

Structural Integrity Analysis of Fixed Offshore Jacket Structures

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ABSTRACT

Offshore structures which are used to support oil and gas exploration and production facilities are subjected to external loadings such as gravity loads, environmental loads, seismic loads, hydrodynamic loads and accident loads. Physically, the natural responses of the structures are specified in term of displacement and vibration. In this paper, the structural response to external loadings of an offshore structure operating in the Malaysian Water, is measured in terms of stress utilization at structural component level. Offshore structures are designed and assessed to meet the requirement as stipulated in international standards. The type of loading, structural assessment, structural response and utilization checks are discussed. The design of the jacket structure that is studied complies with code requirement with sufficient robustness to withstand either in-service condition or extreme condition.

Keywords: *Offshore jacket structures, load analysis, structural response, stress utilization, foundation utilization*

1.0 INTRODUCTION

Fixed offshore jacket structures are commonly used to support oil and gas exploration and production facilities. In the South China Sea, fixed offshore structures are primarily located in shallow waters. In 2010, there were about 1082 fixed offshore platforms installed in the South China Sea region, with about 250 located in Malaysian waters [1]. In operation, offshore jacket structures are subjected to external loadings such as gravity loads, environmental loads, hydrodynamic loads, accident loads and at certain sea locations, seismic and ice loads. It is very important that offshore jacket structures are sufficiently designed to resist these external loads. Structural integrity analysis is performed during the design phase to evaluate the response of the offshore jacket structures to external loads. During in-service, any design changes that are deemed significant require structural integrity reassessment to be performed as per design standard guidelines. Jacket components not meeting design standard requirement can be justified fit-for-purpose by performing ultimate strength analysis.

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If under both conditions the jacket components do not comply with the code requirement, physical strengthening is one of the options to restore the integrity of the jacket structures. In this paper, structural integrity analysis is performed by using the commonly used Structural Analysis Computer System (SACS) software. The SACS software presents the structural response in terms of members stress utilization ratio, joint and foundation utilization ratios. The structure is defined as code compliant if all members have stress utilization ratio of less than 1.0.

In this paper, a particular fixed offshore structure, the Compression Platform A is selected to demonstrate the analysis used in the study. The structure is located in Malaysian waters and had undergone significant topside modification, an increase in topside weight of 2500 metric tonnes compounded with increase in subsidence and environmental design criteria. The structure will be subjected to a process of structural integrity analysis based on the steps shown in Figure 1.

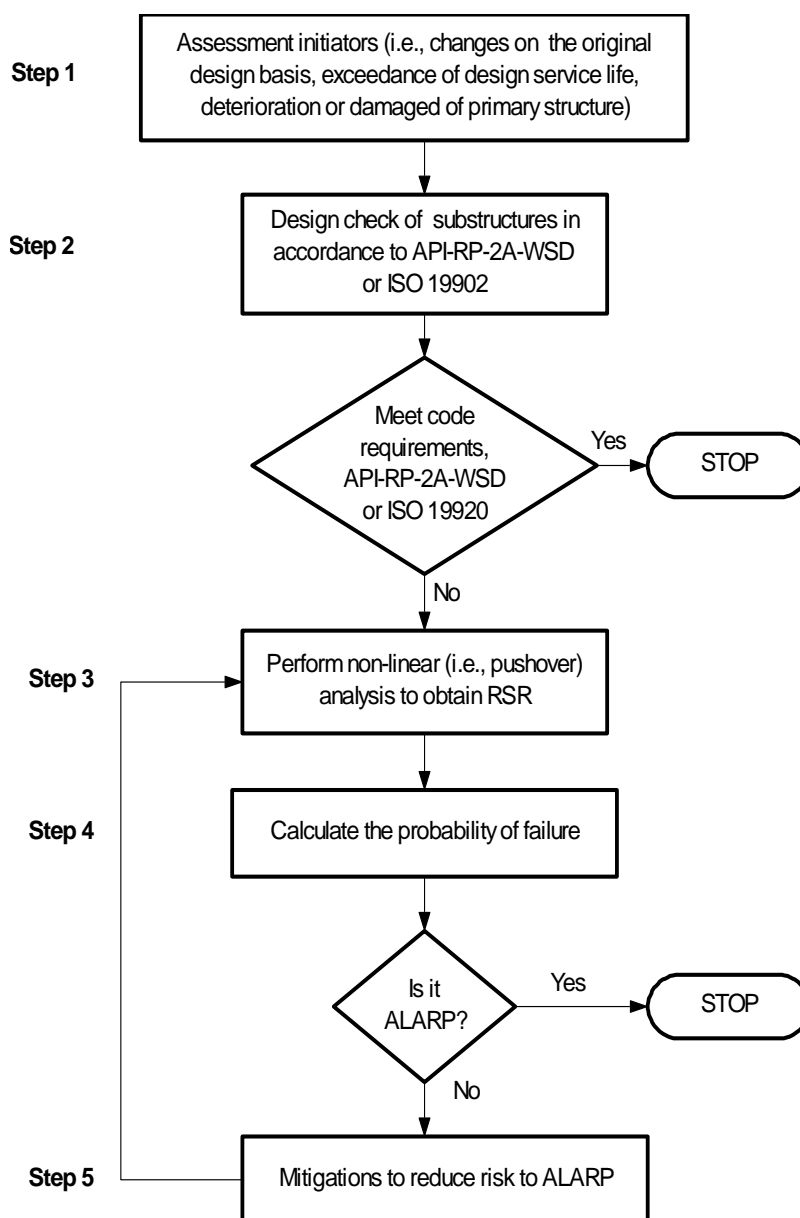


Figure 1: Process of structural integrity assessment of jacket structure

From Figure 1, the main elements in the process of initiating and conducting an assessment of jacket structures are:

- (a) determining if any assessment initiator is triggered
- (b) performing design check assessment
- (c) performing ultimate strength analysis, if required

In the context of Compression Platform A, the increase in topside load and water depth due to subsidence and environmental conditions trigger the need to perform structural integrity reassessment on the platform. The first level of assessment is where the jacket components are assessed against compliance to international design standard such as API Recommended Practice 2A-WSD or ISO 19920. The assessment covers checking for members stress utilization, joint utilization and foundation capacity utilization. If all the components within the jacket structure are assessed to have utilizations less than or equal to unity, the structure is demonstrated to be fit-for-purpose and no further assessment is required, otherwise an ultimate strength analysis is performed to justify the structure has sufficient strength and stability to withstand a significant overload. The jacket strength is estimated through the reserve strength ratio (RSR) which is calculated as ratio of collapse load against 100-year global environmental loading. In the ultimate strength analysis, local overstress and potential local damage are acceptable but total collapse due to excessive deformation is to be avoided.

Structural integrity analysis of fixed offshore structures is carried during the design phase and during the in-service condition of the platforms. Most technical papers on analysis of fixed structures are written with reference to in-service condition of the platforms where changes such as platform modifications, subsidence, age related degradations and member damage are considered. Ayob *et al.* [2] discussed the structural integrity reassessment process to justify fit-for-purpose of in-service fixed offshore structures in Malaysian waters. The reassessment process is very similar to that in Figure 1. Eterdal *et al.* [3] elaborately discussed the reassessment process performed to justify the structural integrity of four jacket structures at Ekofisk field in the North Sea which had experienced significant subsidence that led to wave-in-deck condition. The reassessment process too is similar to that in Figure 1, but with more emphasis on the ultimate strength analysis as the platforms did not pass the design level assessment. Grigorian *et al.* documented on the success story of extending the service life of Ekofisk platforms [4]. Due to the severity of subsidence, Ekofisk platforms did not pass the design check analysis. Thus, ultimate strength analysis was performed, which led to proposed strengthening on selected platform members. The platforms were finally justified fit-for-purpose to continue operation based on the **As Low As Reasonably Practical (ALARP)** approach.

Based on the above literature review on fixed offshore platform structural integrity analysis, it can be seen that the reassessment of fixed offshore structures is a continuous process. From the above examples the reassessment of the platforms went beyond the design check analysis step because all structural members did not meet the code requirement.

2.0 STRUCTURAL MODELING

For the purpose of demonstrating how structural integrity analysis of fixed offshore jacket structures is performed and also to investigate the response of the structure to external loadings, a 4-legged fixed offshore jacket structure, the Compression Platform A, is selected. The detailed description of the offshore jacket structure and operating condition are described in Table 1.

Table 1: General description of Compression Platform A

Items	Description
Water depth	91.5 m
Number of bays	5
Horizontal framing elev. (+) 8.10 m	14.430 m × 20.358 m
Horizontal framing elev. (-) 9.00 m	17.850 m × 23.208 m
Horizontal framing elev. (-) 31.50 m	22.350 m × 26.958 m
Horizontal framing elev. (-) 58.00 m	27.650 m × 31.375 m
Horizontal framing elev. (-) 88.90 m	33.830 m × 36.525 m
Jacket leg batter	7.26:1
Number of legs	4
Pile size - tubular outer diameter	1.3716 m
Pile penetration depth	110 m from seabed
Type of pile	Insert through jacket legs
Location	South China Sea (Malaysian Water)

The jacket structural members can be grouped as horizontal members, diagonal members and jacket legs. The horizontal members consist of tubular 406 mm Outer Diameter (OD) × 13 mm Wall Thickness (WT), 508 mm OD × 13 mm WT and 610 mm OD × 13 mm WT. The diagonal members are made up of tubular member 610 mm OD × 22 mm WT and 762 mm OD × 13 mm WT. The jacket legs have tubular size of 1486 mm OD × 19 mm WT and 1497 mm OD × 25 mm WT. The jacket structure is designed with batter legs to provide stability to the structure and to resist overturning moment induced by wave, current and wind loads. The Compression Platform A is modeled in Structural Analysis Computer System (SACS) as 3D space frame. There are four categories of structural members in the model are:

- 1) Jacket primary structures
- 2) Topside structures
- 3) Appurtenances
- 4) Foundation in which the pile/soil interaction is modeled by means of P-Y, T-Z and Q-Z soil curves

The schematic view of the Compression Platform A is shown in Figure 2.

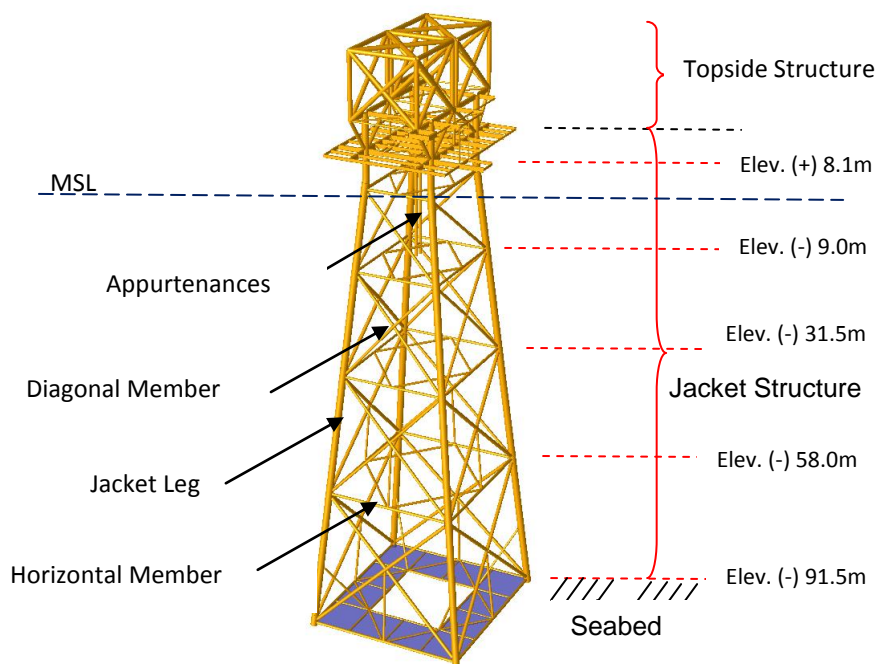


Figure 2: 3D space frame model of Compression Platform A

The appurtenances such as caisson are considered as non-structural members and are modeled as “dummy” which do not contribute to the overall stiffness of the platform but instead modeled for the purpose of wave loading target. The total weights of the topside and jacket structures are 3980.4 tonnes and 2079.8 tonnes, respectively. In SACS the structural members are represented as 2-node elements, with each node having six degrees of freedom, three linear displacements in x, y and z directions and three rotations about axes x, y and z. The material used for the structures is high strength steel with minimum yield strength, F_y , of 345 N/mm^2 . The other properties are tabulated in Table 2.

Table 2: Materials properties

Items	Description	Values
Steel	Density	7850 kg/m ³
	Modulus of elasticity	210 GPa
	Shear modulus	77 GPa
	Poisson's ratio	0.3
Sea water	Density	1025 kg/m ³
Marine growth	Density in dry air	1400 kg/m ³

In offshore jacket structure design practice, the members at the splash zone area are provided with extra steel thickness to compensate the effect of metal loss due to corrosion that may occur during service life. Additional steel thickness of 3 mm is added to all members at the splash zone area. The splash zone area covers an elevation from Elevation 3.0 m below mean sea level (MSL) to Elevation 5.0 m above MSL. Realistically, all offshore jacket structures develop marine growth on all structural members below the MSL throughout the platform life. The marine growth on the jacket structures adds environmental loading which significantly contribute to the overall loading on the jacket structure. In this paper, the Shell Malaysia Exploration and Production (SMEP) guidelines on marine growth profile for fixed offshore structures is adopted [5] as listed in Table 3.

Table 3: Marine growth profile

Depth (m)		Marine growth layer thickness (mm)
From	To	
MSL	- 12.0	100
- 12.0	- 21.0	50
- 21.0	Mudline	0

3.0 LOADING FORMULATION

Fixed offshore platforms are normally designed for service life of 25 to 30 years. Throughout service life, the platforms are exposed to many types of loading such as gravity loads, hydrostatic loads, environmental loads (winds, currents and waves loads), accidental loads (boat impact, dropped object, fire and explosion) and earthquake loads. The overview of external loads acting on fixed offshore platforms is illustrated in Figure 3. In this paper, the analysis only considers gravity loads, hydrostatic loads and environmental loads which continually act on the platforms. Accidental loads and seismic loads may be carried out in separate assessment which requires more advanced analytical method such as nonlinear push over analysis.

3.1 Gravity Loads

Dead and live loads are due to gravity. Dead loads that are imposed on the platforms continuously are the weights of structural steel jacket and topside structures, production equipment and hydrostatic loads. Live loads are those loads that exist temporarily on the platforms, such as weight of consumables during maintenance works, helicopter weight, mooring loads and loads due to activities on the platforms. The gravity load normally contributes to 60% to 70% of the total imposed load.

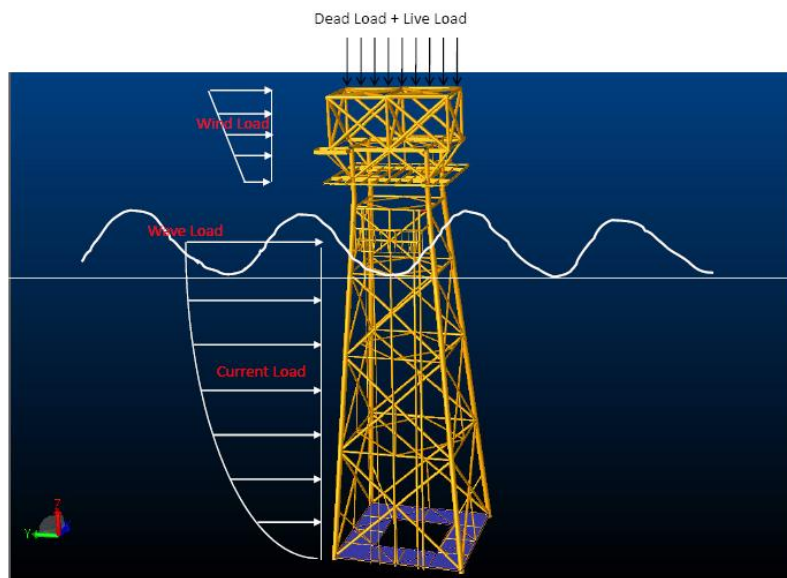


Figure 3: Overview of external loads acting on fixed offshore platform

3.2 Environmental Loads

Environmental loads are due to wind, current and wave acting on the platforms. Current and wave loads contribute to 90% of the total environmental load and 10% is due to the wind. The environmental loading contributes to 30% to 40% of the total loading on offshore platforms. Their contribution normally translates into the Overturning Moment (OTM) and Base Shear (BS) of the jacket structures. The American Petroleum Institute (API), Recommended Practice RP,2A-LRFD and DNV Recommended Practice DNV-RP-C205 give guidelines on how to estimate the wave, current and wind loadings [6]. The following sections discuss the environmental loadings in detail.

3.2.1 Wind load

The wind force exerted on the structure at elevation Z , can be calculated as [1]:

$$F_{wind}(Z) = (p/2).(U)^2.C_s.A \tag{1}$$

where

- F_{wind} : wind force at elevation, Z in [N]
- p : mass density of air at ambient temperature and pressure is 1.226 kg/m^3
- U : wind speed at elevation Z in [m/s]
- C_s : shape coefficient associated with the geometry/shape
- A : area of object in [m^2]

3.2.2 Wave and current loads

The wave and current force imposed on offshore jacket structures is calculated based on *Morison's* equation developed in 1950. The *Morison's* equation consists of two components, namely, the inertia and drag components mathematically expressed as:

$$F_{\text{wave}}(z, t) = 0.5 \cdot \rho \cdot C_D \cdot A \cdot u(z, t) \cdot |u(z, t)| + \frac{\pi}{4} \cdot \rho \cdot C_m \cdot D^2 \cdot \dot{u}(z, t) \quad (2)$$

where

ρ	:	mass density of seawater in [kg/m ³]
A	:	projected area normal to the cylinder axis per unit length (diameter of cylinder) in [m ²]
C_D	:	drag coefficient
$u(z, t)$:	water particle velocity acting normal to the axis of the member, in [m/s]
D	:	diameter of circular cylinder unit length (including marine growth) in [m]
C_m	:	inertia coefficient
$\dot{u}(z, t)$:	water particle acceleration acting normal to the axis of the member, in [m/s ²]

The water particle velocity and acceleration can be calculated based on several wave theories and the most well-known wave theories are *Airy* wave theory, *Stoke* wave theory and *Stream Function* wave theory. The API-RP-2A-LRFD [6] shows graphically the applicability of various wave theories as a function of wave steepness and water depth. For typical fixed offshore platform design and reassessment, the global wave forces are calculated based on the API [6] recommended values of C_D and C_m are as follows:

For a smooth surface:	$C_D = 0.65, C_m = 1.6$
For a rough surface:	$C_D = 1.05, C_m = 1.2$

The C_D and C_m values used in the structural integrity reassessment performed in this report are 1.05 and 1.2, respectively. The C_D is increased by another 5% to take into account of the anodes on the jacket structures which are not modeled. The *Morison's* equation limits its application to tubular members only and its validity for structural member with diameter much smaller compared to the wave length, i.e.:

$$\frac{\text{Wave Length}}{\text{Member Diameter}} > 5.0.$$

The most common current profile to be adopted for the design of fixed offshore structures in the South China Sea environment is the 1/7 Power-Law Current Profile. This current profile is more applicable for tidal-generated current in shallow water and becomes more conservative for deeper water. The 1/7 Power-Law Current Profile can be expressed mathematically by the following relationship [7]:

$$V_c(z) = V_c(0) \left[\frac{d+z}{d} \right]^{1/7} \quad \text{for } z \leq 0 \quad (3)$$

where

$V_c(z)$:	total current velocity at elevation z
$V_c(0)$:	current velocity at the still water level
d	:	water depth to still water level
z	:	distance from still water level (negative sign means below still)

water level)

In offshore and coastal engineering, metocean data is a set of data on the sea state condition at a location based on a combination of measured and modeled data sources. The metocean data used for the structural analysis was derived at Compression Platform A located in Malaysian water. They are shown in Table A1 of Appendix A.

3.3 Analysis Procedure

The overall structural integrity assessment of the present fixed offshore structure is shown in Figure 1. The fixed offshore jacket structure is first assessed at design level by performing linear static analysis using SACS software [8]. The analysis is performed based on API [6] and local guidelines[5]. The components of the platforms are analysed under operating and under extreme storm conditions. The main difference between operating and extreme storm condition is the wave height, current velocity, wind speed and wave period. The day-to-day operating and extreme storm environmental criteria are used to assess the respective structural response of the structures. The operating case defines the occurrence of a sea condition, detailed in Table A1 of Appendix A, with the probability of at least once in every one month while the storm/survival case is an extreme sea state condition with 10^{-2} probability of exceedance in one year. Both operating and extreme sea state (e.g., 100-Year Return Period) conditions must meet the standard requirements for the design and reassessment of fixed offshore structures.

Every member, joint and foundation component of the structure are checked for strength against the following loading conditions:

- (i) 100-year storm with maximum topside load. This is to assess platform components and foundation for failure against extreme sea state conditions of wave and current. Under this condition, if foundation failure is to occur it will be governed by foundation under compression.
- (ii) 100-year with minimum topside load. This consideration is to analyse platform components and foundation against extreme sea state conditions in which failure due to extreme condition is governed by foundation pull-out or foundation under tension.
- (iii) Operating condition with maximum topside loading. This is to analyze the robustness of the platform foundation against platform dead load such as platform self-weight, equipment weight, piping weight and equipment contents.
- (iv) Calm sea condition. This consideration is to analyze the contribution of platform dead load such as platform self-weight, equipment weight, piping weight and equipment contents toward platform overall stability and strength.

These load combinations are taken into account to ensure the full spectrum of loading conditions expected to act on the jacket structure throughout its service life, such as maximum loading under compression for extreme storm and operating conditions, maximum loading under tension and the impact of gravity loading.

The maximum loading on the jacket structural members and foundation is determined by considering the wave, current and wind in eight directions namely 0, 45, 90, 135, 180, 225, 270 and 315-degree directions. This will ensure all members utilization, joints utilization and foundation utilization perform satisfactorily against worst case scenario. The detailed direction of the environmental loading is shown in Figure 4. Since the structure is symmetry about 0° - 180° and 90° - 270° lines, the response is also symmetry about these lines if the wave comes in the directions of 0° , 90° , 180° and 270° .

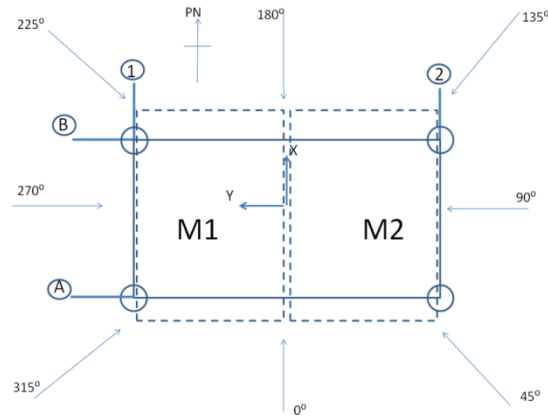


Figure 4: Direction of wave and current loading on Compression Platform A

If the jacket structures do not pass the design level check, an ultimate strength analysis can be used to justify the fit-for-purpose of the jacket structure to continue operation. This approach is more applicable and realistic for reassessment of existing platforms where structural integrity of the platform is based on global failure instead of component failure.

4.0 RESULTS AND DISCUSSION

The degree of structural response to external loadings is represented by the level of stress on each structural member. The degree of stress utilization for each structural member of the jacket structure is checked using interaction ratio as recommended in the Section D of API-2A-RP-LRFD [1]. The type of loading acting on individual structural component of the jacket structure dictates which interaction ratio formulation is to be used. For example, structural components under combined tension and bending should be designed to satisfy Equations (4) and (5). Structural members subjected to combined compression and bending are to be designed to satisfy Equations (6), (7) and (8). Members under shear need to comply with Equation (9). With reference to Figure 1, these checks are equivalent to the design check described in Step 2 of Figure 1.

The stress utilization for combined tension and bending is considered satisfactory if:

$$1 - \cos \left[\frac{\pi f_t}{2\phi_t F_y} \right] + \frac{(f_{bz}^2 + f_{by}^2)^{0.5}}{\phi_b F_{bn}} < 1.0 \tag{4}$$

or

$$f_t < \phi_t F_y \tag{5}$$

The stress utilization for combined compression and bending is considered satisfactory if:

$$\frac{f_c}{\phi_c F_{cn}} + \frac{1}{\phi_b F_{bn}} \left\{ \left(\frac{C_{my} f_{by}}{1 - [f_c / (\phi_c F_{ey})]} \right)^2 + \left(\frac{C_{mz} f_{bz}}{1 - [f_c / (\phi_c F_{ez})]} \right)^2 \right\}^{0.5} \leq 1.0 \tag{6}$$

and

$$1 - \cos \left[\frac{\pi f_c}{2\phi_c F_{xc}} \right] + \frac{(f_{bz}^2 + f_{by}^2)^{0.5}}{\phi_b F_{bn}} \leq 1.0 \tag{7}$$

and

$$f_c < \phi_c F_{xc} \quad (8)$$

For shear, satisfactory condition is defined as:

$$f_v \leq \phi_v F_{vn} \quad (9)$$

where

- f_{bz}, f_{by} : bending stress about z-axis (out-of-plane) and about y-axis(in-plane) due to factored load
- F_{bn}, F_{cn}, F_{vn} : nominal bending strength, nominal axial compressive strength and nominal shear strength.
- F_{xc} : nominal inelastic local buckling strength
- F_y : nominal yield strength
- f_t, f_c, f_v : axial tensile, axial compressive and maximum shear stresses, respectively
- C_{my}, C_{mz} : reduction factors corresponding to the member y and z axes, respectively
- F_{ey}, F_{ez} : *Euler* buckling strengths in y and z axes respectively, in stress units
- $\phi_v, \phi_c, \phi_t, \phi_b$: resistance factors for shear strength, axial compression and axial tensile and nominal bending strength.

From the structural analysis output, the total topside gravity load is 66258 kN. The in-place structural analysis of the jacket structure is meant to determine the structural response of the jacket due to environmental and gravity loads. The total environmental loading on the jacket structures is translated into overturning moment (OTM) and base shear (BS) at the mudline. The corresponding BS and OTM for different wave directions are presented in Figures 5 and 6. From the figures, the maximum BS and OTM occur when the wave attack angle is 180° except for the base shear under storm condition which occurs at 0°. For these wave directions the exposed surface area of the jacket is larger than any other directions and they attract more wave and current loadings. In general, there are significant increases in the BS and OTM as a result of wave height increment from 6.70 m to 11.60 m (refer to Table A1). The percentage increment of base shear ranges from 65.38% to 69.65% and the percentage increment of OTM ranges from 70.55% to 81.40%. This indicates that the jackets are wave dominated structures.

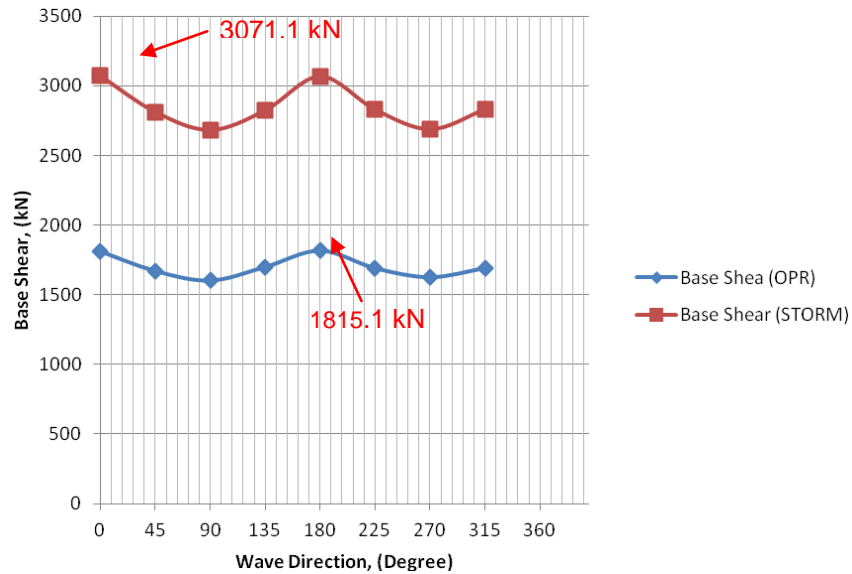


Figure 5: Variation of base shear with wave directions

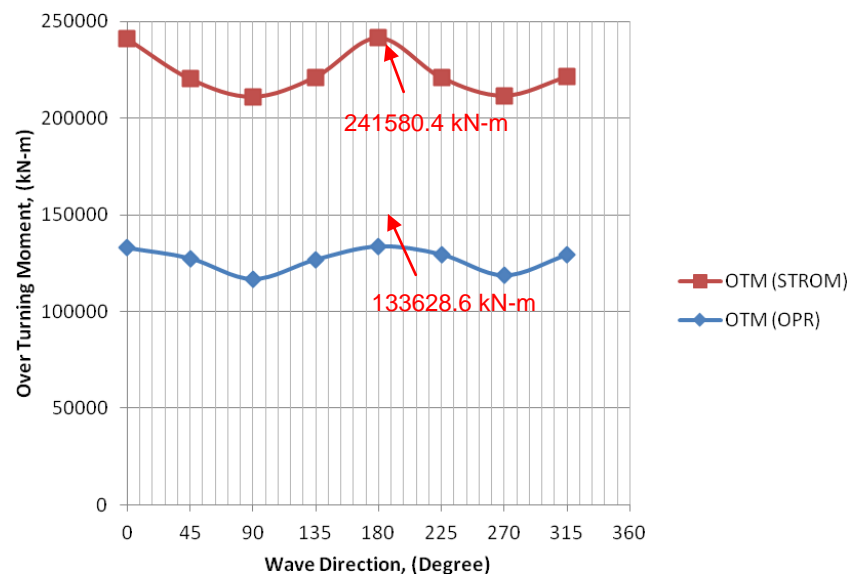


Figure 6: Variation of overturning moment with wave directions

The degree of structural response to the operating and extreme conditions is represented by the level of stress on the structure and it is quantified by using interaction ratio [6]. All members must comply with the code requirement check of less than unity. The analysis gives a maximum unity check of 0.75 under operating condition and it occurs at a jacket leg as depicted in Figure 7. The joints check which is assessed that is based on Section E of API-RP-2A-LRFD [6] indicates that all joints comply with the code requirement. The maximum unity check of 0.5 occurs at joint 5508 (see Figure 7). The result also shows that high uniform utility members and joints are located within wave zone area where the most loaded area of the jacket structure is located. Another area of potential high stress area is at the bottom of the jacket structure where the fixity of the jacket is located.

In addition to member and joint checks, piles are needed to be checked because all topside loads and environmental loads are transferred to the piles. The piles should be designed with sufficient capacity to resist all applied loads.

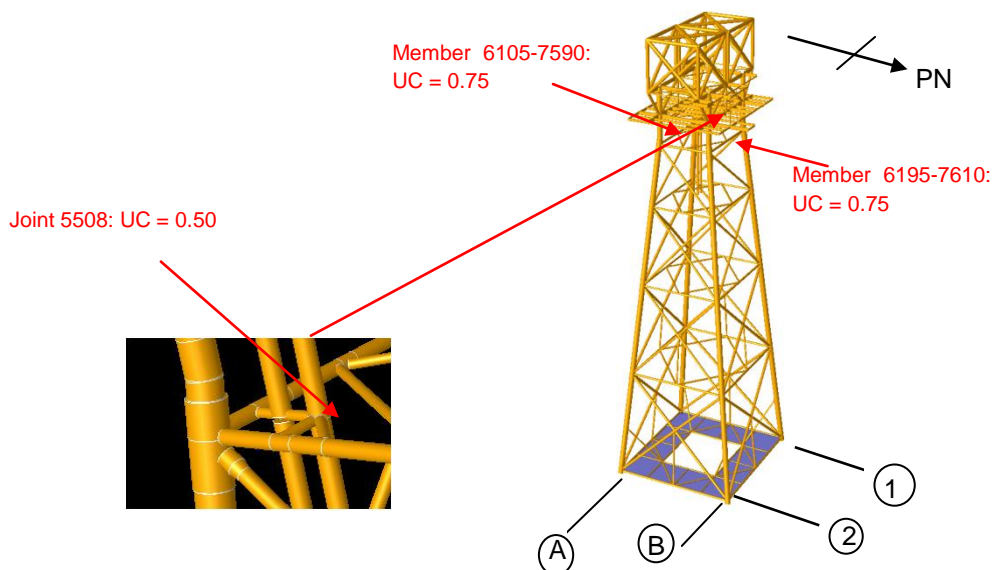


Figure 7: Summary of unity check of Compression Platform A

Table 4 summarizes the pile check due to all the external loads acting on the jacket structure. The results show that all the piles are in compliance with code requirement and have sufficient capacity to resist external loadings. The highest stress and pile capacity utilization ratio are 0.518 and 0.887, respectively which means that the pile design is quite robust to cater for further additional loading or any future modifications on the platform. It is interesting to note that all examples from the introductory literature review and the present Compression Platform A undergo the same structural integrity assessment process, but the reassessment of the Compression Platform A is stopped at the design check analysis step because all the structural members meet the code requirement.

Table 4: Pile stress and capacity checks

Pile row	Load condition	Max. stress check	Pile utilization check
*A1	S_{max}	0.487 (135°)	0.713 (180°)
	S_{min}	0.359 (90°)	-
	OPER	0.481 (135°)	0.846 (135°)
	CALM	0.205	0.602
*A2	S_{max}	0.515 (225°)	0.739 (180°)
	S_{min}	0.347 (270°)	-
	OPER	0.518 (225°)	0.887 (225°)
	CALM	0.268	0.686
*B1	S_{max}	0.476 (45°)	0.697 (0°)
	S_{min}	0.344 (45°)	-0.011 (225°)
	OPER	0.468 (45°)	0.833 (45°)
	CALM	0.177	0.571
*B2	S_{max}	0.489 (315°)	0.722 (315°)
	S_{min}	0.318 (270°)	-
	OPER	0.49 (315°)	0.872 (315°)
	CALM	0.238	0.645

*Note:**For location of pile row, refer to Figure 7; S_{max} : extreme storm condition with maximum topside load; S_{min} : extreme storm condition with minimum topside load; OPER: operating condition with maximum topside load; CALM: calm sea condition with maximum topside load

5.0 CONCLUSION

In conclusion, the Compression Platform A jacket structure complies with code requirement with sufficient robustness to withstand all the modifications either in-service condition or extreme condition. The critical members are jacket legs A2 and B2 at elevation 8.1 m above MSL with stress utilization ratio of 0.75. The most loaded pile is Pile A2 with pile stress and capacity utilization ratio of 0.518 and 0.887 respectively. The most critical joint is Joint No. 5508 located at elevation 8.1 m above MSL. The highly stressed sections are located within the wave zone area where the wave loading is highest. Hence in the case of this particular structure, the structural integrity assessment process is terminated at the design without the need to perform ultimate strength analysis. The maximum BS and OTM experienced by the jacket structure are 3071 kN and 241580.4 kN-m respectively. There is a significant increase in BS and OTM due to increase in wave height from operating condition of 6.7 m to extreme storm condition of 11.6 m. The average increment in BS and OTM is about 67% and 76% respectively which shows the jacket structure is wave dominated.

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APPENDIX A

Table A1: Metocean data

Parameter	100-year return period JOINT criteria	1-month operating Independent criteria
Significant wave height, H_s (m)	6.10	3.50
Mean zero crossing period, T_z (s)	8.60	6.50
Peak period, T_p (central) (s)	12.20	9.20
H_{max} (m)	11.60	6.70
Ass. period T_{ass} (lower, central, upper) (s)	10.1, 11.30, 12.4	7.6, 8.50, 9.4

Current speed profile* (m/s)		
1.00*d (Surface)	0.90	1.01
0.75*d	0.72	0.97
0.50*d	0.54	0.91
0.30*d	0.54	0.85
0.10*d	0.39	0.73
0.05*d	0.30	0.66
0.01*d (seabed)	0.06	0.52
Mean hourly wind speed(m/s)	15.0	16.6
1-minute wind (m/s)	20.7	23.0
Wave kinematics factor	0.893	1.0
Load safety factor, γ_E	1.56 (manned)	1.20