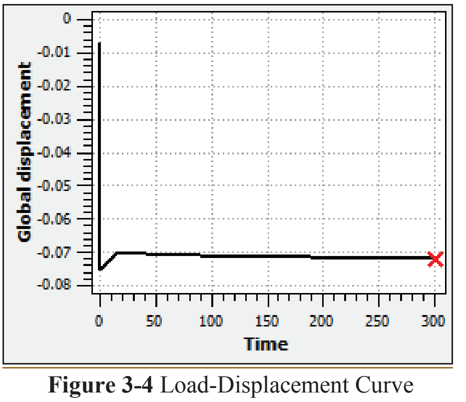

Figure 3-4 Load-Displacement Curve
(Displacement in m; Time in seconds)

The Load-Displacement curve in Figure 3-4 indicates that there is no loss of stiffness and without sharp drop of displacement. The plastic strain is also less than 10%, which means there is no member fracture. All these results show that the overall global structural integrity are maintained without collapse during fire.

4 Conclusion

The analysis results indicate that the topsides structural integrity is maintained without collapse and there is no material rapture during fire with maximum temperature of 1700 ^{o}C. Hence, it is concluded that PFP is not required.

Significant weight and cost reduction can be achieved through advanced technique and proper analysis tool to simulate the complex accidental fire and non-linear structural behavior. The ‘normal’ procedures on assumption that steel structures fail when the temperature exceeds 400 ^{o}C and the need of PFP can be optimized using this analysis approach. Approximately 2/3 of PFP installed in the industry according the ‘normal’ procedures are ‘surpluses’. Application of PFP also comes with a hazard ‘Corrosion Under Fireproofing’, which in many cases are located in area difficult to access and expensive to inspect or repair. Ductility Level Analysis could significantly save the PFP cost and still maintain the safety requirement.

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