REVIEW OF FIRE-RELATED ASSESSMENT DAMAGE OF STEEL OFFSHORE STRUCTURES

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ABSTRACT

Fixed offshore structures are continuously exposed to risk of hydrocarbon fire or cellulosic fire. Hydrocarbon fire generally causes more detrimental effect than cellulosic fire because the rapid increment of temperature gives little response time for people to evacuate the location or to put off the fire. Metallography tests have demonstrated that steel structures continuously exposed to temperature escalation from fires will lose their mechanical properties such as yield strength, tensile strength, toughness, hardenability and elastic modulus. Thus, to understand the structural response during fire, structural integrity assessment with revised steel mechanical properties is advised to be performed. The outcome of the analysis helps to identify the hotspots of the steel structures due to the fire and allow the investigation team to further perform detailed inspection and proposed structural repair to reinstate the integrity of the steel structures. This introductory paper reviews a procedure to appraise structures after a fire incident with the objective of filling the gap of the absence of standard assessment procedure. The procedure is based on experience encounters and proposals of practising engineers and utilizes basic engineering mechanics and materials science. The procedure is not a standard operating procedure but should be employed by engineers to emphasise and reiterate the need of a rigid standard.

Keywords: Fixed Offshore Structures, Hydrocarbon Fire, Hotspots, Metallography Tests, Structural Integrity Assessment

1.0 INTRODUCTION

Fixed offshore structures are designed to accommodate rotating equipment, heaters, pressurized vessels, pipelines, electrical and instrument facilities which operate continuously except during maintenance and shutdowns. The structures are in constant threat to fire hazards because the basic elements to initiate fire, such as oxygen, fuel and heat, are highly present. Fires have high potential to cause major damage to offshore facilities and affect the structural integrity of the fixed offshore platform, globally or locally. The intensity of the fire on offshore facilities depends on the quantity, type and rate of release of combustible materials from the source. Some examples of major hydrocarbon fire incidents in the history of oil and gas industry, see Figures 1, are the 1988 Alpha Piper fire disaster [1], 2005 Mumbai High fire incident [2] and 2010 Deepwater Horizon fire incident [3] which caused a few hundred fatalities as well as environmental and asset damages and losses. These incidents led to the industry having a review at their fire related hazard management, competency of people managing and operating offshore facilities, safety rules and regulation, emergency and evacuation requirements, equipment layout and protection system of offshore facilities.

Offshore facilities are equipped with fire and gas detection system, isolation system, active fire protection system and passive fire protection system. The main function of fire protection system is to prevent or delay the escalation of fire so that onboard personnel can escape and evacuate the platform in due time. Examples of active fire protection system are fire

(a) Piper Alpha Disaster, 1988 (Source: The Maritime Executive, 2018 [1])

(b) Mumbai High North Fire Incident (Daley, 2013 [2])

(c) Deepwater Horizon Disaster, 2010 (Source: University of Texas News, 2019 [3])

Figures 1: Major hydrocarbon fire incidents in the history of oil and gas industry

extinguisher and sprinkler/deluge system while passive fire protection system are intumescent coating system and fire resistance/insulation system. Passive fire protection system is only installed on critical safety elements such as living quarters, temporary refuge, instrument rooms, battery rooms, pressurized vessel and others. However, many major structural components of fixed offshore structures such as beams, braces, columns and deck plates are not protected due to "burn-down" design philosophy being adopted. Therefore, they are exposed to damage and loss of integrity under high temperature fire. This introductory paper discusses the effect of fire on offshore steel structures and considerations to be accounted when assessing structural integrity of offshore structures exposed to fire. Further work is being carried out to propose, systemize and routinize a method to assess structural integrity of steel offshore platform in a fire event.

2.0 TYPES OF FIRE

Fire incidents in offshore facilities are categorized into hydrocarbon fire or cellulosic fire. Hydrocarbon fire has higher rate of incidents than cellulosic fire. It achieves peak temperature instantaneously after ignition as demonstrated in Figure 2. The hydrocarbon fire reaches 800°C within a few minutes after ignition (Promat, 2020) [6]. Since hydrocarbon fuel is very flammable, it will spread rapidly, burns fiercely and generates high heat flux. Steel structures exposed to hydrocarbon fire will lose its strength and stiffness rapidly. For example, at 600°C, the yield strength of steel and modulus of elasticity will be reduced to 17.3% and 26.5% of their respective values at ambient temperature (API FB, 2006) [4].

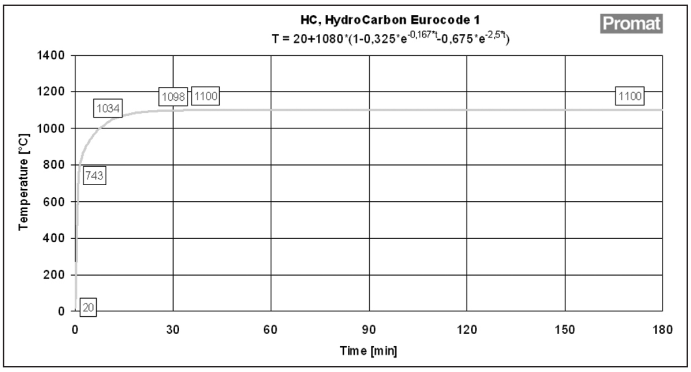

Figure 2: Hydrocarbon fire curve – Temperature vs Time (Promat, 2020) [6]

Cellulosic fire is fuelled by cellulose materials such as timber, paper and cotton. Cellulosic fire relatively grows slower although in some occasion its intensity may ultimately exceed that of hydrocarbon fire. Figure 3 shows the temperature development of cellulosic fire, which demonstrates gradual temperature increment from ignition point. In this example, it takes almost 30 minutes from ignition for the temperature to escalate to 800°C.

In general, hydrocarbon fire is more dangerous than cellulosic fire due to the fact the rapid increment of temperature gives little response time for people to evacuate the location or to put-off the fire. In offshore industry, hydrocarbon fire is more frequently reported because of the continuous presence of hydrocarbon. Due to the threat to people, asset, environment and business reputation, careful consideration in designing offshore platform is required in order to minimize the escalation effect of fire events.

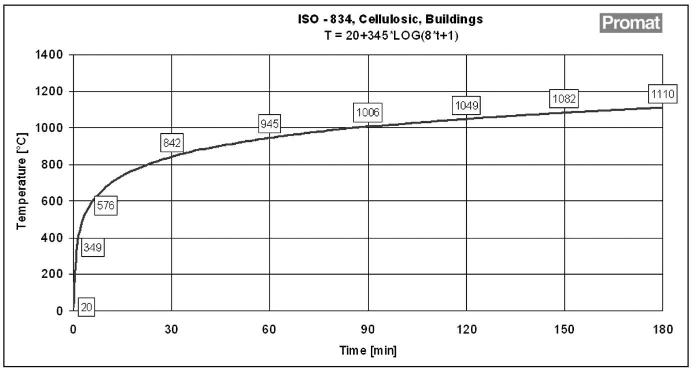

Figure 3: Cellulosic Fire Curve – Temperature vs Time (Promat, 2020) [6]

3.0 STEEL STRUCTURE RESPONSE TO HYDROCARBON FIRE

Worldwide, there are about 6000 fixed offshore platforms installed in water depths ranging from 9.0m to 2100m (Schroeder and Love, 2004) [7]. Fixed offshore platforms are mainly constructed from structural carbon steel because its behaviour is well understood, recyclable and reasonably priced. The mechanical properties of various categories of carbon steel, component shape, cross-section and chemical composition are listed in established standards and codes such as American Institute of Steel Construction (AISC) and American Petroleum Institute (API). An important property of carbon steel is ductility, which allows the redistribution of load in a continuous structural member and at points of high stress concentration. Therefore, carbon steel with high ductility will provide a signal (i.e. substantial distortion) before catastrophic failure. However, when steel structures are exposed to elevated temperatures, in fire or explosion incidents, they rapidly lose strength and stiffness.

The loss of structural yield strength, tensile strength, toughness, hardenability and elastic modulus are due to change in the grain structure of the steel. Other parameters that affect the transformation of carbon steel mechanical properties are phase of metallic structures and elastic-inelastic stress-strain relationship (Villaverde and González, 2012) [8]. Figure 4 shows the comparison on the recommended reduction in yield strength and elastic modulus of carbon steel between codes EN 1993-1-2 and API RP 2FB [4]. The difference between these two design guidelines is that the EN 1993-1-2 [5] is used in the design or reanalysis of onshore building structures exposed to cellulosic fire while API RP 2FB is for offshore structures exposed to hydrocarbon or jet fires. Based on Figure 4, structural steel under cellulosic fire loses its strength at temperature of more than 400°C while for hydrocarbon fire it is as early as 100°C. On the other hand, for stiffness, API RP 2FB recommends the use of gradual reduction in elastic modulus until the temperature reaches 500°C. At temperature of 500°C to 700°C the recommended reduction in the elastic modulus is higher for API RP 2FB than EN 1993-1-2.

Take note, the above procedure is recommended for the design phase of steel structures on shore buildings and offshore facilities or when carrying out structural integrity reanalysis of

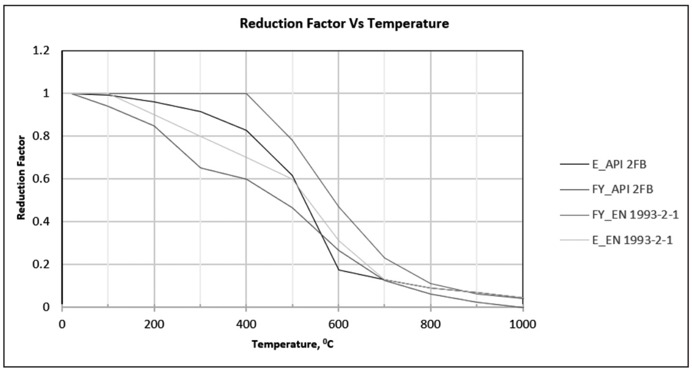

Figure 4: Comparison of yield strength and elastic modulus reduction between EN 1993-2-1 [5] and API RP 2FB [4]

steel structures exposed to fire where no other information are available. Assessment and studies, such as Tide, 1998, Baetu *et al.*, 2016 [11], Villaverde and González, 2012 [8] and Maraves *et al.*, 2017 [10], highlighted the mechanical properties reduction is lower than those predicted by design guidelines. Findings by researchers were also supported by experimental fire tests on full-scale steel structures which observed insignificant strength reduction after the steel structures were heated up to 500°C (Maraves *et al.*, 2017). Maraves *et al.*, (2017) [10] carried out extensive investigation on wide range of experimental studies done on post fire mechanical properties of mild carbon steel and came out with formulations to estimate the residual factor of the mild steel.

$$\frac{f_{yT}}{f_y} = \begin{cases} 1 & T \leq 600°\,C \\ 1.504 - T/1200 & 600°\,C < T < 900°\,C \\ 0.748 & T \geq 900°\,C \end{cases} \quad (1)$$

$$\frac{f_{uT}}{f_u} = \begin{cases} 1 & T \leq 600°\,C \\ 1.208 - T/2900 & 600°\,C < T < 900°\,C \\ 0.896 & T \geq 900°\,C \end{cases} \quad (2)$$

$$\frac{E_{sT}}{E_s} = \begin{cases} 1 & T \leq 600°\,C \\ 1.431 - T/1400 & T > 600°\,C \end{cases} \quad (3)$$

where,
f_{yT} – yield strength at temperature T, (MPa)
f_{uT} – tensile strength at temperature T, (MPa)
E_{sT} – elastic modulus at temperature T, (MPa)
f_y – yield strength before fire exposure, (MPa)
f_u – tensile strength before fire exposure, (MPa)
E_s – tensile strength before fire exposure, (MPa)

Figures 5 and 6 demonstrate that the mechanical properties adopted by design guidelines such as API 2FB and EN 1993-2-1 [5] are much robust or conservative than estimated values in Equations (1) to (3). This clarifies why offshore steel structures, in most cases, show "strong" resistance to hydrocarbon fire.

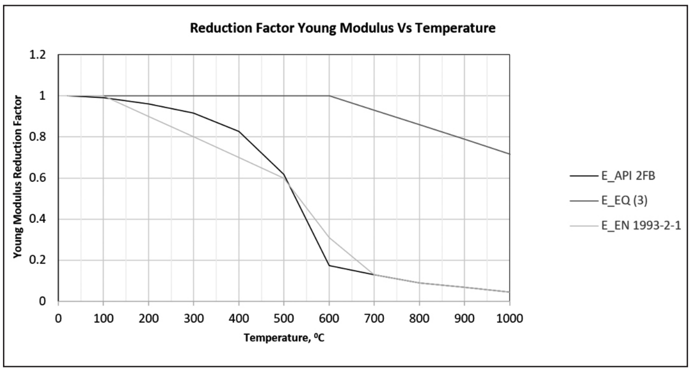

Figure 5: Comparison of elastic modulus reduction factor between EN 1993-2-1 [5], API RP 2FB [4] and predicted post fire property

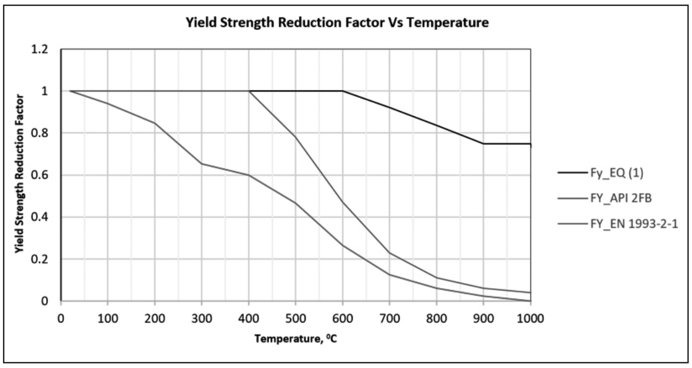

Figure 6: Comparison of yield strength reduction factor between EN 1993-2-1 [5], API RP 2FB [4] and predicted post fire property

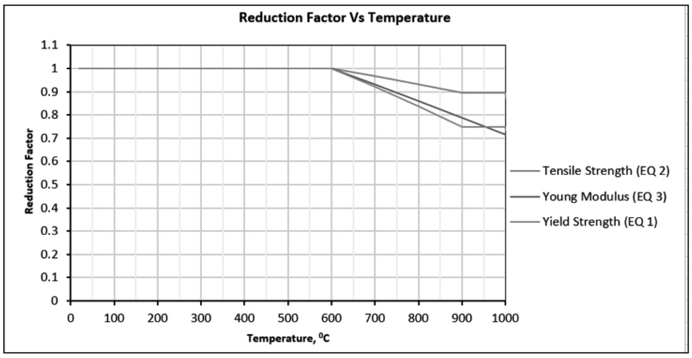

Figure 7: Comparison of reduction factor for post-fire mechanical properties

Figure 7 indicates the post-fire yield strength, elastic modulus and tensile strength of structural steel are not affected by exposure to temperature escalation up to 600°C. For exposure to temperature escalation up to 1000°C, both yield strength and elastic modulus are still maintained at about 75% of intact condition while the tensile strength reduction factor is only about 10% of intact condition. These figures demonstrate that with some repairs or strengthening, steel structures exposed to temperature up to 1000°C will have sufficient strength to continue operation. Based on Figures 5, 6 and 7 it can be concluded that comprehensive evaluation (such as visual inspection, non-destructive test and destructive test) of steel structures in post fire event is very crucial in understanding and determining the mechanical properties of the damaged or affected structure. Information gathered from the post-fire investigation will allow more reliable structural integrity analysis to be done to determine the remaining strength of the structure. The impact of hydrocarbon fire on the overall integrity of the steel structures can be considered minimum because the structural components still behave elastically because the fire does not change the molecular arrangement of the steel grain structure. On the other hand, steel structures can respond plastically if the total applied stress exceeds the elastic limit of steel. In such case, the steel structure will show visible permanent deformation and continuous loading will cause loss of strength and global collapse of the structure.

Temperature escalation induces thermal stress if free expansion is constrained. This generates compressive loading which may result in buckling. Additionally, uneven temperature profile across member cross section or member with two different thermal expansion properties will generate additional bending on the section (API RP 2FB, 2006). These induced stresses normally govern the structural steel response and failure. Figure 8 shows fire test carried out at Cardington, UK to demonstrate structural failure of steel structure due to stresses induced by thermal effect.

Figure 8: Ductile failure of steel structure due to fire (Bailey et al. [12], 1999; Allam, Burgess and Plank, 1999 [13]).

In addition, buckling of steel structures due to thermal effect induces residual stress to the welded joints. As the buckled beam cools and contracts, the connection material such as weld will be torn apart and causes damage to the welded joints (Tide, 1998) [9] and to bolt connections. Damage to critical welded or bolted joints causes significant reduction to the overall reserve capacity of the steel structures especially structures with minimum redundancy. The structural response due to fire exposure is very much dependent on the type of end restraint of the steel members. For example, structural member with cantilever support has significant room for unrestraint expansion while steel members with restraint at both ends will develop significant compressive stress that can cause buckling.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Offshore facilities are exposed to two types of fire, namely cellulosic fire and hydrocarbon fire. Hydrocarbon fire is more dangerous because of swift temperature escalation and gives little response time for people to evacuate or to stop the fire. Thus, offshore facilities are equipped with fire and gas detection system, isolation system, active fire protection system and passive fire protection system to prevent the escalation of fire or to allow sufficient time for people to escape to safe area.

Metallography tests have always demonstrated that steel structures exposed to elevated temperature, from fire or explosion incidents, may lose their mechanical properties such as yield strength, tensile strength and modulus of elasticity. These mechanical properties can be determined through in-situ non-destructive tests or destructive test via laboratory test on steel structural components sample extracted from the steel structures exposed to the fire. To simulate and understand the structural steel response during the fire, structural integrity assessment with revised mechanical properties is performed on the steel structures. Additional stress induced by thermal expansion properties of the steel also needs to be considered in the structural integrity assessment of the steel structures exposed to temperature escalation. The outcome of the analysis will identify the hotspot areas of the steel structures due to the fire and allow the structural engineer or site investigation team to further perform detailed inspection and proposed structural repair to reinstate the integrity of the steel structures. ■

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PROFILES

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