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Report on Component Investigation and Conventional Material Selection for FPSO Turret System Casing Unit Design

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ABSTRACT

The floating production, storage and offloading (FPSO) is a complex vessel that comprises ofdifferent component which operates in severe climates and water depth of more than 1000moffshore. Earliest FPSO design were spread moored with the subsea risers and umbilicalfeeding into a simple porch at the mid of the ship. However, in most deep offshore oil fieldlocations, spread mooring is ideally not practicable, a single mooring is most desirable to allowthe FPSO to weathervane and effectively adjust to the prevailing climatic condition and thewaves. The integral part of the modern FPSO system that make single point mooring possible is the Turret system. The Turret system through the swivel maintain the FPSO on station andallow fluid transfer from the subsea risers to the top side processing plants on-board the FPSOvessel. Recent designs of turret system have used complex multiple swivel assemblies withthe turret positioned internally in the FPSO, handling production fluid from more than 30subsea wells. This complex design includes multiple riser connections, valves, stage separationassembles, seals, pig launchers, securing bolt, gears bearings and processed fluid pipes. Thepossibility of the turret system failure is more severe compare to the simple swivel joint system.Most FPSO have being design to last for more than 25year in the offshore hash environmentand there are strong cost incentives to the operator in maintaining the vessel on station at alltimes. Therefore, selecting the best materials in designing the FPSO critical component suchas the Turret Casing is key to its survival.

Keywords: Report, investigation, FPSO, Turret System, Design, conventional, Material, selection, casing unit

I. INTRODUCTION

The 'Turret System (TS)' and the 'Turret Casing Unit (TCU)'are some of the key components of the Floating Production Storage, and Offloading(FPSO) vessel. The core objective of the turret-system in an FPSO, is to 'maintain' the FPSO on the reservoir field location and allow subsea hydrocarbon fluid transfer from the riser to the FPSO top side processing plants via the swivel stack.It also, allows the ship to weather-vane and adjust to the waves. The 'in-service environmental conditions and the loading modes includes, but not limited to Ocean temperature of 5-18^{0}C, Surface pressure range of 20-45MPa (maximum), Cyclic loading from the ship, bending, torsional and tensional loading, external loads, collision with offloading vessels and other mechanical loads, weather-vanning, longitudinal waves motions/swell, sea current andwinds, Percentage of sea water salinity of 40%, and axial, Radial loading conditions.

Based on the in-service conditions above, the material selection done for the components was the (grade-304 Austenitic stainless steel). Grade-304 'Austenitic stainless steel' is similar to most low carbon alloys steel and the structures are like ferritic steel in appearances (Baiet al, 2001). This is why they can be combined in some occasion (50:50) to form super-duplex stainless steel when the need for high corrosion resistance to stress cracking and higher strength is required (B.Mc Farlane, 2016), in its application such as in the Oil and Gas industry. Iron is mainly present with 74%, 18% chromium as the protective film (Cr203) and 8% nickel gives strength, ductility and stabilizes the face-centred cubic Austenite in varying temperature of the sea water. It is strengthened and hardened by further heat treatment procedures.

Nevertheless, based on the operational (in-service) conditions/loading mode present, the component may well experience dissimilar damage mechanisms and failure modes as would be seen in the report.

II. POTENTIAL DAMAGE MECHANISMS

The Austenitic stainless steel selectedfor the turret casing unit design is susceptible to potential damage and hence, potential failure modes.Nevertheless, the good corrosion resistibility, high fracture toughness and tensile strengths coupled with its moderate cost (Oka et al 2009) makes it suitable as a turret system design material.Generally, potential damage mechanisms cum failure modes are used to describing the environmental and in-service problems and failures the component will undergo. This damage mechanisms may be fatigue, stress induced corrosion cracking, creep damage, fracture damage and associated stress loading damages (Ashby et al, 1993). Failure on the sleeted material to achieve the desire functions can be catastrophic with its severe impact on the surrounding environment and resultant cost effects on remediation.

1.3 Potential creep damage mechanism

Creep damage may ensue due to the application of low strain-stress maximum temperature combination, which could result to stress-creep separations.

1.4 Fracture damage mechanism

Thispotential damage mechanism may happen due to excessive tensile stress and torsional loading on the component due to ocean current and waves/swell which may result to ductile or brittle failure modes.

1.5 Potential Stress load Damage mechanism

According to the cube rule, the damage load varies directly to the cubic stress ($F \alpha \sigma^3$). Therefore, minimal changes in stress can majorly impact on the loading of the turret casing unit.

1.6 Potential Erosive wear degradation

Although very rare with the turret system, erosion damage may occur due to the partial filling of the sea water in the turret riser cavities and also in a situation where there is damage to the fluid transfer riser system, the suspended fluid particles such as sand can cause impingement on the walls of the cavity causing erosive wear. Other forms of degradation are 'severe bearing wear' which could cause damage to the adjacent structure of the vessel.

The core damage mechanism of the turret system includes:

1.1 Fatigue

This damage mechanism can be very critical at the chain attachment point of the turret unit, and possible causes are due to the motion of the ship during weather-vanning, waves/swell, ocean current, frequent loading on the joints, bending, impact on service vessels, cyclic loading, and also corrosion induced fatigue of substructures.

1.2 Stress induced corrosion crack mechanism

This damage mechanisms usually happen due to combinational factor such as tensile stresses and corrosive middling as observed by (Papoola et al, 2013). Though the Austenitic stainless steel selected in part one has Chromium (Cr203) as its protective film, in the presence of sea water, it can be gradually corroded.

III. REVIEW OF POTENTIAL FAILURE MODE(S)

Potential failure mode(s) here means the somatic developments or mode that occurs due to combinational effect e.g., elastic and/or plastic deformation as a result of defects cum deformations of the selected component that can lead to structural/equipment failure as observed by (Maleque et al, 2013). These potential failure modes are analysed below:

1.7 Corrosion Failure Mode

Mostly, pitting, stress and/or intergranular corrosions and galvanic corrosion are commonly associated with the turret system and oil and gas infrastructures in general. Corrosion is the chemical induce degradation of a component material which leads to deterioration of the material and its eventual failure to performing the required services.Any failure due to corrosion is a major safety concern coupled with its economical and severe environmental consequences in the oil and gas industry. Many issues influence turret system corrosion which could leads to the damage or failure. These includes: the natures of corrosions, substantial impact of the corrosion, speed of corrosions, corrosion mechanism interface and a host of other failure mode(s) present (L.Popoola et al, 2013).

Fig. 1: Shows typical turret system corrosion failure (Courtesy: metallurgical technologies, 2015)

1.8 Fatigue failure mode

This can be regarded as the major failure mode that the turret casing unit may encounter during in-service operation. Mainly, it is due to repeated torsional/cyclic loading and can be categorized as localized progressive failure because the stress-strain application on the materials that causes brittle crack propagation. There are three basic phases of fatigue processes involved. These includes:

- Initial crack formations
- Progressive growth of the crack transversely on the component
- Sudden fracture and failure of the components (Kurtz, 2002).

Commonly affected sub-component is the turret transfer system (TTS), (AEA Technology, 2001) as shown in the diagram (Figure 2) below.

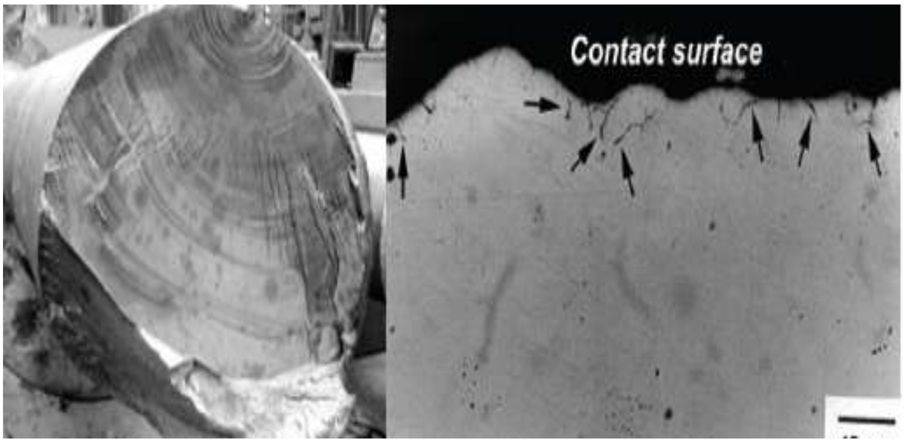


Fig. 2: Shows fatigue failure of a turret system shaft (courtesy: ISTE Ltd, 2006)

1.9 Stress Induced Corrosion Cracking Failure

Stress induces corrosion cracks simply (SCC), is another corrosion related failure mode that may occur in a turret system casing unit. Causes of this crack is due to combination of severe corrosion and tensile stresses acting on the turret system, which may lead to damage of mechanical strength thereby, component material failure.

Brittle failure mode is prevalent with little or no sign of plasticity in the distortion. The saline sea water inside the cavity of the turret system which is corrosive forming thin flaccid films on the walls of the turret system. Therefore, combining residual stresses could initialize crack both transverse and intergranular, gradually progressing in the material microstructures (NPL, 2001) which could cause failure.

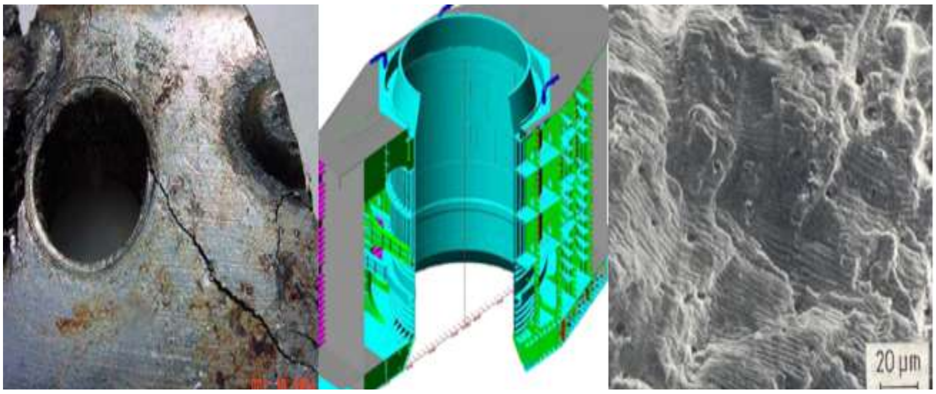


Fig. 3: Shows SCC induced cracking of the turret casing (Courtesy: Nevesbu, 2016)

1.10 Fracture Failure Mode

Austenitic stainless steel Material fracture failure may occur when subjecting it to stresses on temperature lower than its melting-point resulting bit by bit material separation. This type of fracture can be categorised as ductile and/or brittle which depend on either the elongation experienced is slight or big.

The commonly experience type of fracture failure in the turret system is the ductile fractures and or both ductile and brittle fractures depending on the material properties. The parts mainly affected by this failure modes are the bending stiffeners, the dynamic seals, swivel, moon-pool, turret transfer system (TTS), the casing and sub-structures and sub-components. It is worthy to note the differences between brittle and ductile failures.

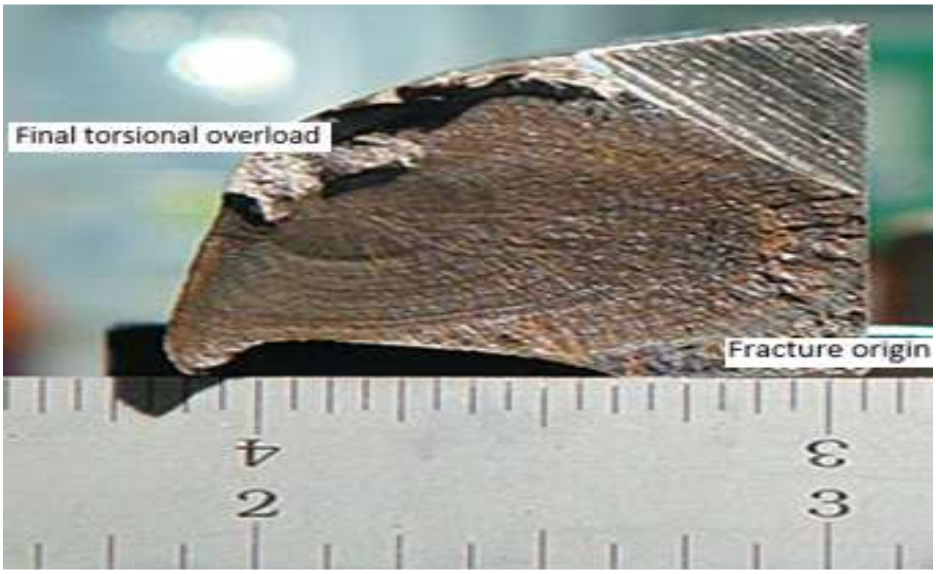


Fig. 4: Austenitic stainless steel Material fracture failure (courtesy: NPL, 2015)

Brittle failure mode is the swift failure cracks initiations that has no sign of plasticity in its deformations. While the ductile failure mode has plasticity in its distortion and cracking process. Due to the multiplicity of components integrated to the turret system, its fracture failure modes are mostly exhibit both ductile and brittle. There is no neck-thinning's in the brittle fractures and it is usually trans-granular/intergranular which hinge on weak-strong borders of the modicums.

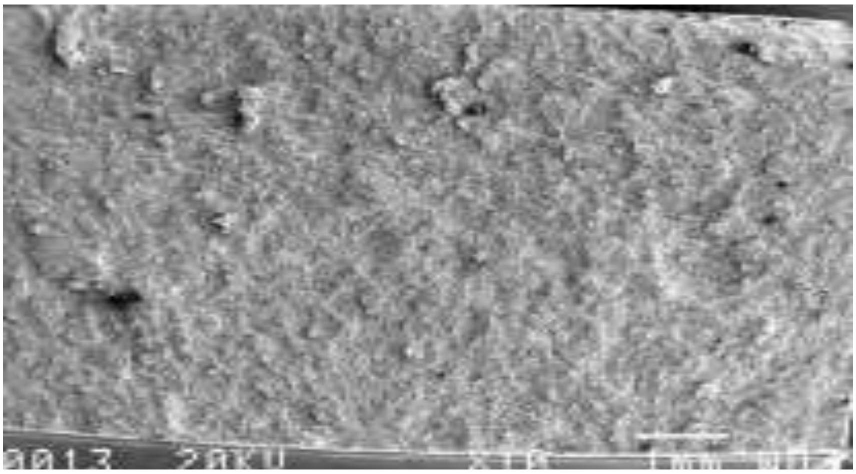


Fig. 5: Showing microscopic image of stainless-steel brittle fracture failure (courtesy: Offshore Tech, 2014)

1.11 Erosive wear failure degradation

Although not so common with the FPSO-turret system, erosive wear failure can occur in the cavity of the turret system especially if there is damage due to the fluid transfer system riser and because of the corrosive nature of the hydrocarbon fluid flowing in the cavity which could induced erosive wear on the surrounding cavity walls.

Secondly, erosive wear may occur inside the turret riser cavity due to the partial filling of the sea water and aided by the up and down yawing of the FPSO due to the swell and waves similar to that of CO_2 injection and sand production that degrades tubing as can be seen in the diagram (Fig. 6) below.

Fig. 6: Shows erosive wear on the turret cavity (courtesy: Schlumberger, 2007)

Other forms of degradation that can affect the turret system is ‘wear and pitting’ corrosions and sulphate reducing bacteria (SRB) corrosions (JIP, 2006), which could affect the chain attachments joints.

IV. APPROPRIATE PROTECTION MEASURES FOR THE TURRET SYSTEM

The various potential damage mechanism vis-à-vis failure modes is extensively identified and critically analysed as shown. Now, it is necessary to carefully select appropriate protection measures that are applicable to the component so as to inhibit the damage mechanism and the observed failure modes which could enhance the performance of the turret system against the in-service environmental conditions.

V. DESIGN AND MANUFACTURING PROTECTION MEASURES

First and foremost, protection of the turret system could start by improving the manufacturing process via a selection of advance material that can inhibit the prevalent damage and failure mechanisms. Also, such manufacturing process could be in the form of increasing the fracture toughness, bulk microstructural treatment, surface protective coating, and corrosion protection by increasing the percentage of chromium from 18% to maybe 20% and also, improving the overall fatigue performance of the austenitic stainless steel.

Increasing fracture toughness of any material could best be the option of preventing fracture and creep failure modes of that material. Mostly, improving on the design of a component could best serve the protective measure against fatigue failure modes of that component.Therefore, in order to inhibit the failure modes discussed above, it is imperative to follow the guidelines stated below to effectively preventing failure modes due to fatigue and its associated creeps.

- Detailimprovementto fabrication/claspingprocesses (Maleque et al, 2013).
- Prevention of exterior disjointedness throughout the manufacturing processing
- Eliminate or reduce residual stresses with manufacturing process and rationalisation component applied stresses
- During stamping and trade mark punching processes, avoid sharp surfaces waterworks

Erosive wear and corrosion related failures in offshore infrastructures is a growing concern in the Oil and Gas industry in terms of investment protection and safety (HSE executive, 2001). The turret system can also be protected against corrosion by cathodic protection or surface coating methods.

VI. SURFACE COATING/TREATMENTS

6.1 Shot Peening

Shot peening could also be useful protective measure for the component. This method involves bombardment of the component surface with metal alloy in a controlled operations to prompt compressional stresses to the material (Murphy, 1995).

Applying this treatment will increase in-service performances, elimination of untimely failure, fairly increases the lifespan and reduction of component frequent overhaul. Surface indentation is created by the media on the component materials forming multiplicity of overlap dimple all over the component so as to reduce failures due to corrosive stresses, freighting and fatigues as shown in the (Fig.7) below with a schematic showing the maximum (ultimate tensile strength) added to the material.

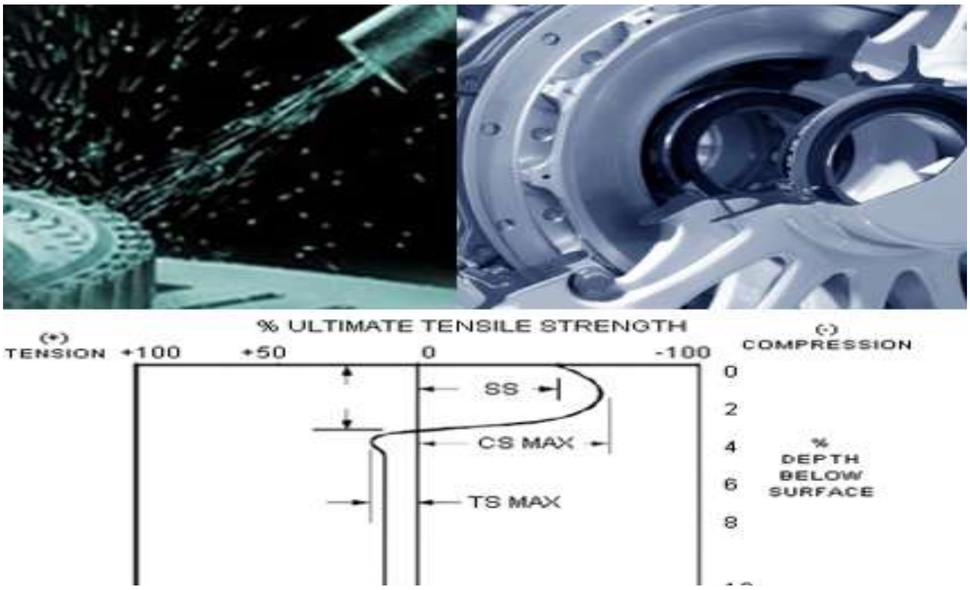


Fig. 7: Shows shot peening on turret bearing casing assembly (offshore Tech, 2001)

6.2 Metallic coating

This provides a good protective film which modifies the properties of the component to the properties of the metal been smeared. The component by virtue of the application of the coating metal become composite materials which exhibits properties that are not achievable by singular use of each individual material.This way, the main materialprovides loads bearing part/ability while the coating material provides the resilient corrosion resistance. The metal deposition process is known as 'wet chemical deposition process and metal such as chromium and nickel are used as the coating metals (Offshore Technology Report, 2001). Zinc can be used also to serve as the sacrificial material to coat the surface and enhance the corrosion inhibition process.

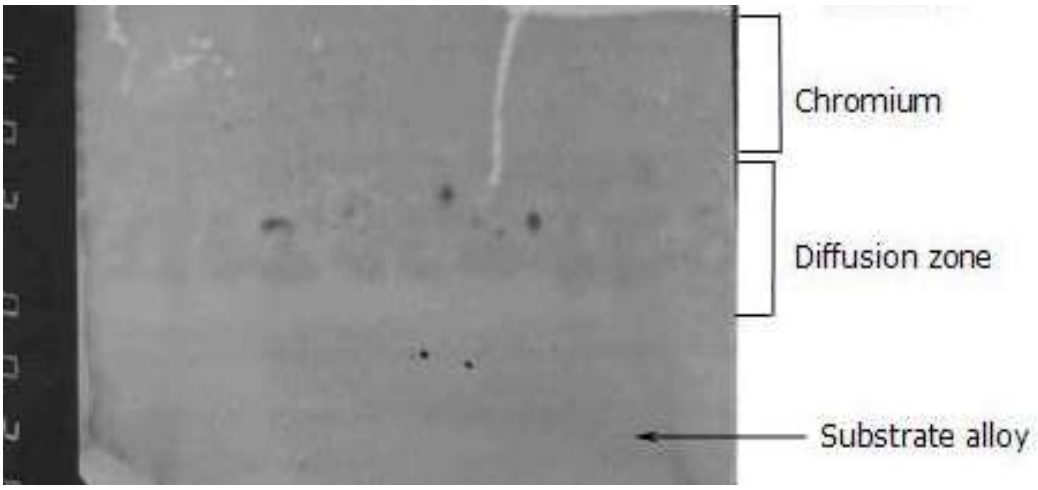


Fig.8: microscopic image of metallic coating (courtesy: Offshore Tech., 2001)

Hot dip galvanizing on some of the sub-components such as the bearings could improve the wear resistance. Also, thermal spraying can be done on the cavity moon-pool that has contact with the sea water to give extra corrosion resistance.

6.3 Bulk microstructural treatments

Buck microstructure treatment can be done on some of the sub-components of the turret system. Although it is expensive and hard to achieve, austenitic material bulk microstructures treatment is an interstitial solution of carbon-in-iron face centred cubic crystals structures that have solubility limits of 2.11wt% at 1147^{0}C by way of cementite. Phase stabilities and solubility's range from 727 to 1495^{0}C and 0-77wt%C in respect to the ferrites. (R. Manna et al 2008) as shown in the (Fig. 9) below.

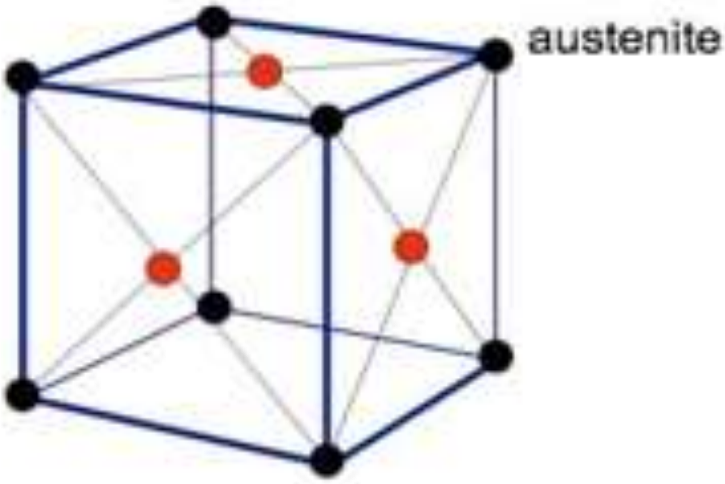


Fig. 9: Shows the location of the austenite in the face centred cubic crystal structures (courtesy, R. Manna et al, 2008)

Furthermore, slow cooling this (allotriomorphs) low carbon steel consume the austenite substantially in advance and transformation of the remains into little pearlite and thereby, the ferrite shapes determination impingement of bits growth in difference nucleation site (DOITMOPS, 2012) as seen in the (Figure 10) below.

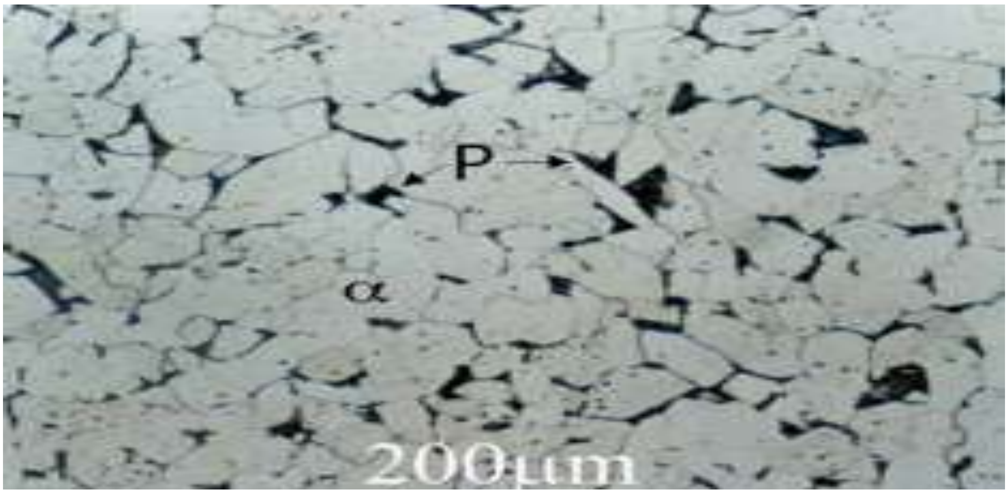


Fig. 10: Microscopic image of slow-cooling of Austenitic steel during bulk microstructure treatment (DOITPOPS, 2012)

6.4 Painting

Painting can also be applied to the component to increase the durability and sustainability performances of the component. This is in line with industry standard in protection of offshore equipment and infrastructure.

Paint coating process is a metallic addition to the surface of the material. This forms largely duplex protective layers that inhibits organic bacteria from corroding the component. Primers are applied and then the finishing intermediates coating is applied, so as to provide the protective layers required which have their own exclusive purpose. The airless spray application is the most common approach in applying paint in oil and gas infrastructures (JPT, 2015).

Other form of protection of the turret system includes: Thermal spraying with aluminium or zinc alloys, cathodic protection, bacteria reducing surfactants that inhibits sulphate reducing bacteria (SRB) and a host of other advance protection methods.

The strength and hardness of the component can be increased in the bulk microstructures of the materials via heat treatment by raising the temperature to form austenite in the structure of the materials.However, the finest available ‘protection measures’ possible is by selecting a high strength material in the nature of super-duplex stainless steel (composite) alloy, to manufacture the component taking into account both the mechanical and physical property(s) of the material and in conjunction with the CES material selector software (justification level 3).This will be critically assessed and discussed in the next (section 4) of this report, taking into consideration the new material desired properties of the component such as: (A) higher performance in corrosions resistance,(B) higher performance in fracture toughness, (C) superb tensile and yield strength performance, (D) high performance in erosive wear resistance, (E) efficient costs, (F) excellent weldability, (G) lower density, (H) higher modulus, (I)excellent thermal properties and (J) superb fatigue failure resistance as explicitly analysed in (section 3a & b) above.

VII. ALTERNATIVE MATERIALS THAT COULD BE USED FOR THE TURRET SYSTEM

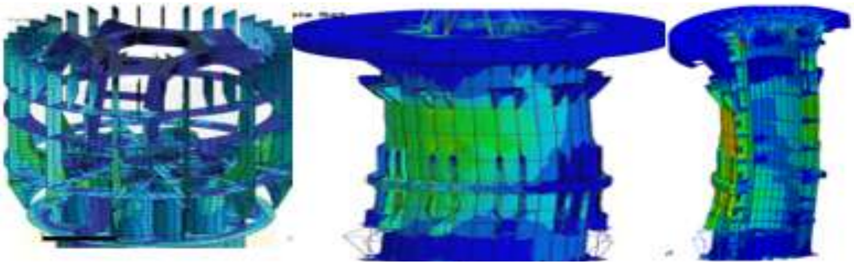
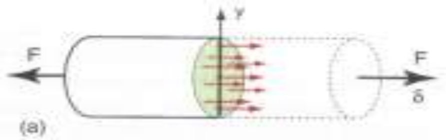
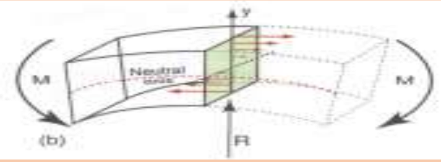
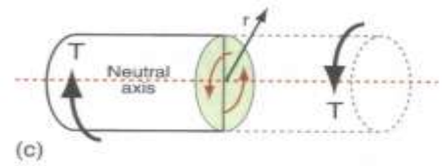
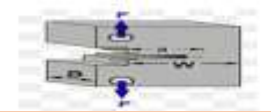


Fig. 11: Shows Computational Fluid Dynamics (CFD) simulation of the loading effect and most impacted zones

The diagram (Figures 11) above, shows (CFD) simulation of the elastic stress distribution in the component-turret casing (tension, bending and torsional) loading and a cross-sectional view showing the loads impacts.The (yellow and red) coloured areas are the most affected zones that potential damage and failure could easily initiated during the turret system in-service conditions.

Mathematically, it can be argued that during in-service condition,these three stresses will act upon the turret casing and other sub-components and as shown in the (Table 1) below.

Table 1: shows Mathematical expression of the types of stress distribution that exist in the component

Elastic stress distribution	Equation	Units
Tension  	$E = \frac{F \times L}{A \times \delta}$	GPa
Bending  	$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$	MPa
Torsion  	$\frac{T}{K} = \frac{\tau}{r} = \frac{G\vartheta}{L}$	MPa
Fracture toughness 	$K_{1C} = \sigma_f \times \beta\sqrt{\pi \times a}$	MPa
Cost	Density /Price	£/kg

Critical analysis of the component shows that the above conditions and all other potential damage mechanism vis-à-vis failure modes previously discussed exists in the component in-service conditions.

Therefore, it is imperative that the new selection of the alternative material should be a material that is better than the austenitic stainless steel-304 used in the initial report.

The new material should have the following characteristics/properties/constrains as shown in (Table 2) below.

Table 2: Shows the design characteristics/properties/constrains/criteria/specifications

S/No.	**Design Characteristics/Properties/Constrains/criteria**	**Range (min.-max)**	**Units**
1	Ocean temperature	18	^{0}C
2	Surface pressure	20-45	MPa
3	Fracture toughness	195	MPa
4	Young’s modulus	195	GPa

5	Tensile strength	700	MPa
6	Fatigue strength at 10^7 Cycles	260	MPa
7	Yield strength elastic limits	530	MPa
8	Percentage of sea water salinity	40%	-
9	Material Compressive strength	-	MPa
10	Density	5.006	Kg/m^3
11	Price	5.50	kg/£
CES Graph Parameters			
10	Fracture toughness Vs Fatigue strength	K_{IC}/σ_f	MPa
11	Tensile strength Vs Yield strength		
12	Density Vs Price		Kg/£
13	Young’s Modulus Vs Density		GPa/kg/m

VIII. SELECTION OF ADVANCE MATERIAL USING CES SOFTWARE

(Fig. 12) below shows the bubble chart plot for Fracture Toughness Vs Fatigue strength. Considering the specified parameters above (Table 2), the Stainless Steel, Duplex (UNS S32760) is selected for the needed fracture toughness and desired fatigue strength.It can be seen from the graph that the super-duplex stainless steel has higher fracture toughness when compared with the austenitic steel which fracture toughness is low even though it has good fatigue strength as can be seen in the report part-one and as shown in the plot below (figure 12). Super-Duplex (UNS S32760) also have good fatigue strength and can withstand the required in-service condition stated above.

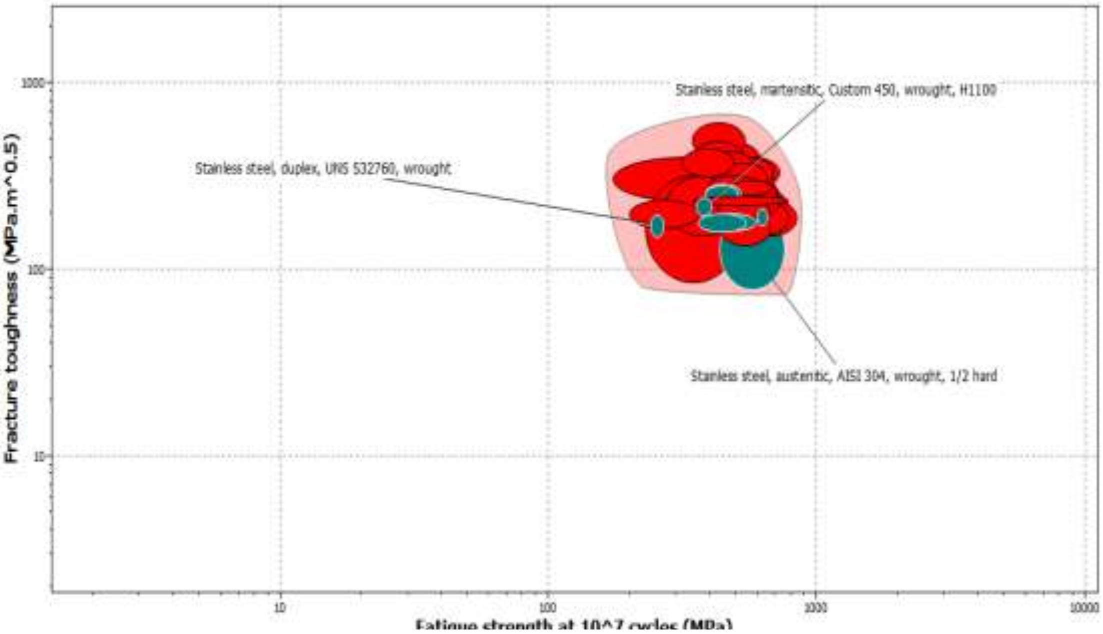


Fig. 12: Shows Fracture Toughness (MPa.m^0.5) Vs Fatigue Strength (MPa)

Another plot, is the bubble chart for (Yield Strength-elastic limit) plotted against the Tensile strength as shown in (Figure 13) below. As can be seen in the graph, it is worthy of note that when Selecting material for the manufacturing of the component, the material should have enough elastic limit and tensile strength. This is so, that it could withstand the damage loading mechanism in the in-service environment coupled with the failure modes such as pitting corrosion, fatigue, and stressed induced corrosion cracks.It can be appreciated from the graph that not only the duplex (UNS S32760) steel has good tensile strength but it also, have excellent pitting and corrosion resistibility coupled with very good yield strength that can withstand the existing potential failure modes and damage mechanisms.

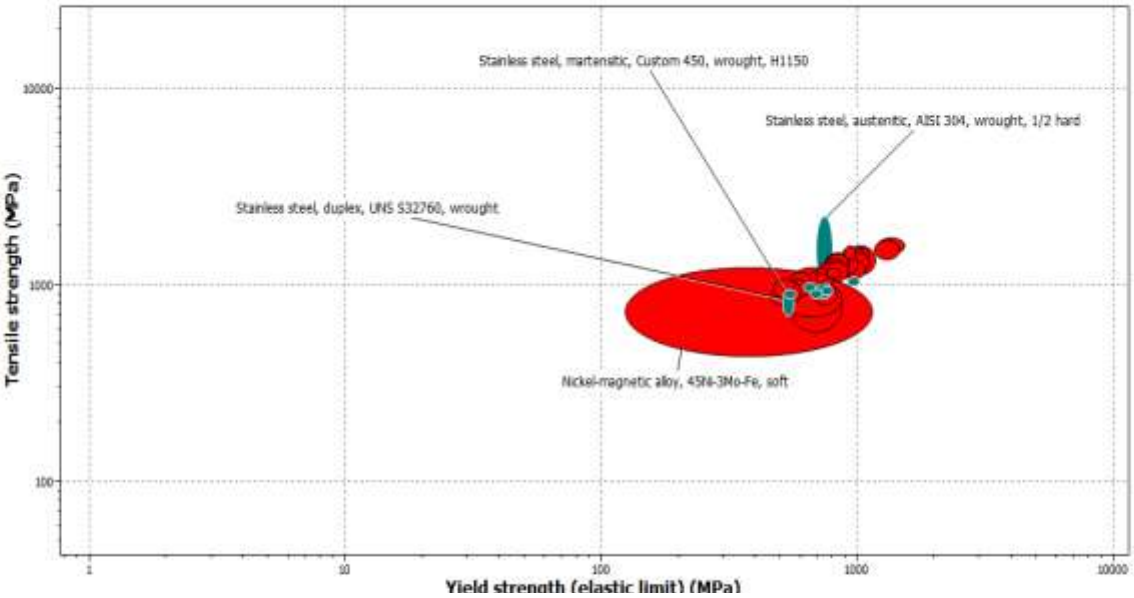


Fig. 13: Tensile strength (MPa) Vs Yield Strength (elastic limit) (MPa)

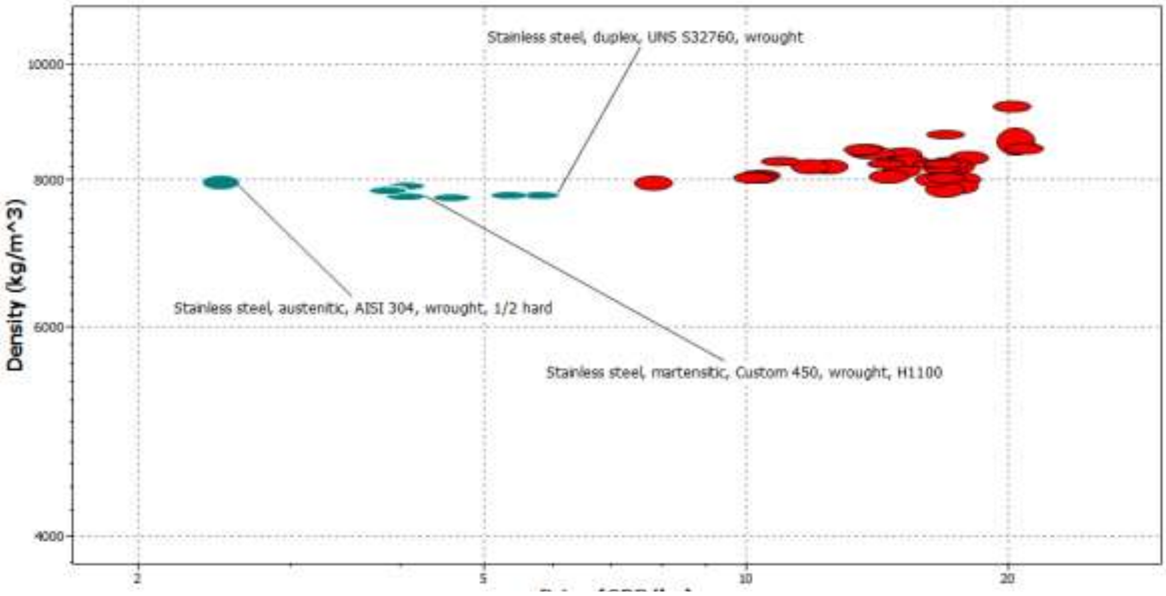


Fig.14: shows Density (kg/m^3) Vs Price (GBP/kg)

The next bubble chart plot (Fig. 14) shown above is the graph of Density Versus Price. It is clear that the austenitic stainless steel and the super-duplex stainless steel has fairly similar density. Also, the price of the Duplex is objectively enough as compared with that of Austenitic steel. Although the price of the super-duplex is slightly high, we cannot totally trade off other important parameters such as good corrosion resistibility's considering the harsh environmentalin-service condition and safety requirement.

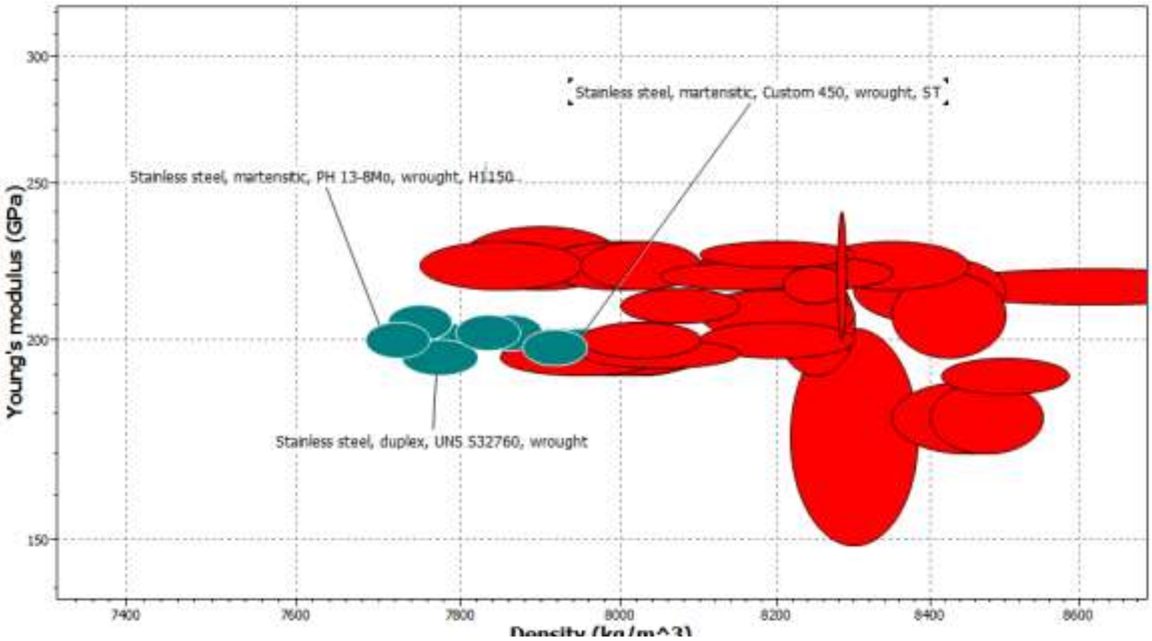


Fig. 15: shows bubble chart of Young's modulus Vs Density

And also, the super-duplex stainless steel additional ability to withstand pitting corrosion good young'smodulus as can be seen in the (Fig. 15) above, good weldability and higher percentage of Chromium (Cr24-26%) compared to the austenitic steel used in part-one of the reports which have only 18% of chromium content. This mean that, the 'super-duplex stainless steel' canwithstand the in-service conditions and potential damage/failure mechanism such as Creep/pitting corrosion and all other damage mechanisms present, as already discussed above.

More so, the stability of the super-duplex stainless steel has made it to be more useful material as selected, considering the durability and reliability that comes with it and with fair manufacturing process.

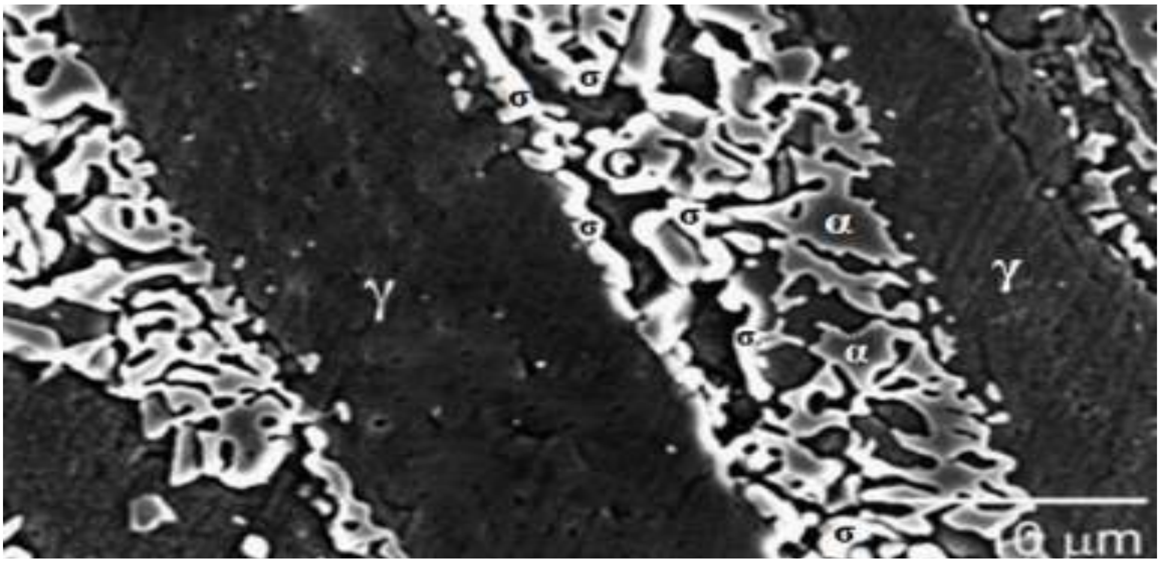


Fig. 16: Shows a microstructural backscattered image of austenitic (bright phase) and ferritic (dark phase) super duplex stainless steel aged at 870^0C for 20min. (courtesy: Material, 2009).

IX. REVIEW OF THE ALTERNATIVE MATERIAL SELECTED FOR THE STUDY

The image (Figure 16) above shows the two distinctive austenitic-ferritic (50%-50%) microstructures of the super-duplex stainless steel selected for the component.

As the name implies, super-duplex (UNS S32760) stainless steel is a combination of two distinct elements as: (austenite 50% and ferrite 50% with 26% chromium and nickel 8%, iron (Fe-65.8%) and low carbon less than 0.03%, coming together forming a microstructure called super-duplex stainless steel. This super-duplex has excellent resistivity to pitting corrosion damage commonly associated with oil and gas infrastructure.

This element is very stable that it does not react with other elements easily. In the manufacturing process, super-duplex steel melts, slightly solidifies to form ferritic phase. At temperature drops closely toward 32^0C, part of the ferritic grains will solidify, and split to form austenite as shown in the diagram (figure 16) above.

(Microstructure of this super-duplex stainless-steel diagram). Comparison, of super-duplex (UNS S32760) stainless steel with single phase austenitic or ferritic steel show that, super-duplex has more durability than both single phases.This makes it more useful in the oil and gas industry application as hydrocarbon production moves into more challenging, corrosive and hash environment.

The following properties there exist in the duplex steel that makes it more suitable for the design and manufacture of the component (FPSO turret system).

- Excellent pitting, crevice, and stress corrosion cracking/resistance when compared with other materials or using single phase austenitic/ferritic stainless steels
- Have excellent strength (fracture toughness and yield strength) when compared with single grade austenite's 304 used in part-one of this report
- Great corrosion-fatigue and erosive wear resistibility
- Excellent potentiality when weight reductions are required compared with austenitic and other alloy.
- Fair enough in terms of cost as shown in (figure 15) above.
- Weld-able

X. KEY MANUFACTURING ISSUES INCLUDES

- Although, super-duplex stainless steel (UNS S32760) has good weldability, (Ashley el tal, 2001), as higher temperature roughly over 680^0C is needed and this comes with high cost
- Reduction of ferrites and increase in austenite is need during manufacturing process which has its own price effects
- Chemical treatment and order post manufacture treatment such as grinding, brushing, blasting etc., (Dr. Phillip Swanson et al, 2016: courtesy, MSc. Lectures/seminars). In restoration of the stainless surfaces are not cost effective.

XI. CONCLUSIONS

It can be concluded that the Super-Duplex (UNS S32760) stainless steel is good enough to perform the necessary in-service conditions and as well handle effectively, the damage mechanism vis-à-vis the potential failure modes for the 35years duration of the case study field-FPSO Turret System.The oil and gas industry are capital intensive and failure of any component has a devastating economical effect. Therefore, careful applications of engineering software such as CES in selecting materials is key when manufacturing various component of the FPSO vessel. However, final decision-making process should not be solely based on the software alone. Advice from reputable expertise in the industry should also be considered before making final decision. Further research is needed on the finite element modelling of the turret system in-service conditions and also to analyse the different stress modethe turret system is subjected during operation.

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