On the Fatigue of Steel Catenary Risers

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Steel catenary risers (SCR), though an appropriate and cost effective tool for deepwater development, are fraught with difficult fatigue challenges derived from loads due to the actions of wind, wave and current. In this study, a model SCR-AB with end-A attached to floating production, storage and offloading vessels (FPSO) and end-B anchored to the seabed was created using OrcaFlex© finite element software. Also attached to this model is a 10^4 kg 6D buoy of 6 m height and volume 20 m^3, which was fixed to the SCR at 900 m of the riser length. The various sections of the homogenous 2200 m long SCR pipe include 50 m flex joint section, 350 m strake length, 1300 m riser pipe length, and 500 m flowline section. Metrological ocean data, geotechnical data and SCR data were input into the model which was subjected to the Ochi-Hubble and Joint North Sea Wave Project (JONSWAP) wave spectra. Analyses to determine the influence of fatigue damage on the model was made using system simulation under both static and dynamic modes. The results for JONSWAP wave spectra showed the fatigue life of the SCR to be 1.8 years at the touch-down-point (TDP) while that of Ochi-Hubble wave spectra showed a fatigue life of 13.6 years at SCR TDP, differing by a factor of 7.5. Furthermore, the S-N curves obtained from both wave spectra corroborated an inverse relationship between Stress values S and the number of stress cycles to failure N on a log-log scale.
Keywords: steel catenary risers, touchdown point, Ochi-Hubble, JONSWAP

Highlights
- *Fatigue life at SCR TDP and SCR hang-off obtained are very low, indicative of higher stresses derived from FPSO dynamics, ocean current, wave spectra, and other environmental loadings.*
- *There is a sharp rise in the SCR tension (mooring line effective tension) from zero at FPSO hang-off point to a maximum of $30×10^6$ kN at 5 m arc length due to the reasons mentioned above.*
- *JONSWAP and Ochi-Hubble wave spectra used for SCR design are used to determine the SCR fatigue life, tension, cost, etc. by the oil and gas industry operators.*
- *JONSWAP wave spectrum is often used by engineers for SCR designs in the Gulf of Guinea leads to overdesign with the attendant cost (time, material, logistics, etc.) and is compared to Ochi-Hubble wave spectrum, which is closer to the real-time wave spectra.*

0 INTRODUCTION

0.1 Background

Oil & gas exploration and production activities in deep waters of the Gulf of Mexico, Gulf of Guinea, Brazil, and the North Sea have increased dramatically in recent years, nearly doubling, compared to the activities of a decade ago [1]. Regardless of the floating platform concept adopted for many offshore field development activities, there is always need for a riser system, which has played a massive role as offshore infrastructure [2]. There is, therefore, a need to ensure that the integrity of riser systems is not compromised; that is, ensuring high fatigue life in performance. In West African deepwater, for example, steel catenary risers (SCR) are commonly used because of the prevalent conditions, though fatigue remains a challenge [3]. SCR is a cost-effective alternative for oil and gas export and for water injection lines on deepwater fields, where large-diameter flexible risers present technical and economic limitations [4]. Among the riser concepts (e.g. flexible risers, hybrid risers), SCRs have enjoyed widespread acceptability for deep and ultra-deepwater applications in recent years. This is due to their relatively low cost, conceptual simplicity, significant structural capacity, and ease of fabrication and installation. However, their fatigue response has been a concern to the industry, especially in West Africa [3]. SCR fatigue damage can be caused by vortex-induced vibration (VIV) and vortex-induced motion (VIM) at the touch-down-point (TDP) [3]. Fatigue of SCR at TDP has been one of the most challenging problems in deep water due to interactions with the seabed [5]. The fatigue damage induced by VIV and VIM can be fatal to the riser [6].

0.2 Wave Environment

Harsh environments influence motions of floating platforms, which in turn affect the riser system dynamics. For instance, the application of SCRs with semi-submersibles or floating production, storage and offloading vessels (FPSOs) in harsh deepwater environments presents design challenges due to large wave-induced motions on the platform, and large vessel offsets caused by wind, currents, and slow-drift

wave motions. The resulting large heave motions of the vessel cause buckling and fatigue-related issues of the riser at TDP [7]. The wave spectra adopted in SCR design becomes crucial. The two-parameter Pierson-Moskowitz wave spectrum (Eqs. (1) and (2)) is recommended by the American Bureau of Shipping [8] for an open ocean, such as the Atlantic.

$$S_\eta(\omega) = \frac{5H_s^2\omega_p^4}{16\omega^5}exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right],\qquad(1)$$

or,

$$S_\eta(\omega) = \frac{H_s^2\omega_p^4}{4\pi\omega^5}\left(\frac{2\pi}{T_s}\right)^4 exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_s}\right)^4\omega^{-4}\right].\quad(2)$$

The Joint North Sea Wave Project (JONSWAP) spectrum (Eqs. (3) and (4)) modified the Pierson-Moskowitz spectrum [9] above to account for regions with geographical boundaries the limit the fetch in wave generation.

$$S_\eta(\omega) = \frac{5H_s^2\omega_p^4}{16\omega^5}exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^a(1-0.287\ln\gamma),\ (3)$$

where: $a = exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right]$ and

$$\sigma = \begin{cases}0.07 & \text{for } \omega \le \omega_p \\ 0.09 & \text{for } \omega > \omega_p\end{cases}.$$

Factor $(1-0.287\ln\gamma)$ limits JONSWAP application since the spectral value is zero for $\gamma=32.6$; in which case,

$$S_\eta(\omega) = \frac{\alpha g^2}{\omega^5}exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^a.\qquad(4)$$

To cover the variety of wave shapes associated with swell, storm growth and decay, the six-parameter Ochi-Hubble wave spectrum (Eq. (5)) was proposed [10].

$$S_\eta(\omega) = \frac{1}{4}\sum_{j=1}^{2}\frac{\left(\frac{4\lambda_j+1}{4}\omega_{pj}^4\right)}{\Gamma(\lambda_j)}\times\frac{H_{sj}^2}{\omega^{4\lambda_j+1}}\times$$
$$exp\left(\left(-\frac{4\lambda_j+1}{4}\right)\left(\frac{\omega_{pj}}{\omega}\right)^4\right).\qquad(5)$$

where $j = 1, 2$ stands for the swell (lower) and wind-sea (higher) frequency components. The six

parameters $H_{s1}, H_{s2}, \omega_{p1}, \omega_{p2}, \lambda_1,$ and λ_2 are determined numerically to minimize errors.

0.3 Governing Equations

The governing equations that run the OrcaFlex [11] to [13] algorithm include Newton's Second Law, Morrison, Navier-Stokes and catenary equations.

0.3.1 Newton's Second Law of Motion;

Newtonian force F is the sum of the inertia, damping (viscous) and elastic force-components as in Eq. (6):

$$F = Ma + Cv + kx.\qquad(6)$$

0.3.2 Morrison Equation

In the Morrison equation, fluid force F is the sum of the Froude-Krylov force F_{FK}, hydrodynamic force F_H and the drag force F_D.

$$F = \rho V\dot{u} + \rho C_a V(\dot{u}-\dot{v}) + \frac{1}{2}\rho C_d A(u-v)|u-v|.\quad(7)$$

On simplifying, the fluid force becomes equal to the sum of the inertia force and drag-force.

$$F = (\Delta a_w + C_a\Delta a_r) + \frac{1}{2}\rho C_d A V_r|V_r|.\qquad(8)$$

0.3.3 Navier-Stokes Equation

Fluid inertia is equal to the sum of the pressure gradient, viscous force and body force.

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right) =$$
$$= -\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+F_y,\qquad(9)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) =$$
$$= -\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+F_z,\qquad(10)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) =$$
$$= -\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+F_z.\qquad(11)$$

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0.3.4 Catenary Equation

Steel catenary risers being pipelines suspended between a production platform and the seabed adopts an approximate catenary shape, defined by Eq. (12).

$$y = \frac{H}{w}\left[\cosh\left(w\,\frac{x}{H}\right) - 1\right]. \qquad (12)$$

where w is weight per unit length of riser and H is a constant representing horizontal component of tension.

1 MATERIALS AND METHODS

To study the influence of fatigue in SCR adequately, two wave application modes (Ochi-Hubble wave spectra and JONSWAP wave spectra) were adopted using Orcina OrcaFlex software. The software quality assurance is based on the requirements of BS 5750, 5887, and 5515, and on Defence Standard 00-16. Its validation checks include checking the program against mathematical theory, the real world, and against other institutional computer programs.

Larsen [14] reported results from static and dynamic analyses of standard flexible riser systems performed by eleven different institutions using their in-house software. OrcaFlex developers took part in the major comparison of flexible riser programs initiated by the International Ship and offshore Structures Congress (ISSC) "Slender Marine Structures" committee. The study contains a complete description of the test cases and results that provide a benchmark test for users and programmers of computer code for flexible riser analysis. The results showed good agreement between OrcaFlex and other established programs with a 10 % to 15 % coefficient of variation.

A large-scale test has been carried out in Lake Pend Oreille under a joint industry project by scientific marine services (SMS) [15] for PMB Engineering; Australia. OrcaFlex results showed very close agreement with the test results, including details of SCR behaviour at touchdown. A major validation exercise was carried out to compare OrcaFlex with model test results obtained from a joint industry project [16]. Good agreement was obtained.

In this study, an SCR [17] and [18] comprising a line with the end-A of the riser attached to the FPSO and end-B anchored to the seabed as in Fig. 1 is modelled by carrying out the following tasks using the OrcaFlex post-processor software:

a) Set the SCR line length to be 2,200 m and as a homogenous pipe with flex joint, strake, riser

pipe and flowline lengths modelled on the line (in that order) with the height of 1000 m set above the seabed with an azimuth angle of 180º.
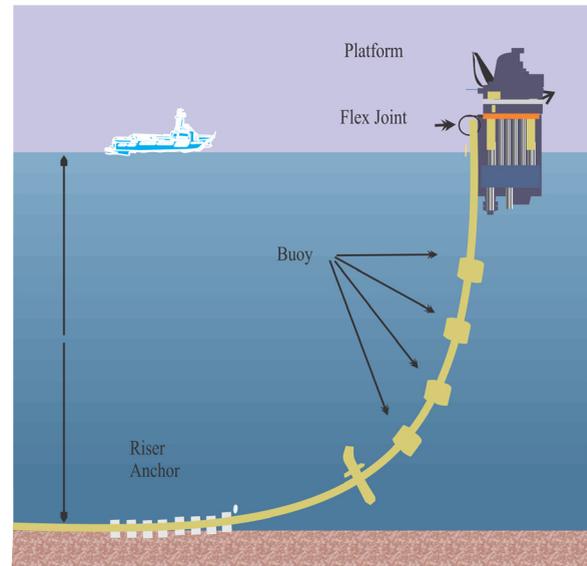
Fig. 1. *Typical steel catenary riser between an FPSO and seabed*

b) A 6D buoy is modelled and anchored onto the SCR-line.
c) The design parameters and environmental properties, which included the wave train of both Ochi-Hubble, a two parameter wave spectra that fully describes the typical sea state (valid for the swell and wind-sea conditions) of the Gulf of Guinea and that of JONSWAP were inputs in the different cases.
d) The line modelled as a riser is given real life data-values. Typical SCR data imputed to this study include: pipe of outer diameter 273.1 mm, inner diameter 205.7 mm, and thickness 67.4 mm, density 7850 kg/m³, elastic modulus 200 GPa, second moment of inertia 8.67×10^{-5}, mass per unit length 128.2 kg/m, bending stiffness 3.27×10^6 kN, axial stiffness 1.73×10^4 kN, torsional stiffness 10 kNm²/rad, design life 20 years, bulk modulus 160 GPa, yield strength 483 MPa, tensile strength 562 MPa, kinematic viscosity 1.35×10^{-6} m²/s; and the SCR-contents, which is a crude oil of density 800 kg/m³ and flow rate of 0.1 kg/s.
e) Global analysis: This describes the overall static and dynamic structural behaviour of the riser by exposing the system to a stationary environmental loading condition [19]:
• Static analysis investigates the equilibrium position of the model without considering

environmental forces, weight, buoyancy and drag forces. After running the static analysis of this model, there was a static convergence for the model after a maximum of 100 iterations.

- The dynamic analysis is a time simulation of the SCR-model motion for a specified period, starting from the static analysis position. The real life environment data for current, wind and seabed conditions were used as inputs. Typical environment data used as input parameters in this study include: (i) metrological Ocean data for 100 years return period: significant wave height 4 m, most probable maximum wave height 7.8 m, crest of maximum individual wave 4.5 m, peak spectral period 15.5 s, mean zero crossing 7.17 s, mean wave direction 189°, (ii) wind data 10 min wind speed 20.4 m/s, wind direction 180 Set the SCR line length to be 2,200 m and as a homogenous pipe with flex joint, strake, riser pipe and flowline lengths modelled on the line (in that order) with the height of 1000 m set above the seabed with an azimuth angle of 180°, (iii) current data: current speed (below 1000 m depth) 0.15, surface directions 180°, (iv) sea water data: sea surface temperatures 25 °C, near-bed sea temperatures 4 °C, sea water density 1025 kg/m³, depth of water 1000 m, (v) seabed data: soil friction coefficient 0.45 (nonlinear soil model was adopted). In running this dynamic analysis, the simulation time was first set at 16 s and observed before being run for 3 h, the severest sea state in the Gulf of Guinea.

f) Fatigue analysis was carried out on the SCR model for both Ochi-Hubble and JONSWAP wave spectra for comparison. Before the fatigue analysis was performed, a set of Orcaflex simulation files that model the system was prepared under possible real-time load conditions. This load case was assigned an exposure level of 20 years (175,200 h) riser design life.

2 RESULTS AND DISCUSSION

2.1 Fatigue Life - Arc Length Analysis

From Fig. 2 based on the JONSWAP wave spectrum, it can be observed that:
- hang-off fatigue life, HOFL is 10 years;
- fatigue life range, FL; 500 years < FL < 5,000 years;
- TDP fatigue life, TDPFL = 1.8 years at 1828.8 m;
- maximum fatigue life beyond TDP FL_{max} = 10,000 years.

From Fig. 3, based on Ochi-Hubble wave spectrum, it can be observed that:
- hang-off fatigue life; HOFL ≈ 7 years;
- fatigue life range, FL; 100 years < FL < 5,000 years;
- TDP fatigue life; TDPFL = 13.6 years at 1828.8 m;
- maximum fatigue life beyond TDP FL_{max} = 10,000 years.
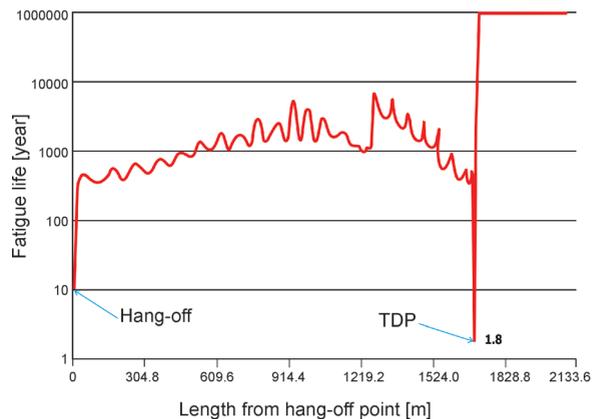
Fig. 2. *Fatigue life versus SCR length from hang-off point in JONSWAP wave spectra*

From Fig. 2, the fatigue life of the SCR when subjected to stress due to environmental loadings is 1.8 years, or approximately 2 years, which is very low. Low fatigue life at the SCR TDP zone is indicative of severe fatigue damage therein. From Fig. 3, the SCR fatigue life is showing a high value of 13.6 years, or approximately 14 years, though less than the proposed 20-year design life. However, Figs. 2 and 3 show that the least fatigue life is observed in the SCR hang-off and TDP section. Hence, from Figs. 2 and 3, the fatigue life of SCR in Ochi-Hubble wave spectra is 7.5 times that of SCR fatigue life in JONSWAP wave spectra. This implies that the common practice of SCR designs based on JONSWAP wave spectrum applied in the Gulf of Guinea, where the real-time wave pattern follows the Ochi-Hubble spectra is an overdesign and the cost implication is of order 7.5 high. Figs. 2 and 3 showed the same order of fatigue life beyond TDP arc length. The low hang-off fatigue life is corroborated by the sharp rise in SCR tension from (0 m, –30E6 kN) through (2.5 m, 0 kN) to (4.5 m, 29E6 kN) along the SCR arc length in Fig. 4.
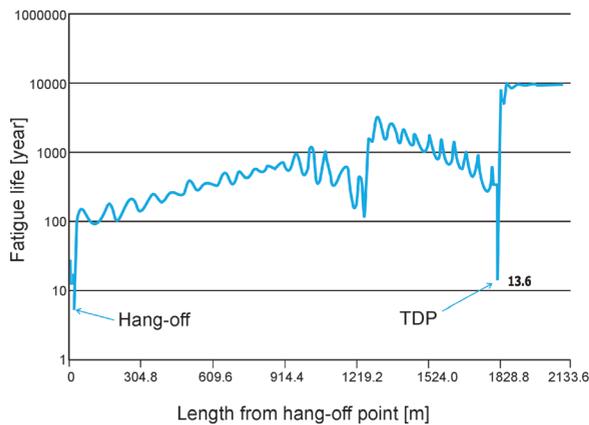
Fig. 3. *Fatigue life versus SCR length from hang-off point in Ochi-Hubble wave spectra*
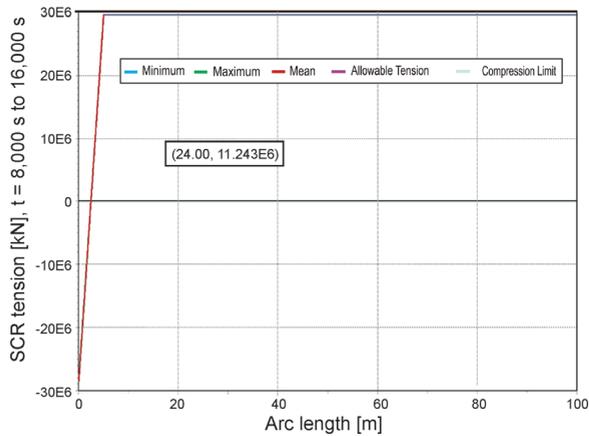
Fig. 4. *SCR tension versus arc length curve*

2.2 Stress (S) – Cycles (N) to Failures

The *S-N* curves in Figs. 5 and 6 showed that higher stress values (*S*) caused a lower number of cycles to failure (*N*), that is, lower endurance limits.
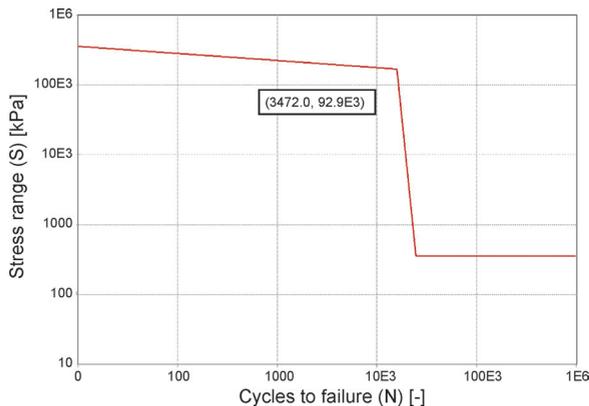
Fig. 5. *Stress S versus cycles to failure N curve for SCR in JONSWAP wave spectra*

The fall rate of stress with respect to cycles is higher with the JONSWAP spectra than the Ochi-Hubble spectra. Comparing the slopes of the *S-N* curves, it can be observed that the fall-rate for JONSWAP spectra is almost of order > 100 on a log-log scale relative to the Ochi-Hubble spectra. This implies that when the stresses due to environmental loading vary, it will have an effect on the riser life before failure.
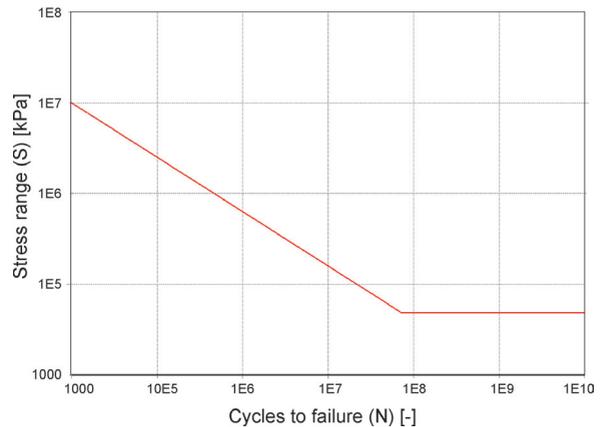
Fig. 6. *Stress S versus cycles to failure N curve for SCR in Ochi-Hubble wave spectra*

3 CONCLUSION

Using an SCR model in Ochi-Hubble wave spectra gives a higher fatigue life than JONSWAP spectra, which are often used by design companies. With a higher SCR fatigue life in Ochi-Hubble wave spectra, there is no overdesign since it thoroughly describes the actual sea state in the Gulf of Guinea.

SCR modelled in JONSWAP wave spectra gave a misrepresentation of the SCR fatigue life leading to overdesign, which implies high cost both on the side of multinational companies and contractors.

Stress variations due to environmental loading contributed immensely to SCR fatigue damage.

The high tension observed at the SCR hang-off, close to the FPSO, with both wave-spectra can be attributed to the combined action of waves, wind and current, as well as, FPSO heavy motion.

4 NOMENCLATURE

A drag area, [m²]
C viscosity damping factor, [Ns/m]
C_a added mass coefficient of body
C_d drag coefficient for the body
$F_{x,y,z}$ body force in *x,y,z* directions, [N/m³]
F fluid force, [N]

H_s — significant wave height, [m]
M — mass, [kg]
P — pressure, [Pa]
S_η — wave spectral density, [m²/Hz]
T_s — average zero up-crossing period, [s]
V — volume, [m³]
V_r — fluid velocity relative to body, [m/s]
a — acceleration, [m/s²]
a_r — fluid -body relative acceleration, [m/s²]
a_w — fluid acceleration rel. to earth, [m/s²]
g — acceleration due to gravity, [m/s²]
j — integer counter
k — stiffness, [N/m]
u, v, w — x, y, z axis velocity components, [m/s]
t — time, [s]
ω — circular frequency of the wave, [rad/s]
ω_p — peak frequency for peak spectrum; [rad/s]
γ — peaked-ness parameter (1 to 7).
α — parameter
ρ — density, [kg/m³]
μ — dynamic viscosity, [Pa·s]
Δ — Mass of fluid displaced by body, [kg]
λ — Ochi-Hubble's parameters 5 & 6

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