Vortex Induced Vibration on Lazy Waves Steel Catenary Risers: A Case Study of Deep-Offshore Nigeria

Abisoye Abidakun[1], Franklin Okoro[2]
[1]*University of Aberdeen, United Kingdom*
[2]*Clean Script Group, Nigeria*

Abstract*:- This work was carried out on Deep – Offshore Nigeria JONSWAP based Steel Catenary Riser (SCR) design data of length of 3044m with buoyancy section of 600m clamped to an FPSO in water depth of 2000m. Also, appropriate meteocean data for Offshore Nigeria was used to simulate the environmental conditions. The entire process was statically and dynamically simulated using different wave spectra on Orcaflex software. The fatigue analysis results for the lazy-wave SCR with Vortex Induced Vibration (VIV) gave life and damage values as 15.4 years and 0.000177 respectively. While the fatigue life and damage results without VIV gave 17.99 years and 0.000152. At the buoyancy section, the Effective Tension (EF) for the VIV analysis at arc lengths 2000m, 2120m, 2240m, 2360m, 2480m and 2600m gave maxima values at 477KN; 418KN; 420KN; 477KN; 571KN and 685KN respectively. Similarly, results from the Non-VIV analysis for the arc lengths gave 440KN; 386KN; 390.8KN; 451KN; 547KN and 663.5KN respectively. The results show that VIV analysis led to a reduced fatigue life and higher damage value while buoyancy section gave higher tension when compared with Non-VIV. From the foregoing, this work shows that VIV plays a significant role in the overall fatigue of a lazy wave SCR in Deep Offshore Nigeria with great impact at the buoyancy section and hence should be properly taken into consideration in its design in Deep-Offshore Nigeria.

***Keywords:* Steel Catenary Riser, Deep-Offshore Nigeria, Vortex Induced Vibration, Orcaflex software.**

I. INTRODUCTION

Increasingly oil and natural gas deep water exploration and production in deep waters has increased the cost and technological challengesof the riser systems. The use of steel catenary risers (SCR) has become a real-time potential solution for deep-water production systems and has become of increasing interest to oil and gas companies due to the low cost in relation to the flexible riser prices and the technical limitations imposed by the ultra-deep-water and deep-water scenarios (Mooroka and Tsukada, 2013).

A riser is a long cylindrical pipe employed in offshore oil fields to transport the produced hydrocarbon or injection fluids from subsea well to the offshore platforms or vessels or from a production platform to another. Based on the various operational offshore conditions, there are various configurations for the risers.

With an increasing deep offshore and forecasted increase in deep offshore activities in Nigeria, the lazy wave steel catenary riser would become increasingly popular.

A lazy wave steel catenary riser is a form of steel catenary riser with the attachments of buoyancy materials at certain length from the hang-off point of the riser, thus forming a wave configuration (called the hog bend or arch bend) at a certain height above the touch down location of the riser on the sea bed. As seen in figure 1.1, this riser configuration was the focus of this work.

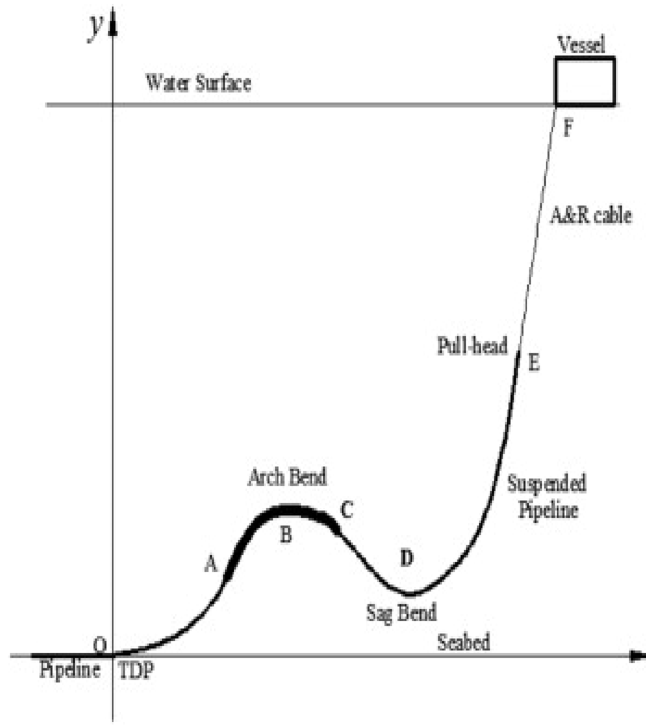

Figure 1.1: Configuration of a lazy wave steel catenary riser. (Wang et al., 2015)

Vortex induced vibration (VIV) has been known as the most important design issue for slender marine structures such as cables, pipelines and risers, especially for environments with high current profile (Xue*et al.*, 2014). When the riser is exposed to fluid flow, vortices are generated in the wake of the riser. The alternate vortex shedding leads to oscillating cross-flow (CF) and in-line (IL) forces, which cause the riser to vibrate perpendicularly and in-line to the ambient flow (Wang *et al*, 2014). The high frequency vibrations generate severe cyclic stresses, which would contribute significantly to fatigue damage. This problem becomes more crucial in riser design as oil and gas explorations move to deeper water area, since large current variation acting on the riser may lead to the Strouhal frequency varying over the riser's length, having the effect that high order and multi-frequency can be candidate for lock-in oscillation (Xue*et al*, 2014).

SCR lines are commonly subjected to fatigue loads due to VIV, particularly in the touchdown zone, due to platform motions, waves and current and research has shown that the Touch- down point (TDP) where SCR starts to contact the seabed is one of the critical positions prone to fatigue failure. Therefore, it is essential to predict the VIV response near TDP accurately in a SCR design. (Wang et al, 2013).

According to Srinil et al. (2009), one of the key issues in the analysis and design of SCRs in the ocean current is to estimate and control the fatigue damage due to vortex-induced vibration. This is particularly important especially in the Offshore Nigeria waters where low currents exists at the bottom sea environment which incidentally is the Touch Down Zone (TDZ). At this region, as shown by Ezeonwumelu et.al (2017), fatigue damage accumulation is high especially due to In-line VIV. This is of great importance to International Oil Companies designing SCRs for Nigeria waters as taking into consideration VIV will minimize cost as well as maximize profit in the long term.

II. LITERATURE REVIEW

2.1 Concept of Flow around Cylindrical Bodies

An introduction to flow-induced vibrations, an examination of the fluid dynamic forces on a rigid body when placed in a flowing fluid and the way in which these dynamics are modified when the body is elastic or compliant is considered. The body experiences dynamic forces that are created by the way in which the fluid flows around and past the body. These forces, which are primarily a function of the shape of the body, arise from flow separation and possible reattachment, and can be both quasi-steady and fluctuating. If the body is not entirely rigid and able to deflect or respond to these dynamic forces, interactions transmitted through a displacement feedback mechanism from the structure can cause alterations to the forces such that continuous or near continuous structural vibrations can be excited. These are referred to as fluid-elastic vibrations and are especially common for circular cylindrical structures and cables (King, 1977). Such vibrations are the subject of this article.

2.1.1 Excitation of cylindrical structures

In steady flow, both steady and fluctuating forces are created on a circular cylindrical member due to flow separation and vortex shedding (King, 1977). Although the excitation mechanism considered here is restricted specifically to vortex shedding there are several other sources of excitation which are reported in varying degrees of completeness elsewhere.

In ocean waves (particularly long period waves) and in waves plus steady currents, transient vortex shedding and impact excitation have been recorded (Wiegel, 1964). Structures situated in the wakes of other structures can be excited by buffeting (generally broad band turbulence) as well as wake galloping and vortex shedding. Galloping (or flutter) of bridge decks and cables, particularly iced transmission lines is another related class of problem as is acoustic resonance in shell and tube heat exchangers. There are many other examples of fluid-elastic vibrations not covered in this paper including heat exchanger tubes, cooling towers, ships' hulls, hydraulic gates and valves (Weaver, 1976).

If the cylinder remains essentially stationary, the steady and fluctuating drag forces, and fluctuating lift forces (for an isolated cylinder there are no steady lift forces) can be calculated from empirical methods based on experimentally derived figures. According to King (1977), the ranges of these variables shows that they are functions of Reynolds number and that they are also dependent upon turbulence scale and intensity and body surface roughness. The cylinder "steady" deflection can be calculated by assuming a uniformly distributed loading of one velocity head and the appropriate force coefficient. In much the same way, the fluctuating deflection can be calculated, although this will probably result in an over-estimate because the vortex shedding occurs in "patches" along the cylinder length, with the vortex-generated forces in adjacent patches not necessarily being in phase or being equal in magnitude. The lengths of cylinder over which the vortex shedding patterns are comparable and complementary are termed the "correlation lengths" and these vary as a function of Reynolds number (Re) for a comparatively rigid cylinder, as shown in Table 2.1 below.

Table 2.1: Correlation Lengths and Reynolds Numbers of Smooth Cylinders (Source: King, 1977)

Reynolds number	Correlation length
$40<Re<150$	15-20d
$150<Re<10^5$	2-3d
$1.1\times10^4<Re<4.5\times10^4$	3-6d
$\geq10^5$	0.5d
2×10^4	1.56d

The frequency (*fv*) of pairs of vortices is a function of velocity (*V*) cylinder diameter (D) and Reynolds number. The non-dimensional wake Strouhal number, *S*, is defined as $S = f*D/V$, and over a wide range of Reynolds numbers 102<*Re* <105, S = 0.2. The general relationship between *S* and *Re* is well documented (Fig. 2.1), but absolute values of *S* also depend upon cylinder surface roughness, length/diameter ratio, turbulence levels, proximity effects and velocity profiles. Also shown in the figure are the Reynolds number ranges of interest in typical marine applications. Each time a vortex is shed from the cylinder, it alters the local pressure distribution, and the cylinder experiences a time-varying force at the frequency of vortex shedding. If the natural frequency of the cylinder is sufficiently close to the dominant frequency of vortex shedding, and if the cylinder damping is sufficiently low, sustained vibrations of the cylinder can be excited. During vibration amplitude build-up, the correlation length of vortex shedding increases appreciably and the vortex shedding is controlled by the cylinder motions.

2.2 Overview on VIV in risers

As most of the oil and gas industry exploration and exploitation operations have been increasingly moving into the deep water offshore zones which has prompted the use of cylindrical risers in deep waters.

During production the risers are exposed various flow condition which contributes to the fatigue performance and life of the riser, one of which is VIV. Therefore, an extensive research into the fatigue of risers which are installed in deep water areas due to VIV needs to be more investigated. Although various VIV mitigation methods are have been implemented which includes VIV suppression device like fairings and strakes, VIV is still regarded as a very pivotal part in deep water SCR design process, especially when they operate in regions with high current(Bai & Bai, 2005).

2.2.1 Vortex induced vibration

Vortex-induced vibration is a prominent design problem affecting risers most especially in the deep-water offshore areas where the current intensity is high. VIV takes place whenever there is an alternate shedding of vortices behind a cylindrical structure due to the separation of flow by the cylindrical structure experiencing a steady flow developing an unsteady force of vibration which leads fatigue or when exposed to fluid flow resulting to the generation of oscillatory flow around the body close to its natural mode of frequency. Risers at greater depths of water (deep-water) have a higher tendency to experience VIV because, the intensity of currents are exceptionally higher in areas of greater depth, the longer the length of the riser the lower its natural frequency mode resulting in the reduction of the size of current needed to stimulate VIV (API RP 2RD,1998).

2.2.2 Types of vortex induced vibration

VIV effects on risers can be said to be in-line and cross-flow to the riser, with the later, being the most significant causes of fatigue damage on riser (API RP 2RD,1998).

Also, accurate prediction of VIV was dependent on whether the riser was in a shallow water or deep-water. On the first condition, the occurrence of VIV was based on the magnitude of the current which further determines whether it is in-line or cross-line. On the second condition, VIV will occur even in low magnitudes of current along the length of the riser due to the reduction of the natural frequency mode of the riser which in turn will vary along the length of the riser (API RP 2RD,1998).

This paper investigated the effect of VIV on the fatigue SWLR if applied in deep offshore West Africa environment.

III. METHODOLOGY

3.1 Riser Material Properties

A typical SCR design data for an FPSO in Offshore Nigeria was collated. Relevant data below were imputed into Orcaflex software interface.

Steel physical data include:

i. Riser length – 3044m (assumed)
ii. Buoyancy length – 600m (i.e. from 2000 – 6000m - Felisita et al, 2015)
iii. Inner diameter – 0.254m
iv. Wall thickness- 0.026m
v. Pipe material density – 7850 kg/m^3

The general design criteria considered were the following environmental data.

i. Design water depth: 2000m
ii. Seabed Temperature: +4^{o}C
iii. Sea surface Temperature: + 30^{o}C

As displayed in the figures 3.2-3.4, the Orcaflex interface for the modelling processing of the riser taking into consideration the above design materials and other design parameters and criteria.

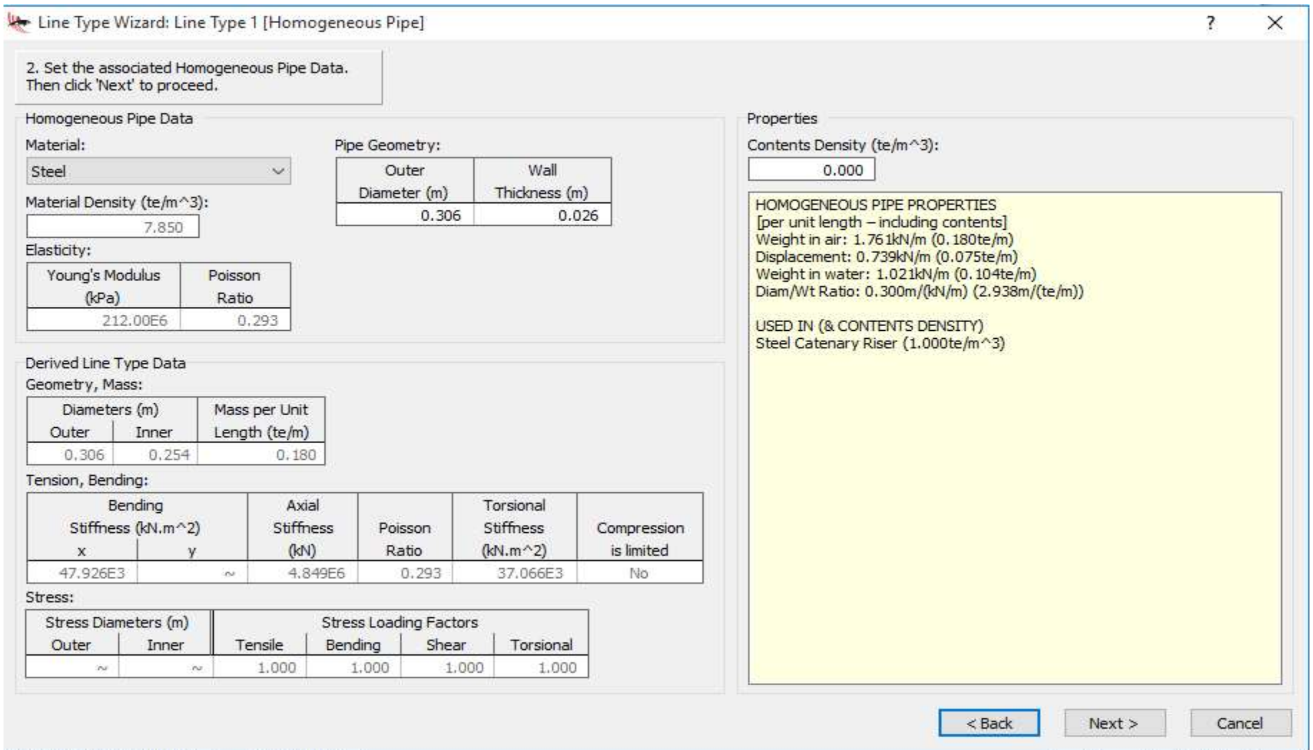

Figure 3. 1: SCR Material Description on Orcaflex Interface 1

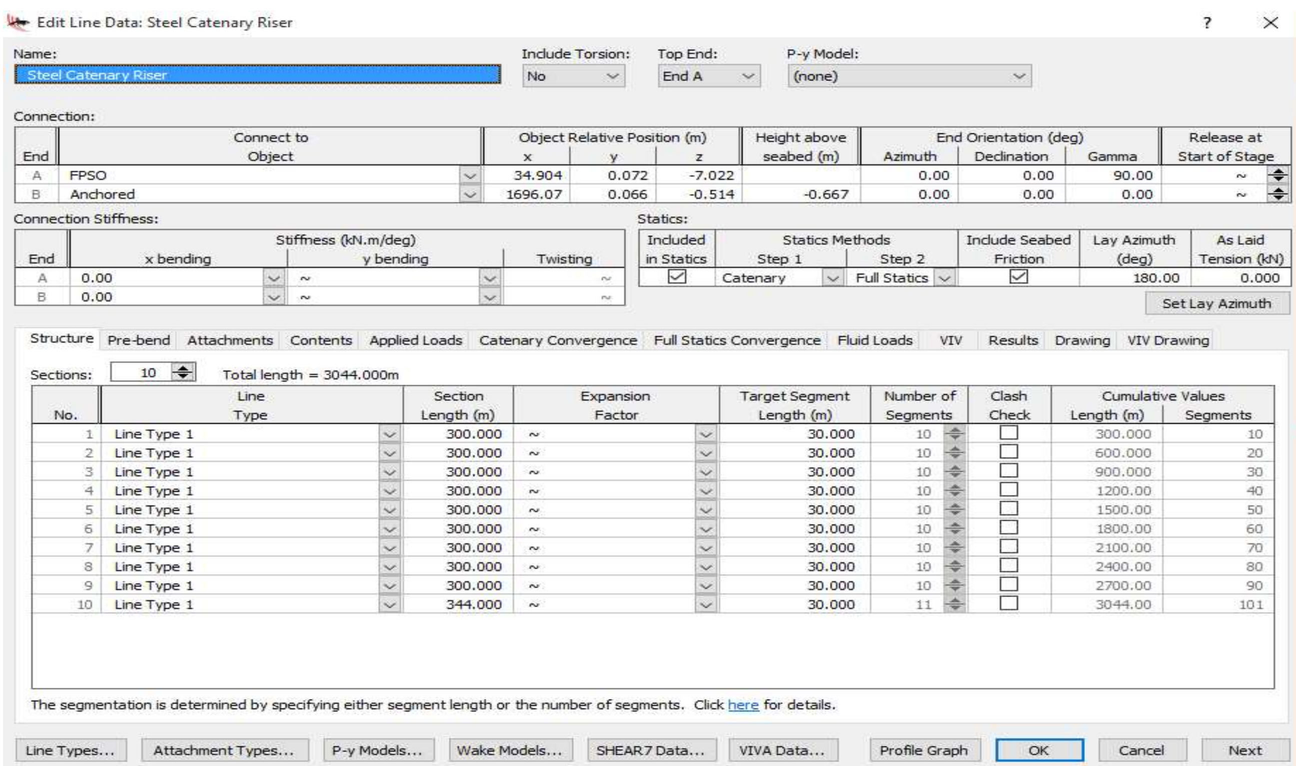

Figure 3. 2: SCR Material Description on Orcaflex Interface 2

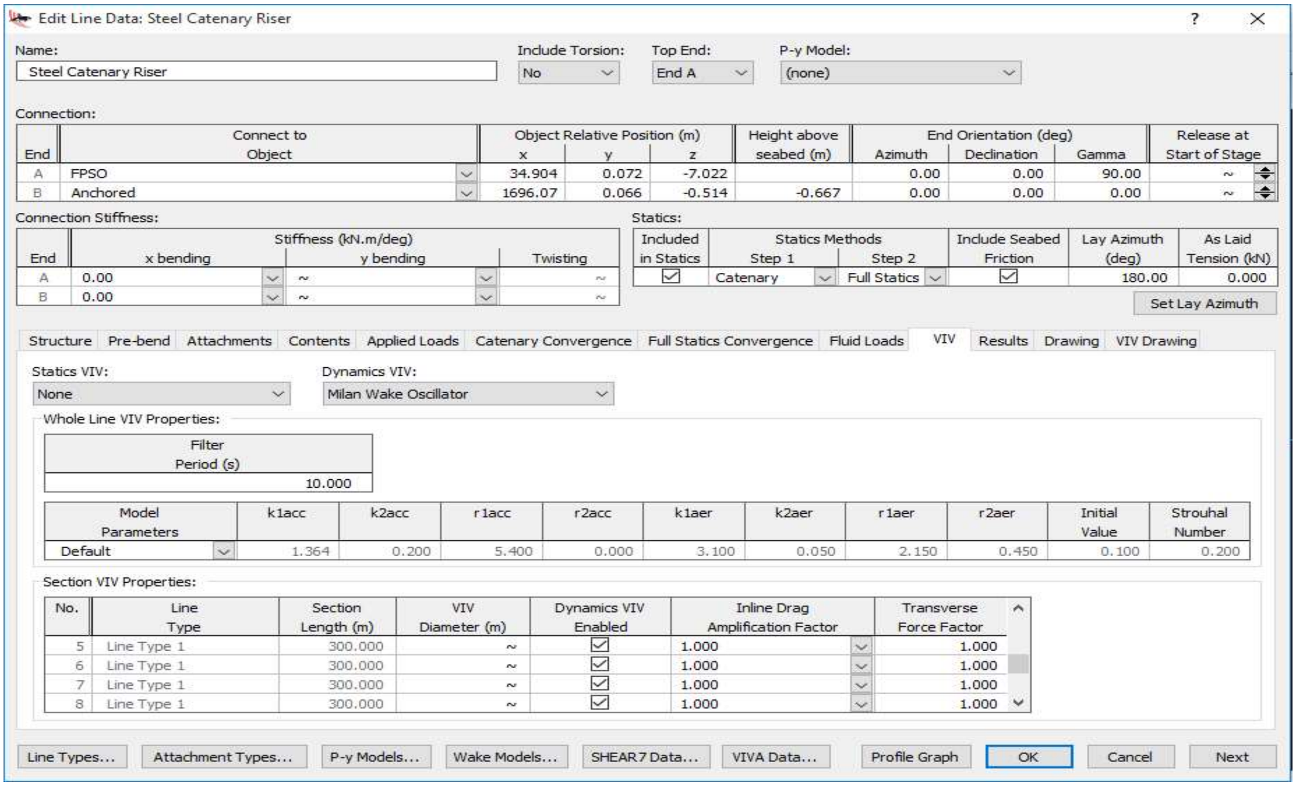

Figure 3. 3: SCR Material Description on Orcaflex Interface 3

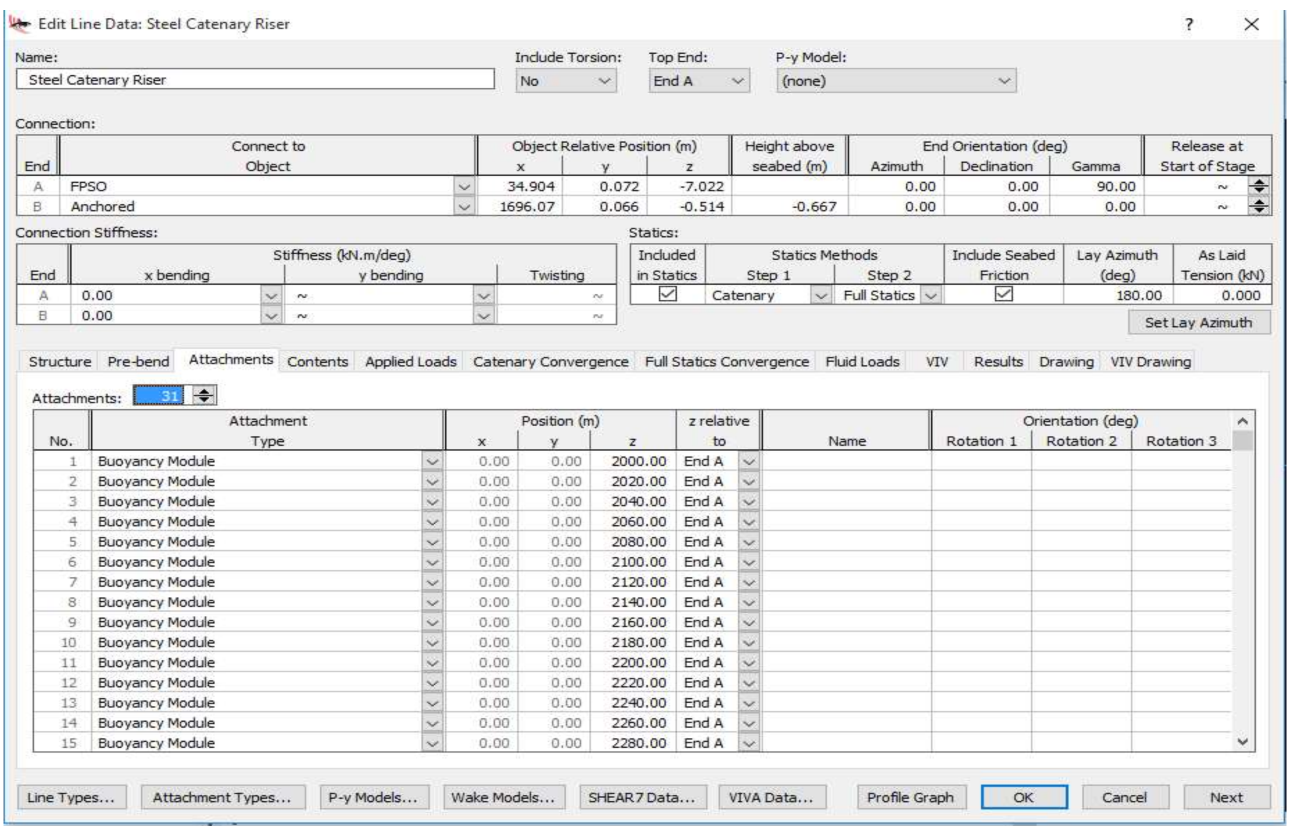

Figure 3. 4: SCR Material Description on Orcaflex Interface 4

3.2 Meteocean data

Meteocean data for Offshore Nigeria showing water depth, current factor, rotation, near-surfaces and near-bottom current speed and direction were inputed into the Orcaflex platform for JONSWAP wave spectra. They are shown in Table 3.2 to 3.6.

Table 3. 1: Current Profile of Riser Environment

Number	Depth(m)	Factor	Rotation(deg)
1	0	0.6	0
2	250	0.6	45
3	500	0.8	90
4	750	1	135
5	1000	0.6	180
6	1300	0.6	225
7	1600	1	270
8	2000	1	315

Table 3.2 shows environmental data for the current factor and the angle of rotation at the various levels of water depth.

Table 3. 2: Current Direction (Near Surface)

Simulation Time(s)	Direction(deg)
0	0
2	45
4	90
6	135
8	180
10	225
12	270
14	315
16	360

Table 3.3 shows the current direction at near surfaces corresponding to the simulation time on the Orcaflex software.

Table 3. 3: Current Velocity (Near Surface)

Simulation Time(s)	Velocity(m/s)
0	0
2	0.103
4	0.206
6	0.309
8	0.412
10	0.514
12	0.617
14	0.72
16	0.823

Table 3.4 shows the velocity of the current at near surfaces corresponding to the simulation time on the Orcaflex software.

Table 3. 4: Current Direction (Bottom Surface)

Simulation Time(s)	Direction (deg)
0	0
2	45
4	90
6	135
8	180
10	225
12	270
14	315
16	360

Table 3.5 shows the current direction at the bottom surfaces corresponding to the simulation time on the Orcaflex software.

Table 3. 5: Current Velocity (Bottom Surface)

Simulation Time(s)	Velocity(m/s)
0	0
2	0.103
4	0.206
6	0.309
8	0.412
10	0.514

Table 3.6 shows the velocity of the current at near surfaces corresponding to the simulation time on the Orcaflex software.

3.3 Methods

The steel catenary riser material characteristics and meteocean data were inputed into the Orcaflex 9.8b software and simulated using the Milan wake oscillator model for VIV. Results were obtained for the Fatigue Life and Damage as well as the effective tension at the buoyancy section using JONSAWP spectra for VIV and Non-VIV conditions.

3.3.1 Procedure for dynamic analysis of riser on Orcaflex

i. Click on model browser and input the general and environmental data.
ii. Click on vessel and drop on the sea surface.
iii. Attach a line of 3044m to the vessel (End A is to the vessel while End B is anchored).
iv. Under Line type 1 data, increase the sections to 10
v. Under "Attachment Type" click Clump type and values for buoyancy modules from 2000m to 2600m of each line.

vi. For Riser use "Homogenous Pipe" and attach the relevant design data.
vii. Run static simulation (lazy wave configuration).
viii. Then run dynamic simulation to check the riser response.
ix. Click "Select results" icon and select "Time history"
x. Check results for Effective Tension at buoyancy length.

3.3.2 Procedure for fatigue analysis of riser on Orcaflex

i. Click on model browser and input the general and environmental data.
ii. Click on vessel and drop on the sea surface.
iii. Attach a line of 3044m to the vessel (End A is to the vessel while End B is anchored).
iv. Under Line type 1 data, increase the sections to 10
v. Under "Attachment Type" click Clump type and values for buoyancy modules from 2000m to 2600m of each line.
vi. For Riser use "Homogenous Pipe" and attach the relevant design data.
vii. Run static simulation (lazy wave configuration).
viii. Then run dynamic simulation to check the riser response.
ix. Click "Results" icon and select "Fatigue Analysis"
x. Input simulation and calculate fatigue.
xi. Results for both fatigue life and damage are presented in graphical and tabular format.

IV. RESULTS AND DISCUSSION

4.1 Results

The dynamic and fatigue analysis due to VIV and Non-VIV were simulated using Orcaflex 9.8b software and effective tension, fatigue life and damage values were obtained. The results were well represented figuratively for proper understanding. Meteocean data for Offshore Nigeria which includes wave, current speed and direction where properly simulated for JONSWAP wave spectra alongside the riser design parameters. Based on these, the effective tension were properly analyzed at the buoyancy section of the SCR on a graph. Comparison was also made between fatigue life and damage values for VIV and Non-VIV conditions using JONSWAP wave spectra and proper inferences were made. Proper conversion was made from English to Metric units from raw data sources prior to simulation.

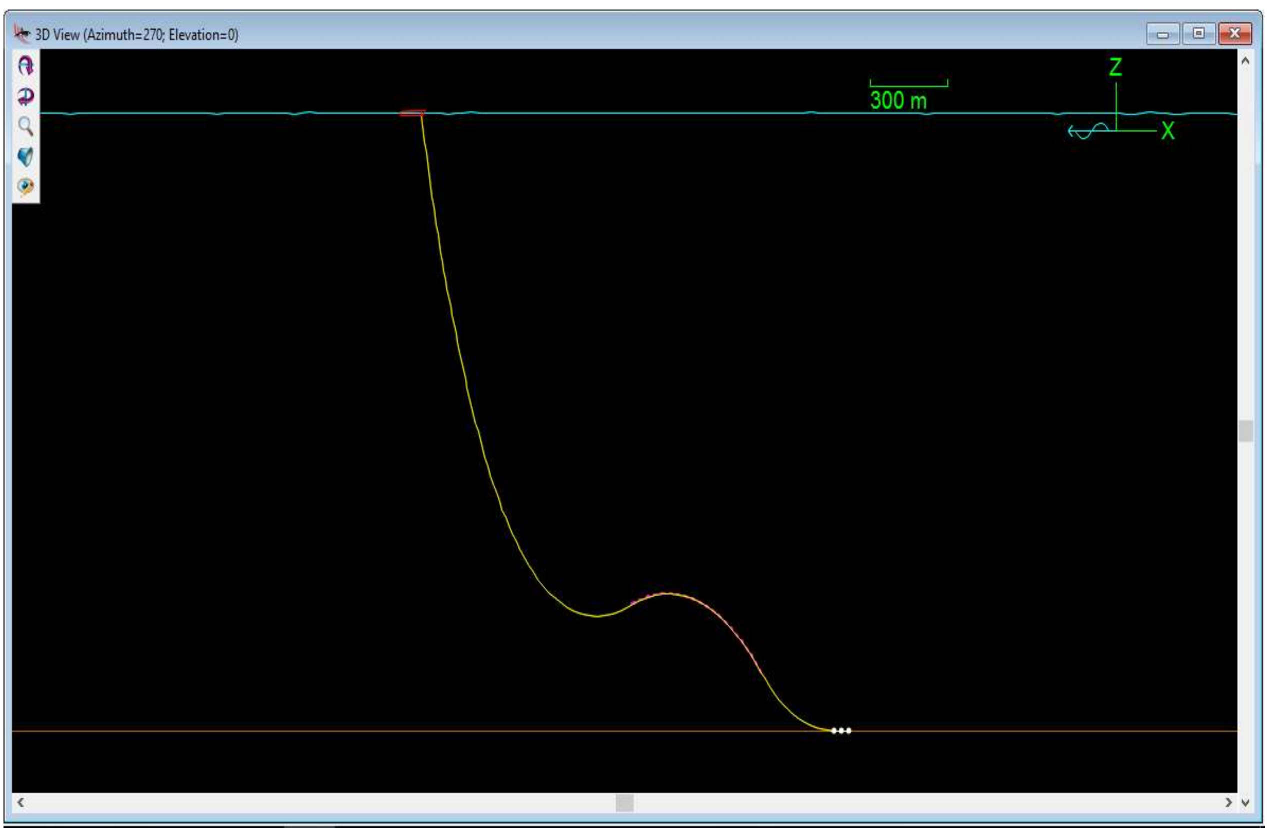

Figure 4. 1: Completed Dynamic Simulation of SCR lazy wave on Orcaflex

For Non-VIV the following results were obtained for effective tension at the different arc lengths;

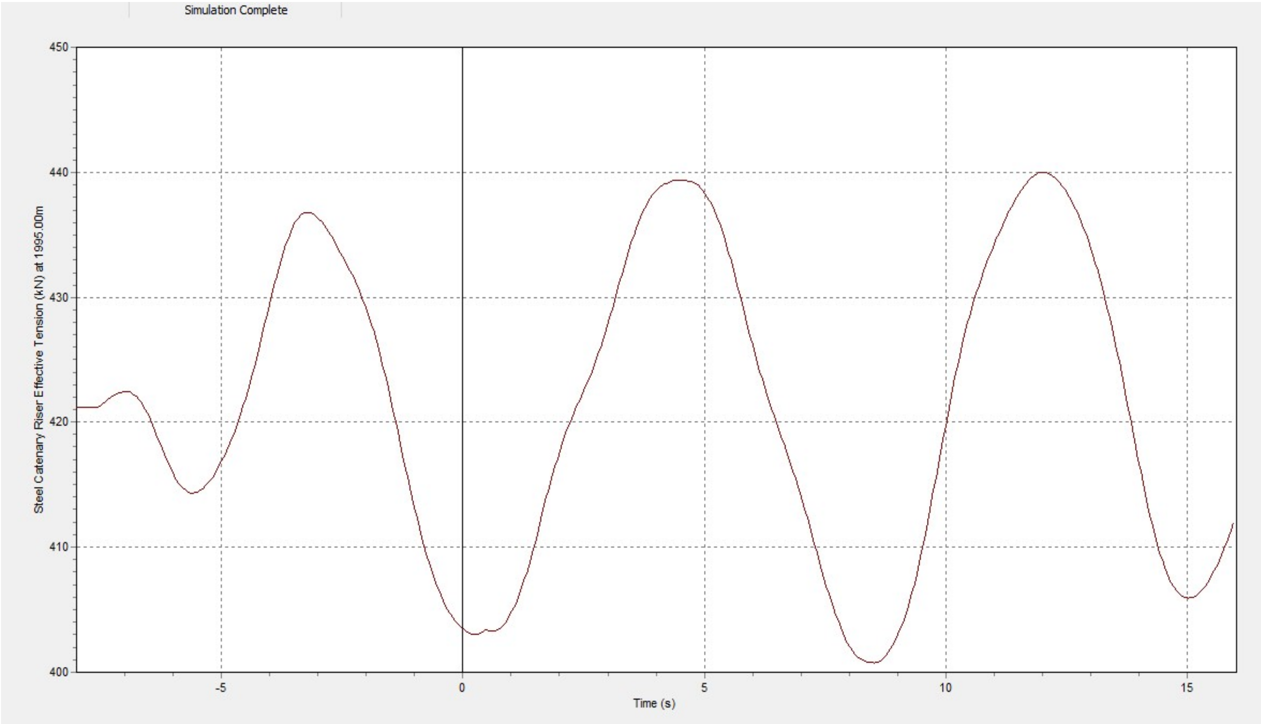

Figure 4. 2: Effective Tension- Time graph of SCR at 2000m Buoyancy Section

Maxima (t, EF) = (4, 439); (12, 440). The highest maxima is 440KN.

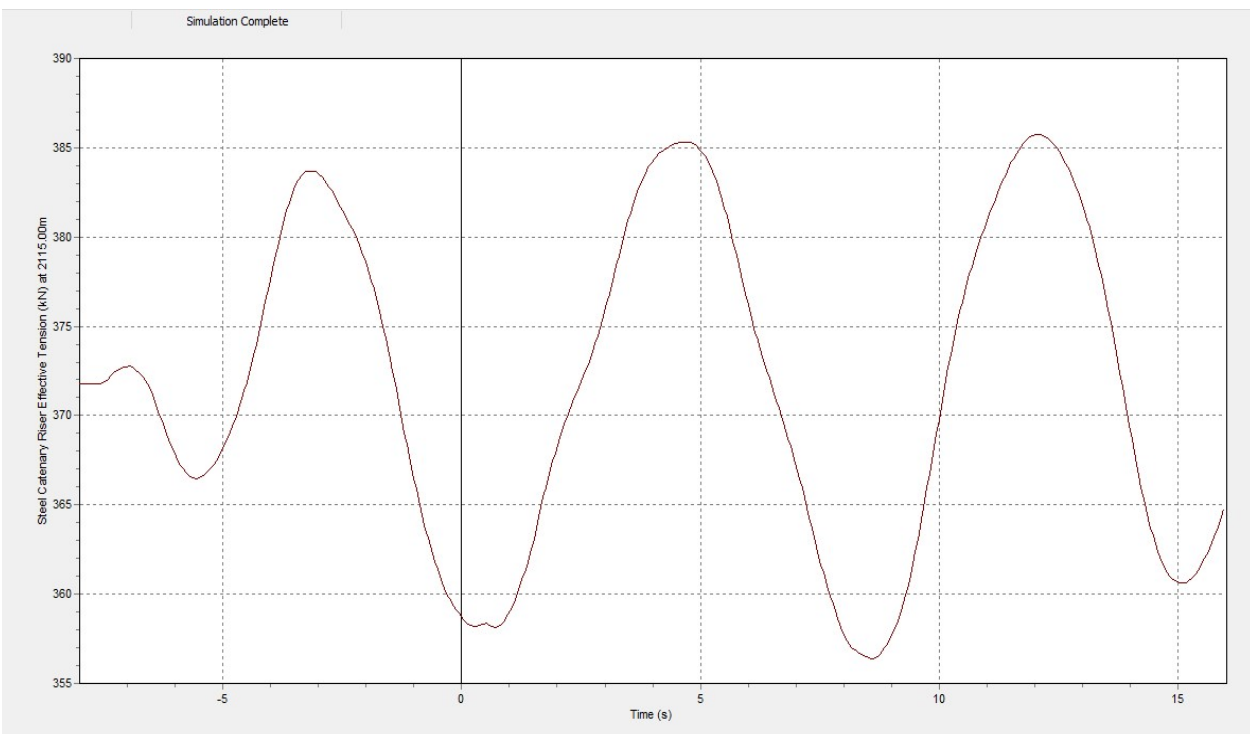

Figure 4. 3: Effective Tension- Time graph of SCR at 2120m Buoyancy Section.

Maxima (t, EF) = (4.8, 385.2); (12.3, 386). The highest maxima is 386KN.

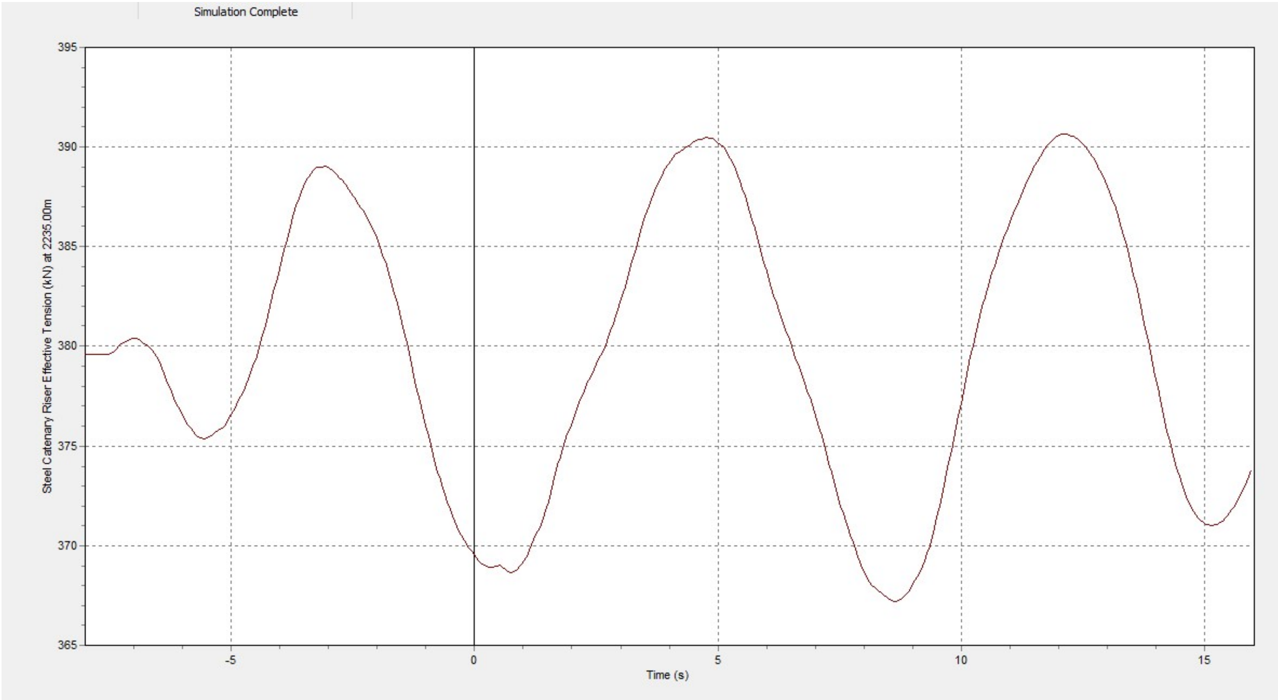

Figure 4. 4: Effective Tension- Time graph of SCR at 2240m Buoyancy Section.

Maxima (t, EF) = (4.9, 390.5); (12.2, 390.8). The highest maxima is 390.8KN.

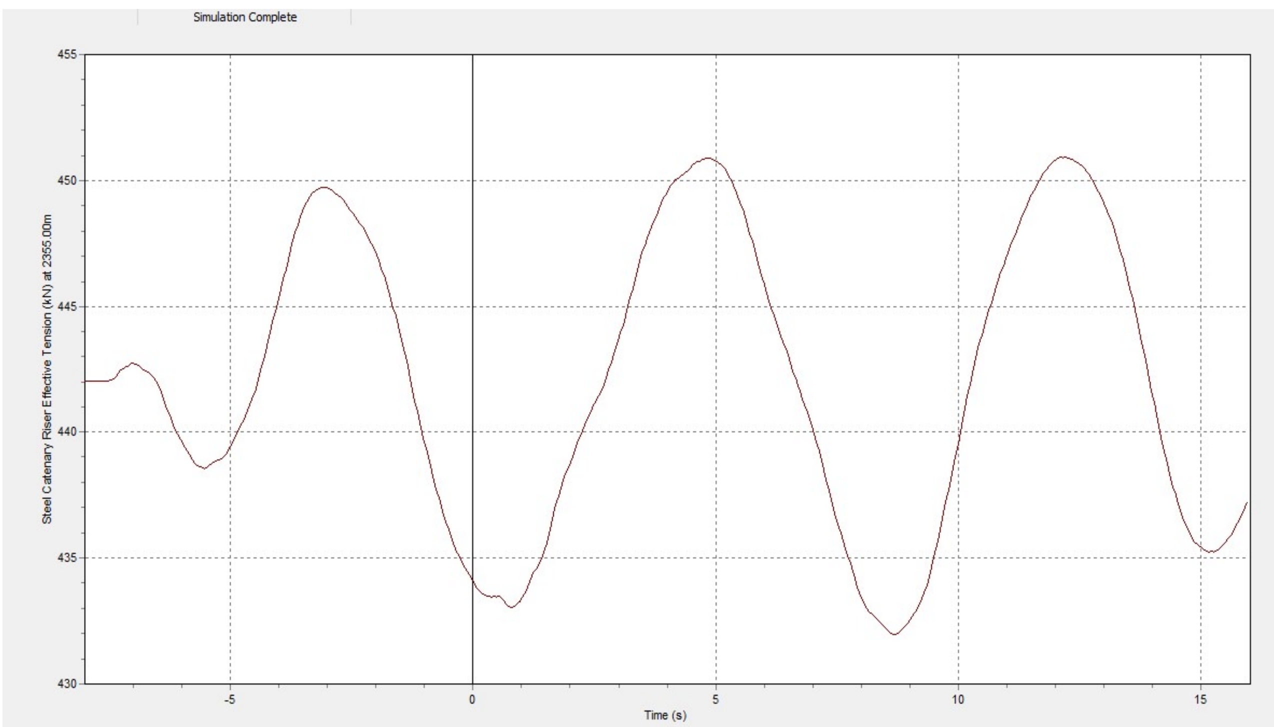

Figure 4. 5: Effective Tension- Time graph of SCR at 2360m Buoyancy Section

Maxima (t, EF) = (5, 451); (12.2, 451). The highest maxima is 451KN.

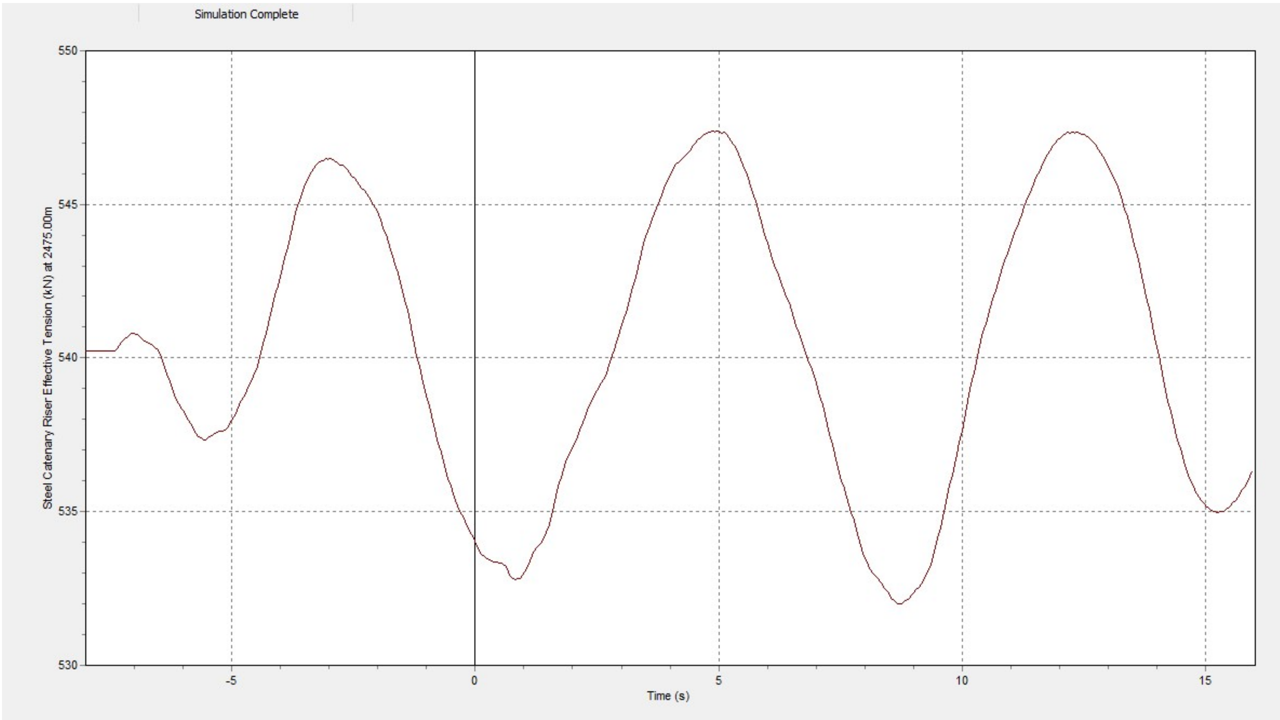

Figure 4. 6: Effective Tension- Time graph of SCR at 2480m Buoyancy Section

Maxima (t, EF) = (5, 547); (12.2, 547). The highest maxima is 547KN.

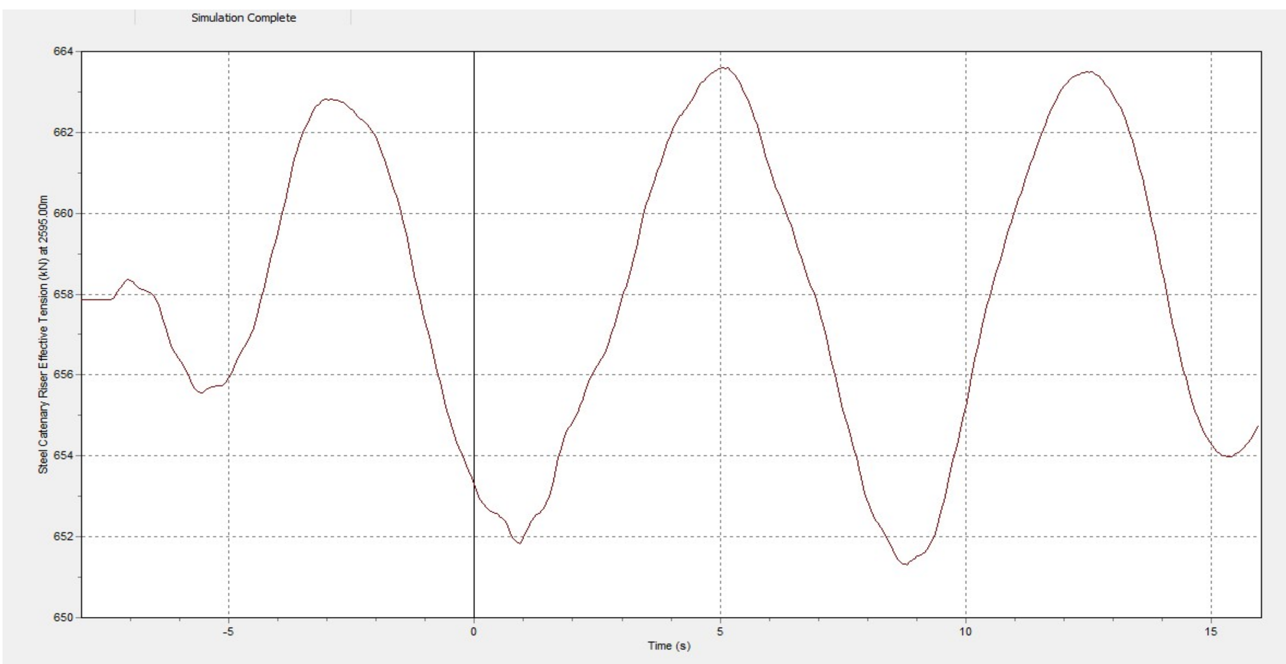

Figure 4. 7: Effective Tension- Time graph of SCR at 2600m Buoyancy Section

Maxima (t, EF) = (5, 663.5); (12.2, 663.5). The highest maxima is 663.5KN.

For VIV the following results were obtained for effective tension;

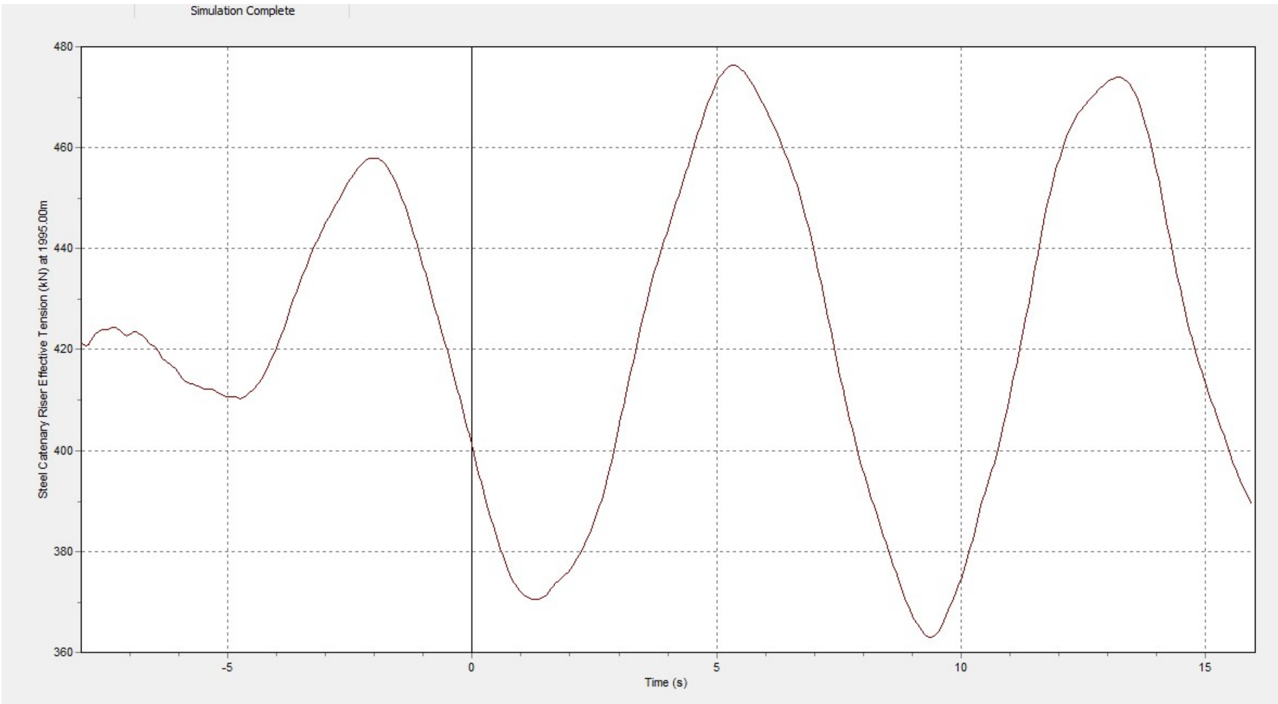

Figure 4. 8: Effective Tension- Time graph of SCR at 2000m Buoyancy Section

Maxima (t, EF) = (5.5, 477); (13.6, 472). The highest maxima is 472KN.

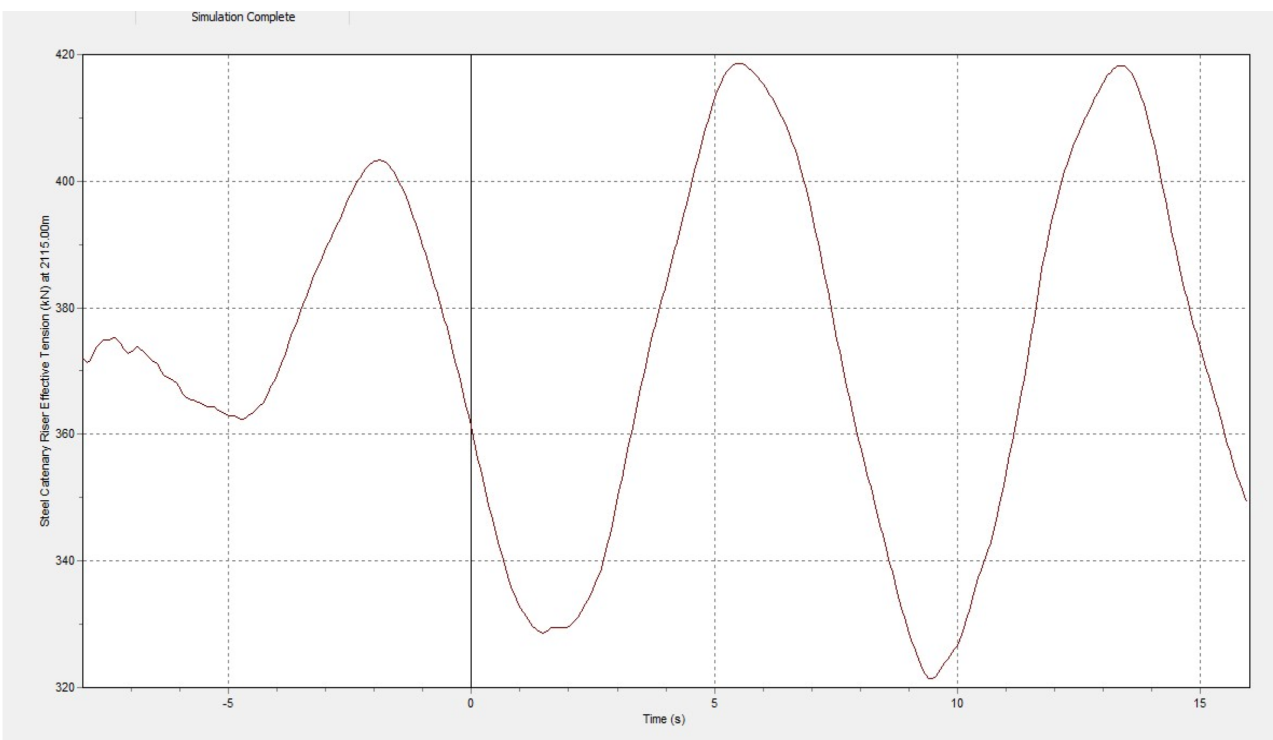

Figure 4. 9: Effective Tension- Time graph of SCR at 2120m Buoyancy Section

Maxima (t, EF) = (5.5, 418); (13.3, 417). The highest maxima is 418KN.

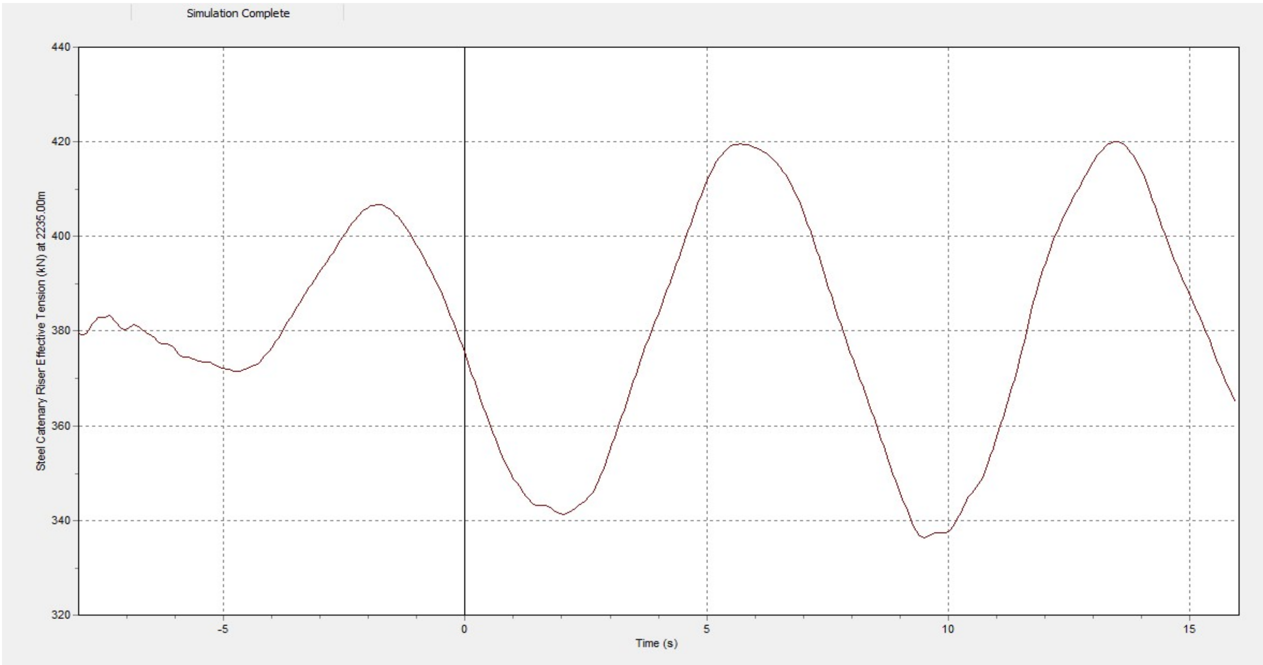

Figure 4. 10: Effective Tension- Time graph of SCR at 2240m Buoyancy Section

Maxima (t, EF) = (5.8, 419.7); (13.5, 420). The highest maxima is 420KN.

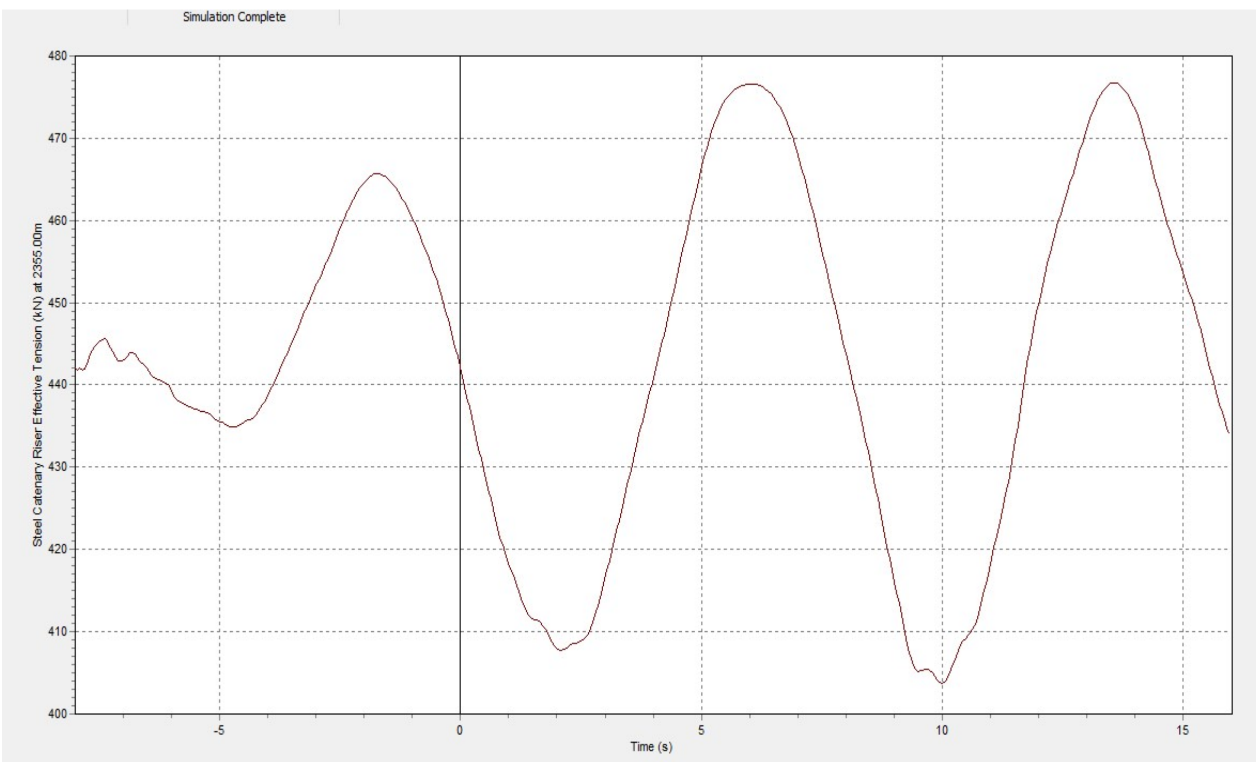

Figure 4. 11: Effective Tension- Time graph of SCR at 2360m Buoyancy Section

Maxima (t, EF) = (6.2, 476); (13.6, 477). The highest maxima is 477KN.

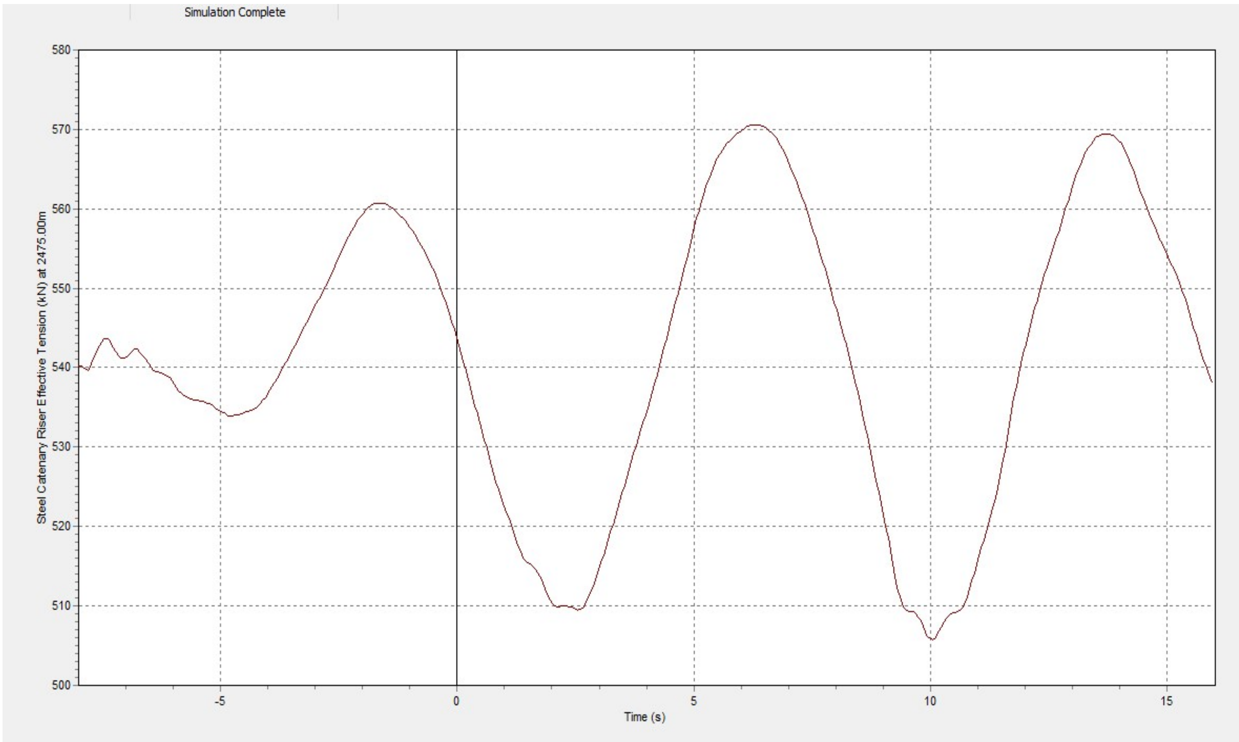

Figure 4. 12: Effective Tension- Time graph of SCR at 2480m Buoyancy Section

Maxima (t, EF) = (6.4, 571); (13.7, 569). The highest maxima is 571KN.

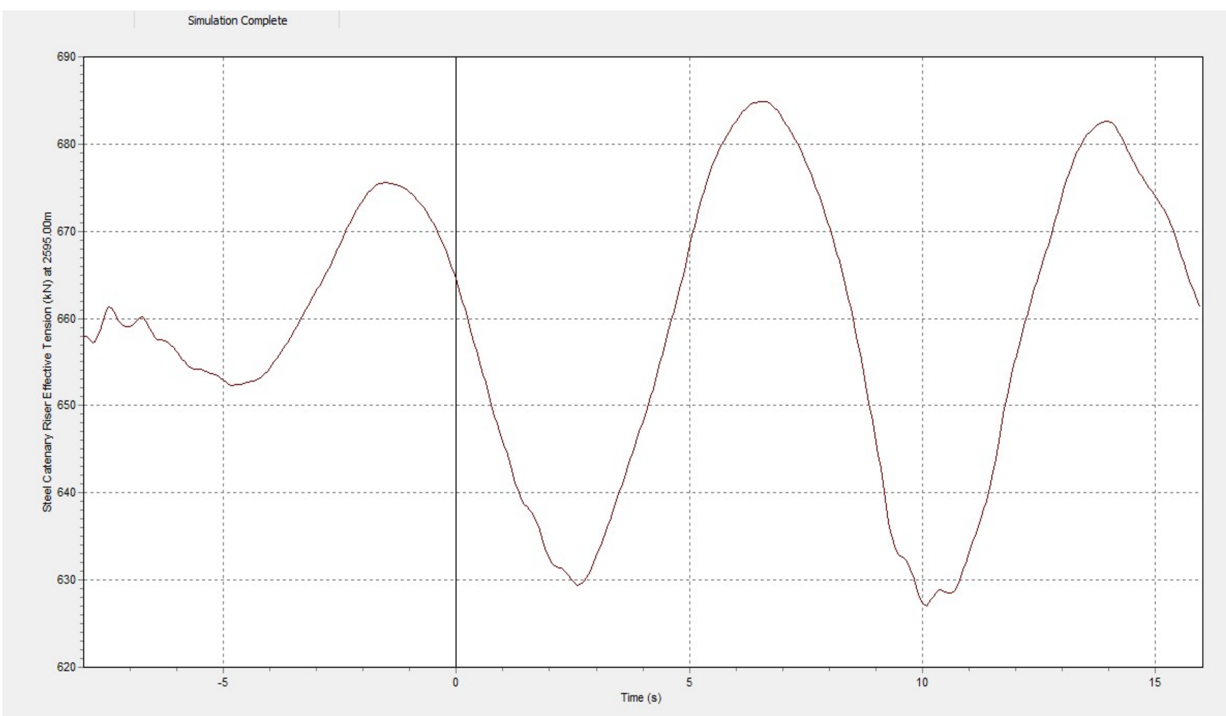

Figure 4. 13: Effective Tension- Time graph of SCR at 2600m Buoyancy Section

Maxima (t, EF) = (6.7, 685); (14, 683). The highest maxima is 685KN.

The fatigue damage results were shown below;

Fatigue Damage Summary

OrcaFlex 9.8b: Abi(Jonswap_VIV).ftg (modified 11:03 AM on 18/09/2018 by OrcaFlex 9.8b)

Title: Fatigue Analysis Example Data

Damage Calculation: Homogeneous pipe stress

Analysis Type: Rainflow

Worst Damage	
Damage over Total Exposure	0.000177765
Total Exposure Time (years)	0.002737851
Life (years)	15.40151622
Arc Length (m)	2934.545455
Theta (deg)	45
SN-curve	S-N Curve1
Radial Position	Outer
SCF	1.3
Thickness Correction Factor	1

Figure 4.14: Fatigue Life and Damage for SCR (VIV)

Fatigue Damage Summary

OrcaFlex 9.8b: Abi(Jonswap).ftg (modified 11:01 AM on 18/09/2018 by OrcaFlex 9.8b)

Title: Fatigue Analysis Example Data

Damage Calculation: Homogeneous pipe stress

Analysis Type: Rainflow

Worst Damage	
Damage over Total Exposure	0.000152155
Total Exposure Time (years)	0.002737851
Life (years)	17.99388586
Arc Length (m)	45
Theta (deg)	270
SN-curve	S-N Curve1
Radial Position	Outer
SCF	1.3
Thickness Correction Factor	1

Figure 4.15: Fatigue Life and Damage for SCR (Without VIV)

4.2 Discussion

Considering the JONSWAP spectra Non-VIV and VIV in the analysis of the buoyancy section of the SCR, the results for Non-VIV were shown in figure 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7. SCR at buoyancy arc length 2000m, 2120m, 2240m, 2360m, 2480m and 2600m gave highest maxima EF values for

440KN; 386KN; 390.8KN; 451KN; 547KN and 663.5KN respectively. It can be seen that the EF values at the hog bend were highest at the buoyancy section close to the touchdown zone. Similarly, for VIV, results were shown in Figure 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13. SCR at buoyancy arc length 2000m, 2120m, 2240m, 2360m, 2480m and 3000m gave highest maxima EF values for 477KN; 418KN; 420KN; 477KN; 571KN and 685KN respectively. Also it can be seen that the EF values on the hog bend were highest at the buoyancy section close to the touchdown zone. Figure 4.7 and 4.13 show the highest maxima EF values for Non-VIV and VIV respectively at 663.5KN and 685KN for 2600m. Generally, EF results show that VIV increases the tension the SCR experiences. From the literature review, JONSWAP though it was designed for the North Sea, is used almost anywhere because the bandwidth can be adjusted by changing its peakedness parameter γ. According to Felisita*et al.* (2015), SCR applications are challenging in deep water due to fatigue at the touch down zone and applying buoyancy gives the lazy wave configuration which affects fatigue of SCR model by improving its performance.

Therefore, the fatigue analysis for the lazy wave SCR for VIV and Non-VIV gave life and damage values as 15.4 years; 0.000177 and 17.99 years; 0.000152 respectively. The result clearly shows that VIV is a major factor in fatigue life reduction as its number of years before failure is less than that without VIV.

V. CONCLUSION

From the results and discussion in Chapter four, the dynamic analysis on the SCR gave highest maxima effective tension values at the buoyancy section arc lengths (i.e. 2000m, 2120m, 2240m, 2360m, 2480m and 2600m) for the VIV against the Non-VIV. While the fatigue life due to VIV showed lesser number of years to failure and a higher damage value when compared to Non-VIV. This clearly shows that using JONSWAP wave spectra, VIV plays a significant role in the overall fatigue of a lazy wave SCR in Deep Offshore Nigeria with the right application of buoyancy modules. Design and installation of buoyancy modules on the SCR for installation in Deep-Offshore Nigeria should be adapted to Ochi-Hubble wave spectra.

The results of this work show that VIV analysis led to a reduced fatigue life and higher damage value while buoyancy section gave higher tension when compared with Non-VIV. From the foregoing, this work shows that VIV plays a significant role in the overall fatigue of a lazy wave SCR in Deep Offshore Nigeria with great impact at the buoyancy section and hence should be properly taken into consideration in its design in Deep-Offshore Nigeria.

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