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Strength Analysis of Catenary Offshore Buoyancy Riser Assembly Riser due to Hydrodynamic Load

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ABSTRACT

This paper present the strength analysis of COBRA riser due to hydrodynamic load in deep water environment of Sabah offshore. The risers were design under ULS design limit and analyze using LFRD method. The riser was modelled and analyze using finite element analysis via Orcaflex software with the 100 year return period of typical Sabah offshore metocean data. The analysis consist of Global strength analysis between COBRA riser and Lazy Wave riser, and also Sensitivity Case analysis between configurations of COBRA risers with different depth of sub-surface buoy from sea surface. Based on detailed Global Strength analysis result in this paper concludes that COBRA riser concept has a robust design and it is feasible for 1400 m water depth, in particular for Sabah offshore rather than Lazy Wave SCR. Sensitivity case analysis result in this paper found that the COBRA riser with deepest depth of sub-surface buoy from sea surface has a robust design, this shows that deeper depth of sub-surface buoy from sea surface gives less dynamic effect on the riser due to application of flexible jumper that able to decouple and dampen the energy from vessel due to excitation wave force and it shows that the current force decrease with deeper depth.

KEY WORDS: *Hydrodynamic load, COBRA Riser, Lazy Wave Riser, Hang-off, Touchdown point*

NOMENCLATURE

COBRA	Catenary Offset Buoyancy Riser Assembly
FPSO	Floating Production Storage and Offloading
VIV	Vortex Induce Vibration
SCR	Steel Catenary Riser
FPU	Floating Production Unit
RAO	Response Amplitude Operator
VIM	Vortex Induce Motion
ULS	Ultimate Limit State
LFRD	Load and Resistance Factor Design
DNV	Det Norske Veritas
API	American petroleum Institute

1.0 INTRODUCTION

The exploration of deep water environment promises to support the local oil and gas reserve. Due to harsh environment of deep water environment, the riser structure has to be design robustly as the deep water challenges are likely to be higher and give greater impact on the structure compared to shallow water environment. The typical deep water riser such as Steel Catenary Riser (SCR) has significant design issue such as fatigue at the touchdown point and high vessel payload due to long suspended length [Karakunaran, 2012]. Recent researchers has come out with different type of SCR configuration such as Lazy Wave Steel Catenary Riser, a Steel Catenary Riser with clumped buoyancy modules attach to the riser structure near the touchdown point in order to reduce the fatigue and increase tension, however Lazy Wave SCR also has significant design issue such as high static utilization and low minimum effective tension at hang off and top section of buoyancy module that resulting compression [Karakunaran, 2015].

The latest technology of offshore riser which is COBRA riser is design to be able to withstand the deep-water challenges [Masturi, 2012]. COBRA riser consist of SCR that attach at the bottom of long slender sub-surface buoy that tethered down by two mooring lines, the flexible jumper is use as connecter between SCR and floating production unit [Lurohman, 2014]. However the performance and suitability of COBRA riser in deep water Malaysia has not been study yet. To analyze the feasibility of COBRA riser in Malaysia, strength analysis of COBRA riser has been analyzed and compared with Lazy wave SCR.

2.0 SYSTEM DESCRIPTION AND DESIGN BASIS

The risers system investigated in this thesis is in water depth of 1400m under harsh environment based on 100-year return period Sabah offshore metocean [Selamat, 2013]. A 227m inner turret moored FPSO is considered as the floating production unit. A 254mm inner diameter of production riser is studied to ascertain the feasibility of the design concept.

2.1 Environmental Data

The wave condition was defined by significant wave height in excess of 5.6m. The typical surface current in Sabah offshore is 1.3m/s. Pierson Moskowitz wave spectrum is used to represent irregular wave. The direction of the wave is considered as 180°, it will give the worst impact and worst condition to the riser [Masturi, 2012].

2.2 Soil-Riser Interaction

Soil-Riser interaction is modelled by linear soil stiffness and friction. Soil riser interaction data is important to get the accurate friction experience by riser at touchdown point location [Karunakaran, 2015]. The soil stiffness data used in this analysis is given in table 1.

Table 1: Soil Properties

Horizontal friction coefficient	0.5
Axial friction coefficient	0.3
Horizontal soil stiffness (KN/m^2)	200
Vertical soil stiffness (KN/m^2)	50

2.3 Hydrodynamic Coefficient

The hydrodynamic coefficient that have been taken into account in this analysis is based on first approximation of hydro dynamic coefficient that can be used for steady flow circular pipe. The hydrodynamic coefficient for riser and flexible jumper considered in this analysis are shown in table 2.

Table 2: Hydrodynamic Coefficient

Coefficient	**Flexible Jumper**	**Steel Riser**
Drag Coefficient, C_D	0.8	1
Added Mass Coefficient, C_M	2	2

2.4 Riser Data

The COBRA riser and Lazy wave SCR are designed in accordance with DNV-OS-F201. The first step in the riser design is determination of the required minimum wall thickness. The wall thickness of steel riser considered in this analysis is 48mm after it was determined based on pressure containment, collapse, and combined loading criteria in accordance with DNV-OS-F201. API grade X65 steel is used for the steel riser system. A corrosion allowance of 3 mm is used. The high density polyethylene three layer coating is considered as riser coat. The riser is considered to conduit 500 bar hydrocarbon with density of 800 Kg/m3. The riser global sizing details are presented in Table 3.

Table 3: Riser Data for COBRA and Lazy Wave Riser

SCR Data	**Value**
outer diameter (m)	0.35
inner diameter (m)	0.254
Wall thickness (m)	0.048
Material	Carbon-Steel
Material Density (kg/m^3)	7850
Young modulus (Pa)	2.07E+11
Poison Ratio	0.3
Yield Stress (Mpa)	448.2
Tensile Stress (Mpa)	550.9
Compression Limit (KN)	-13693
Tensile Limit (KN)	711200
Bending stiffness (N.m^2)	1.10E+08
axial stiffness (N)	9.43E+09
Coating density (kg/m^3)	970
Coating thickness (m)	0.076
Corrosion allowance (mm)	3

2.5 Flexible Jumper Data

The inner diameter of flexible jumper is same as steel riser diameter. The design basis of flexible jumper is shown in table 4:

Table 4: Flexible Jumper Data

Parameter	**Value**
Outer diameter (m)	0.356
Inner diameter (m)	0.254
Wall thickness (m)	0.051
Minimum Bend Radius (m)	5
Bending Stiffness (N.m^2)	1.25E+05
Axial Stiffness (N)	7.11E+08
Poisson Ratio	0.5
Density (kg/m^3)	4640

2.6 Sub-surface Buoyancy Data

The subsurface buoyancy can is use to decouple the motion of FPSO with riser. The buoy is encompassed of a long slender cylinder with 6 number of compartments and bulkheads as a separator. The dimension of buoy are shown in table 5:

Table 5: Sub-surface Buoyancy Data

Parameter	Value
Outer Diameter (m)	7
Length (m)	14.2
Mass (kg)	1.66E+05

2.7 Sub-surface Buoy Mooring Data

The buoyancy model was tethered down by using mooring line anchored on the seabed as indicator to maintain the buoyancy can model in design position and to avoid VIM. The mooring line are made up by wire rope with fiber core and the configuration should be maintain as straight as possible. The mooring line properties are shown in table 6:

Table 6: Buoy Mooring Data

stiffness (N)	4.00E+08
Material	Wire Rope with Fiber Core
diameter (m)	0.14

2.8 Clumped Modular Buoyancy of Lazy Wave SCR Data

The clumped buoyancy module for Lazy Wave SCR is following the industrial standard products. The hydrodynamic coefficient of the buoyancy module was assumed based on Baarholm case study in 2015. The properties of buoyancy module are shown in table 7:

Table 7: Modular Buoyancy Data

mass (kg)	3118
volume (m^3)	7.894
diameter (m)	1.75
added mass	1
drag coefficient	0.5
Density (kg/m^3)	395
mass in buoyancy (kg)	2848

2.9 COBRA Riser Configuration Model

The top end of flexible jumper for COBRA riser is connected to the FPSO at -6 m below the surface level. The bottom end is connected to the bottom of sub-surface buoyancy can, located at -250 m below the surface for Global analysis. Meanwhile, for Sensitivity analysis the bottom end of the flexible jumper is connected to the bottom of sub-surface buoyancy can, located at -250m, -160m and -90m below sea surface respectively. Two mooring lines of buoyancy can are tethered it to the seabed. The lines are connected at the bottom of sub-surface buoyancy can, the distance between the lines are 3.0m side by side to the SCR. The lines anchor points spaced in the same distance as the connection point at the buoy. The SCR is hanging at the sub-surface buoy, and laying to the seabed in simple catenary configuration. Figure 1 shows the configurations of COBRA riser and its dimension.

2.10 Lazy Wave Riser Configuration Model

The top end of Lazy Wave SCR is connected to the FPSO at -6 m below the surface level. The bottom end is connected to the bottom of the riser is anchor on seabed -1400m below the surface. The SCR is hanging at the vessel, and laying to the seabed in simple catenary configuration. The layback distance of the SCR to the anchor point is same as COBRA riser which is 638m from hang-off point at vessel. The number of clamped buoyancy module is 25. Figure 2 shows the configuration of Lazy wave SCR

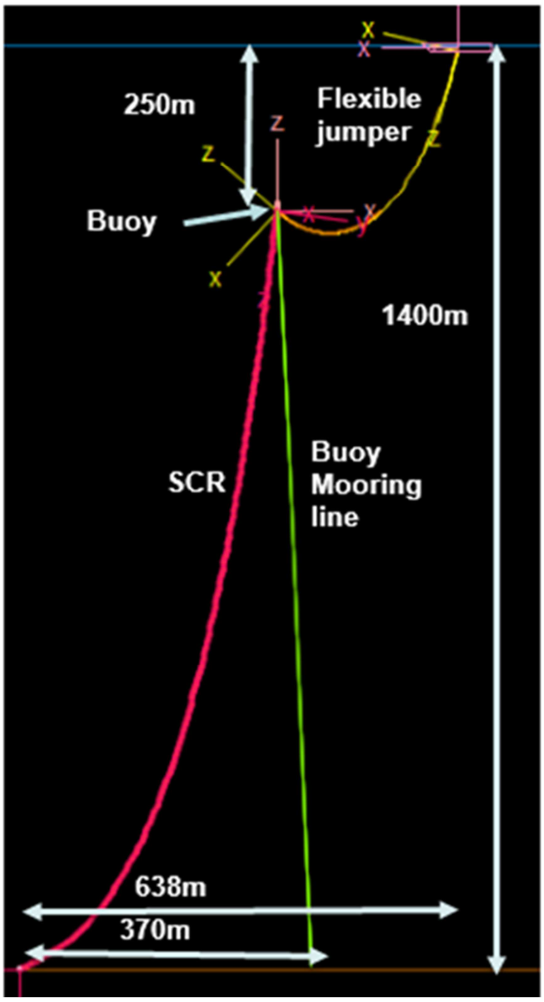


Figure 1: COBRA Riser

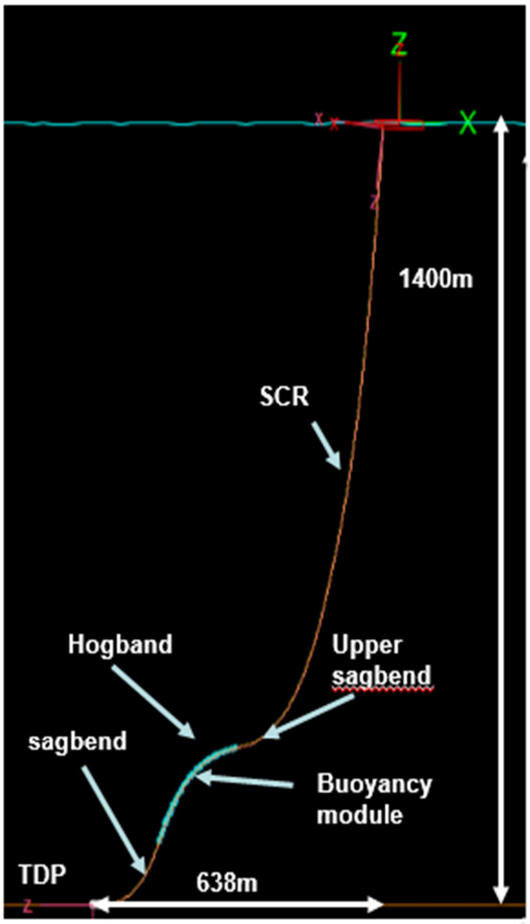


Figure 2: Lazy Wave SCR configuration

3.0 ANALYSIS PROCEDURE

The analyses work is carried out in 2 steps following Load Resistance Factor Design method which consider static and dynamic condition for Global Strength analysis as defined below. All analyses were performed using OrcaFlex software version 9.5. Static condition only considered the pressure and weight effect act on the riser. Dynamic condition considered based on the wave frequency of floater motion and direct waves as an addition to current loadings. The wave frequency floater motions are represented by RAO. The interaction between riser configurations and environmental loadings produce nonlinearities in the riser system.

3.1 Global Strength Analysis

The global analysis consist of the strength analysis of COBRA riser and Lazy Wave riser. The environmental load is same and the vessel response for both riser are also same. The difference between these risers are only the configuration. The analysis and model of the riser is using Orcaflex software, the riser model that is used in the finite element analysis is modelled using segmented model. The segments length in the riser model is used in order to capture adequate representative riser response in particular critical section. The segment lengths that are considered in this thesis work are in table 8:

Table 8: Line Segment

Component	Segment
Flexible Jumper	1m
SCR	1m

3.2 Sensitivity Case Analysis

Sensitivity case study is intended to assess the COBRA riser strength in various alternative configuration. In this thesis, only one sensitivity case study is perform to determine the robustness of COBRA riser design. The sensitivity case is describe in regard by the different of depth of sub-surface buoyancy can configuration. The analysis will analyze which is the best depth to install the sub-surface buoy that can give the most robust structure. The depth of the sub-surface buoy are -250m, -160m and -90m from sea surface. This analysis also intend to analyze the effect of wave excitation at the sea surface towards sub-surface buoy depth.

3.3 Design Acceptance Criteria

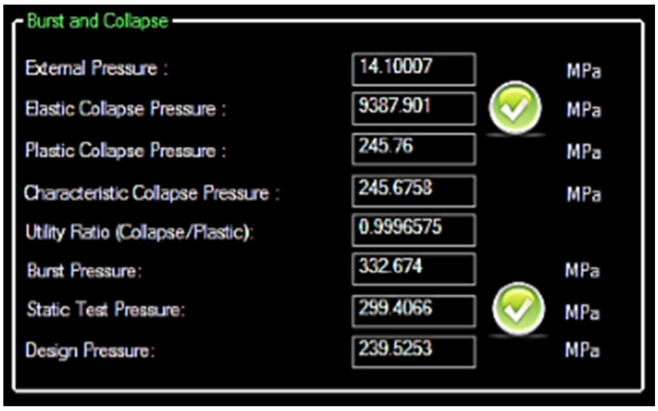
The following points describe the criteria that need to be fulfilled in this thesis work:

- The maximum and minimum tension of riser according to the riser material tensile stress.
  Tension limit: 711.2 MN
  Compression limit: -13693.465 KN
- No compression load is permitted along the flexible jumpers.
- Bending radius is the minimum radius of the riser can be bended without damaging it or making it buckle. The smaller the bend radius, the greater is the flexibility. In this thesis work, the minimum bend radius of the flexible jumper is given as 5 m.
- Static Hang-off Declination at Nominal Position must less than 10 Degree
- Utilization must be less than 1 according to ULS
- Dynamic Hang-off angle variation must be less than 20 Degree
- No Compression force at Hang off-riser of Lazy Wave riser

4.0 ANALYSIS RESULT

4.1 Ultimate Limit State Factored Design Resistance

According to DNV-OS-F201, the riser with Ultimate Limit State (ULS) design has to be remain intact and has no rupture but unnecessary to be operate. The riser also is design to withstand the maximum resistance of environmental load with 100 year-period. For ULS, the design resistance consist of bursting, collapse and buckling. The riser need to withstand all design resistance by not exceeding the design resistance, hence it is very crucial to determine the wall thickness of the riser correctly so that the riser will still intact with the maximum resistance from inner pressure and external environmental effect that will cause burst and collapse respectively [J.Koto, 2015]. The wall thickness of the riser is same for both Lazy Wave and COBRA riser which 48mm. The evaluation has been made by using Subsea Pro software to calculate the bursting and collapse utilization design resistance pressure and the result is shown in figure 7.1.1 below:


Burst and Collapse

External Pressure :	14.10007	MPa
Elastic Collapse Pressure :	9387.901	MPa
Plastic Collapse Pressure :	245.76	MPa
Characteristic Collapse Pressure :	245.6758	MPa
Utility Ratio (Collapse/Plastic):	0.9996575	
Burst Pressure:	332.674	MPa
Static Test Pressure:	299.4066	MPa
Design Pressure:	239.5253	MPa

Figure 3: Burst and Collapse determination from Subsea Pro Software

Based on figure 3 above, it shows that the wall thickness of the riser is able to withstand the elastic collapse pressure and static burst test pressure, hence it is confirm that wall thickness 48mm is acceptable. Design the riser wall thickness based on propagating buckling criteria will give inefficient and uneconomical design. Normally, propagating buckling can be simply avoided by using buckle arrestor on the particular critical location [Nurwanto, 2012].

4.2 Global Strength Analysis

In this analysis, the Global analysis is to determine the structural strength of Steel Catenary riser of COBRA riser and Lazy Wave Steel Catenary riser. The Global analysis include static analysis which affect by static weight and pressure that act upon the riser and dynamic analysis which consider the environmental load and vessel dynamic response toward the riser behavior. Table 9 and table 10 shows the result of static and dynamic respectively:

Table 8: Static Response Global analysis

STEEL RISER Static	**COBRA**	**Lazy Wave**	**Acceptance Criteria**
Maximum angle at hang-of point	2.1	1.8	10
Maximum effective tension at Hang-of point (KN)	3735	3466	711200
Minimum effective Tension at TDP (KN)	443	249	-13693
max von mises stress at Hang-Off (Mpa)	192	201	448
max von mises stress at TDP (Mpa)	200	332	448

Based on table 8, both COBRA riser and Lazy Wave SCR are comply with the acceptance criteria. Maximum hang-off effective tension of COBRA riser is greater than hang-off angle of Lazy Wave SCR, same goes with the effective tension at hang-off point for each type of riser configuration. However, the effective tension of Lazy Wave SCR at touch down point (TDP) is lower than the effective tension of COBRA riser. Interestingly, the Von Mises Stress of Lazy Wave SCR at hang-off and TDP is higher than Von Mises Stress of COBRA riser respectively.

Table 9: Dynamic Reponse Global Analysis

STEEL RISER Dynamic	**COBRA**	**Lazy Wave**	**Acceptance Criteria**
Maximum angle at hang-off point	3.6	2.1	20
Minimum angle at hang-off point	2.1	1.2	-
maximum effective tension at Hang-of point (KN)	3735	3775	711200
Minimum effective tension at Hang-of point (KN)	3463	3322	-13693
Minimum effective tension at TDP (KN)	366	231	-13693
Von Mises Stress- Hang-off Point (Mpa)	192	205	448
Von Mises Stress - TDP (Mpa)	211	298	448
Maximum buckling utilization - Hang-off point (Mpa)	0.63	0.68	1
Maximum buckling utilization - Sagbend (Mpa)	0.96	1.3	1
Maximum buckling Utilization - TDP (Mpa)	0.81	1.1	1
Maximum bend Stress - Sagbend (Mpa)	219	328	448
Maximum API 2RD Stress - Hang-Off point (Mpa)	150	163	240
Maximum API 2RD Stress - TDP (Mpa)	195	276	240

Based on table 9, same trend can be observed from the static condition and dynamic condition, COBRA riser has greater value of hang-off angle and TDP effective tension than Lazy Wave SCR, and also the value of Von Mises Stress of Lazy Wave SCR is greater than COBRA riser. In addition, API 2RD stress, is Von Mises stress under code check from American Petroleum Institute, shows that Lazy Wave SCR has greater stress value than

COBRA riser at hang-off and TDP. The maximum buckling utilization of Lazy Wave SCR has greater value than COBRA riser at hang-off point, sagbend and TDP respectively and it shows that the utilization has exceed the maximum utilization value which is 1.

4.3 Sensitivity Case Analysis

The Sensitivity Case analysis is an analysis to assess the robustness of COBRA riser according to different riser configuration. As in previous chapter, the analysis is done by using 3 different COBRA riser configuration respect to the sub-surface buoy depth. The depth of sub-surface buoy use in this analysis are -250m, -160m and -90m below surface level.

Table 10: Static Behavior Sensitivity Analysis

Static Jumper	**Buoyancy Can Depth (m)**			**Acceptance Criteria**
Position	**250**	**160**	**90**	
Angle at vessel	0.84	0.77	0.61	Max 10
Angle at buoyancy can	3.4	4.1	4.3	-
Effective tension at vessel (KN)	440	374	329	No compression
Effective tension at buoyancy can (KN)	149	192	230	No compression
MBR (m)	89.4	76.2	72.6	5

From the result in table 10, it can be seen that the jumper is still in feasible static configuration. The maximum tension at vessel is increased with deeper sub-surface buoyancy can depth, but the maximum tension at sub-surface buoy is reduced with increasing depth of sub-surface buoyancy can.

Table 11: Static Behavior of Riser Sensitivity Analysis

Riser Static	**Buoyancy Can Depth (m)**			**Acceptance Criteria**
Position	**250**	**160**	**90**	
Maximum angle at hang-of point	2.1	2.25	2.7	Max 10
Maximum effective tension at Hang-of point (KN)	3735	4030	4200	711200
Minimum effective Tension at TDP (KN)	443	485	515	-13693
Von Mises Stress- Hang-off (Mpa)	192	198	202	448
Von Mises Stress- TDP (Mpa)	200	203	212	448

From the result in table 11, the Von Mises Stress at hang-off is decrease with the increasing depth of the sub-surface buoy because of the effective tension of flexible jumper at sub-surface buoy also decrease and also the Von Mises Stress at TDP also follow the trend as same as the stress at hang-off. The maximum effective tension is decreasing with deeper sub-surface buoy same goes to the maximum effective tension at hang-off. Surprisingly, the minimum effective tension of 90m sub-surface buoy depth has the highest tension at TDP among the three of them.

Table 12: Dynamic Behavior of Jumper Sensitivity Analysis

Dynamic Jumper	**Buoyancy Can Depth (m)**			**Acceptance Criteria**
Position	**250**	**160**	**90**	
Maximum angle at vessel	7.6	5	4.6	20
minimum angle at vessel	0.04	0.03	0.05	-
Maximum angle at buoyancy can	18.7	19.8	20.7	-
minimum angle at buoyancy can	0.09	0.1	4.3	-
maximum tension at vessel (KN)	518	423	378	No compression
minimum tension at vessel (KN)	401	336	298	No Compression
maximum tension at buoyancy can (KN)	316	396	398	No Compression
minimum tension at buoyancy can (KN)	149	186	213	No Compression
MBR (m)	70.6	54.4	60.7	5

From table 12 above, the result shows that minimum radius of jumper for each depth of sub-surface buoy, resulted in acceptable limit. Minimum tension of flexible jumper for each sub-surface buoyancy can shows that there is no compression load on the flexible jumper where the less tension is 149KN for 250m depth of sub-surface buoy. The flexible jumper of depth 250m sub-surface buoy also has the most effective tension at vessel as the maximum angle at vessel is the greatest among them. The lowest effective tension at sub-surface buoyancy can is 316KN from 250m sub-surface buoy depth.

Table 13: Dynamic Behavior of Riser Sensitivity Analysis

Riser Dynamic	**Buoyancy Can Depth (m)**			**Acceptance Criteria**
Position	**250**	**160**	**90**	
Maximum angle at hang-off point	3.6	4.3	5.1	20
Minimum angle at hang-off point	2.1	2.25	2.7	-
maximum effective tension at Hang-of point (KN)	3735	4030	4200	711200
Minimum effective tension at Hang-of point (KN)	3463	3601	3564	-13693
Minimum effective tension at TDP (KN)	366	330	306	-13693

Von Mises Stress- Hang-off Point (Mpa)	192	198	202	448
Von Mises Stress - TDP (Mpa)	211	221	230	448
Maximum buckling utilization - Hang-off point (Mpa)	0.63	0.65	0.67	1
Maximum buckling Utilization - TDP (Mpa)	0.81	0.87	0.91	1
Maximum bend Stress - Sagbend (Mpa)	219	198	167	1
Maximum API 2RD Stress - Hang-Off point (Mpa)	150	156	160	240
Maximum API 2RD Stress - TDP (Mpa)	195	209	221	240

The maximum effective tension of riser at hang-off point for -250m sub-surface buoy depth is the lowest with only 3735KN to be compared with riser of sub-surface buoyancy can depth 160m and 90m. Riser at 90m buoyancy depth has the least minimum tension at TDP and the highest Von Mises Stress at TDP and hang-off, hence the buckling utilization of the riser always resulted the highest among them. The Von Mises Stress of -250m depth of sub-surface buoy give the smallest value compare to the stress of more shallow sub-surface buoy depth both at hang-off and TDP.

4.4 **Concluding Remarks**

For Global Strength analysis between COBRA riser and Lazy Wave SCR, the results shows that COBRA riser has greater advantage than Lazy Wave SCR according to effective tension, Von Mises stress and buckling utilization. This is due to:

- The effective tension of Lazy Wave SCR at TDP and hang-off point is lower than COBRA riser, this indicate that Lazy Wave has low tension and compression might occur at the critical point. To prove that the Von Mises stress of Lazy Wave SCR is higher than COBRA riser at both critical point, indicate that the risk of failure of Lazy Wave SCR is higher than COBRA riser.
- The application of flexible jumper, reduce the dynamic motion of vessel by absorb and dampen the dynamic effect thus the movement of riser at TDP location might be reduce. Then, the Lazy Wave hang-off point located at the vessel near the surface of sea because the riser experienced the excitation wave greater than COBRA riser.

For Sensitivity Case analysis, found that COBRA riser with -250m depth of sub-surface buoy from sea surface has better score rather than -160m and -90m, hence it indicate that COBRA riser with -250m depth of sub-surface buoy has less dynamic effect on riser and has more strength to withstand the hydrodynamic load of Sabah Offshore due to:

- The deeper the sub-surface buoyancy the more less the vertical distance between lowest curvature of flexible jumper with flexible jumper connection at sub-surface buoyancy, hence resulting low tension
- There is correlation between hang-off riser effective tension and effective tension of flexible jumper at sub-surface buoyancy. Lower effective tension of flexible jumper at sub-surface buoy resulting lower hang-off riser tension at sub-surface buoy.
- Deeper depth of sub-surface buoy has less effect of current force, the riser with -250m depth of sub-surface buoy has lowest Von Mises stress at critical point. This is due to the current force is least, hence riser have minimize movement at TDP and hang-off point.

5.0 CONCLUSION AND RECOMMENDATION

COBRA riser has higher robustness design than Lazy wave SCR. The COBRA riser has lower effective tension at hang-off point due the position of riser under the surface of sea and the effect of wave excitation has been diminished. COBRA riser has higher effective tension at TDP thus it has low buckling and fatigue potential rather than Lazy Wave SCR, this is due to less movement of riser at the bottom as the application of flexible jumper able to decouple, absorb and dampen the vessel dynamic motion effect, and thus COBRA riser has lower Von Mises Stress at TDP and hang-off point. The buckling utilization at critical point of COBRA riser are comply with the design acceptance critea, meanwhile for Lazy Wave SCR has high potential for buckling to occur at TDP and sagbend.

The deeper the depth of sub-surface buoyancy of the riser, the better the robustness of riser design. Deeper depth of buoy reduce more effect of excitation wave and vertical distance of lowest jumper curvature to the buoy has effect the effective tension of flexible jumper at sub-surface buoy, deeper sub-surface buoy has less vertical distance of lowest flexible jumper curvature and thus the lower effective tension will occur. Lower flexible effective tension effect riser hang-off angle and effective tension, thus also effect the Von Mises Stress. Shorter suspended length give impact to the static effective tension at TDP while in dynamic the effective tension at TDP is majorly effect by the movement of riser at bottom near TDP, hence it shows that the deeper sub-surface buoy the lower the effect of current load.

In a nutshell, COBRA riser has greater strength to withstand 100 year return period metocean hydrodynamic load and feasible in 1400m depth of Sabah offshore rather than Lazy Wave SCR, and the deeper the depth of sub-surface buoy from sea surface the lower the dynamic effects toward riser hence the higher the structural robustness.

6.0 ACKNOWLEDGEMENTS

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