FATIGUE DAMAGE AND LIFE OF A COMPOSITE PRODUCTION RISER

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Abstract

This research investigates the long term serviceability of a production riser which consists of specially orthotropic carbon-epoxy layers. All the cyclic stress magnitudes and number of cycles generated by a long term sea state are obtained by utilizing the Rayleigh probability function along with a series of frequency domain finite element analysis. In this study, the problem is reduced to estimations of lamina-level fatigue, and various unidirectional S-N relationships are used in order to present a range of possible fatigue life for the composite riser.

As expected, the results suggest that the composite riser will satisfy the intended service life and is likely to have an infinite life provided that the material has average fatigue properties. However, prediction on dominant sea characteristics may differ depending on the choice of S-N representation and parameters.

1 Introduction

Composite materials have emerged as an attractive alternative to steel and titanium in the offshore industry. Although there are major obstacles to overcome before composites can be used for major structural components with confidence, numerous joint industry projects and studies [1-2] have been carried out to accelerate the application of the advanced materials to the enormous offshore structures.

Deep water oil and gas production presents technical and economical challenges. Many of the challenges stem from the tremendous weight gain caused by increased water depth. For this reason, composite risers and mooring lines have drawn considerable attention. A riser is a series of mechanically connected pipe segments that connects the well and the surface facility. A production riser transports oil / gas to the platform, and usually there are multiple risers attached to a platform. As water depth increases, so is the total submerged weight of the risers, which inevitably causes enormous buoyancy requirements for the platform, since the platform needs to provide a tension up to twice the total weight of the risers. Due to their high specific strength, composites offer substantial weight savings which translates into economical advantages in spite of the higher material and manufacturing costs [3-5]. In addition to weight reduction, composite materials generally provide extra benefits, such as excellent fatigue, damping, insulation, and corrosion resistance properties.

Through the past joint industry projects, composite riser design and manufacturing technique has attained a good level of maturity. It has been demonstrated that a composite production riser offers large safety margins under short-term extreme loading conditions, that is, combined tension and bending moment caused by environmental and functional loads [6]. Also, its burst and collapse capacities meet the required design pressures and can potentially be enhanced by redesigning the internal liner. In this study, the long term serviceability of the composite riser under dynamic loads caused by irregular waves is explored. Various S-N curves with different types and degradation constants are applied, and the results are compared in terms of estimated life and most influential sea state.

2 Composite Riser Model

The composite riser system is configured for 1,829 *m* water depth in the Gulf of Mexico. The production system a Tension Leg Platform (TLP), which is attached to the sea floor by vertical mooring lines called tendons. The riser is also vertical and kept taut through top tension applied by a hydraulic unit called tensioner. Fig. 1 shows a typical TLP.

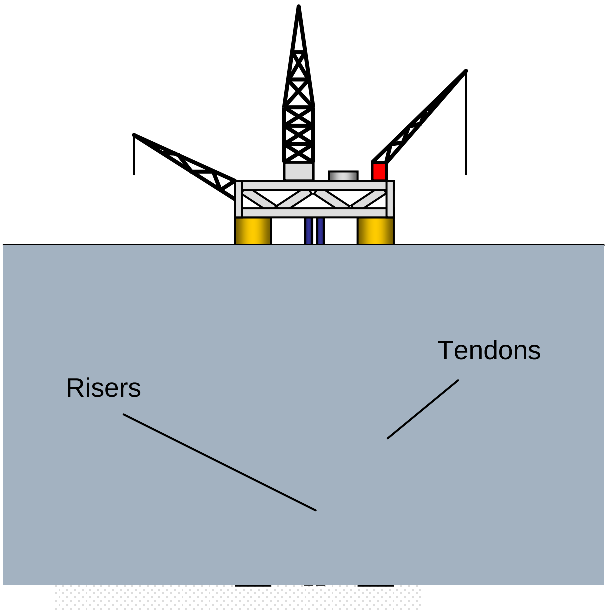

Fig. 1. Schematic of typical tension leg platform

The riser system largely consists of a tensioner joint above the mean water level, riser joints and a stress joint in the water. Here " joints" refer to relatively short sections that comprise the entire structure. One composite riser joint in this study is approximately 19 *m*. It is assumed that only a single riser is installed. Fig. 2 describes the configuration of the riser system.

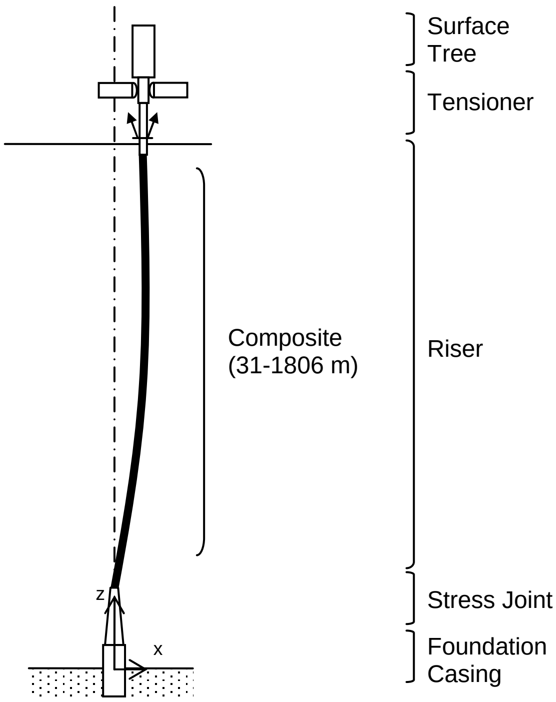

Fig. 2. Riser system configuration

The composite riser has an inner diameter of 24.6 *cm*. On the inside is a steel liner for fluid-tightness, and 19 layers of alternating hoop and axial carbon-epoxy are wrapped around the liner. The combined wall thickness is 3.3 *cm*. The submerged weight per unit length of the composite riser with internal tubing and fluids is merely 26% of the weight of a steel riser designed for the identical condition. The composite riser alone is almost neutrally buoyant.

3 Wave Fatigue

A wave excites the riser with a periodic lateral force whose magnitude is represented by Morison's equation. At the same time, the wave causes the platform to vibrate, which decides the displacement boundary condition at the upper end of the system. The phase angle and magnitude of the platform motion is dependent on the frequency of the wave excitation.

The riser system is subjected to multiple waves of various magnitudes at any given moment, and environmental condition constantly changes throughout the service life of the riser. A long-term sea state is usually modeled by multiple short-term sea states. Each sea state has unique wave spectral characteristics, i.e., significant wave height and zero-crossing period, and it can be decomposed into a number of regular waves.

There exist many different possibilities of combining these multiple regular waves into an irregular wave train. For this reason, a direct integration time domain riser analysis requires multiple realizations. To overcome this difficulty, the frequency domain analysis technique is often used in the offshore community. This technique superposes linearized regular wave solutions for individual wave frequencies and outputs the statistical values of the responses. In this study, 27 short-term sea states are analyzed through RAMS, a finite element analysis software for deep water systems developed by Stress Engineering Services. Using the finite element analysis results, fatigue at the top (1806 *m* above sea floor) and bottom (31 *m* above sea floor) of the composite riser region is evaluated.

4 Analysis Procedure

4.1 Simplification of analysis

Although no experimental S-N data for this particular composite laminate is available, a simplified analysis procedure based on lamina-level fatigue is applicable since the composite riser is nearly a specially orthotropic tube. It is assumed that fatigue mechanisms involved in this particular case are only matrix cracking in the hoop layers and fiber rupture in the axial layers, excluding secondary mechanisms such as longitudinal fiber splitting and delamination. Being a tube, the composite wall has no free edges where excessive interlaminar stresses often lead to delamination. In general, fatigue of the primary load bearing layers (0°) in cross-ply laminates is hardly affected by other damage modes, and the only way matrix cracking in the hoop layers influences fatigue of the axial layers is by increasing the stresses on the axial layers [7-8].

In this study, fatigue failure of the composite riser is defined as failure of the outermost axial layer, which experiences the largest stress among all layers due to combined axial tension and bending moment. When calculating the stresses in this layer induced by wave loading, it is assumed that the hoop layers carry no axial loads. This approach not only yields more conservative values of stress in the primary load-carrying layer, but also eliminates the need for taking the effect of developing fatigue damage in the hoop layers into account. Discounting the entire hoop layers causes an increase of a few percent in σ_1 of the outermost axial layer. It is also assumed that stiffness degradation of the axial layers over long term exposure to service loads is negligible.

4.2 Conversion of global results to stress cycles

Usually, fatigue analysis of an offshore structure utilizes a stress energy spectrum. To obtain the stress energy spectrum, wave energy spectrum is scaled by a transfer function at a location of interest for the given sea state. Instead of constructing a transfer function for the composite riser, this study uses an alternative method to obtain individual stress magnitudes and number of cycles. The frequency domain analysis gives the mean and root mean square (RMS) of axial tension and bending moment at the locations of interest. These values are translated into stresses in the outermost axial layer. The translation is carried out based on finite element analyses results for unit axial tension and unit bending moment. This local finite element analyses are performed using ABAQUS software, and the model utilizes quadratic shell element with individual layer properties specified.

The combined (axial and bending) RMS stress can be used to create a stress distribution. The Rayleigh probability density function for a stress range distribution of each sea state is given by the following equation:

$$p(\Delta\sigma) = \frac{\Delta\sigma}{4\sigma_{RMS}^{\ 2}} \exp\left[-\frac{\Delta\sigma^2}{8\sigma_{RMS}^{\ 2}}\right] \qquad (1)$$

where $\Delta\sigma$: stress range (= 2 × stress amplitude), σ_{RMS}: root mean square of stresses generated by the sea state. Using the probability density, one can create a stress histogram where the number of cycles per unit time (e.g., year) for each small interval of stress range is displayed. When calculating the number of applied cycles (n_i) for each stress level, the probability of occurrence for the sea state is taken into account as well as the period of the cycle.

4.3 Calculation of fatigue damage

The cycles to failure (N_i) of each stress level is found using an S-N relationship. The most common representation for composites is the following semi-log form:

$$S = a - b \log N \qquad (2)$$

where S: maximum stress (= mean + amplitude) normalized by the static strength, a and b: material constants. There are a limited number of S-N curves for unidirectional carbon-epoxy laminates reported in the literature [7-12]. Due to the differences in constituent materials and number of data points available for curve fitting, the curves are dispersed significantly. Since it is difficult to define a typical uniaxial S-N curve for unidirectional carbon-epoxy laminae, the most recent and excellent relationship (a=0.861, b=0.01) [7] is utilized for the estimation of the fatigue life. In addition, with the parameter a fixed at the ideal value (one), the degradation parameter b is replaced by larger values (0.02 to 0.05) to study its effect on the predicted amount of damage and fatigue life. Table 1 shows the semi-log S-N relationships used in this study.

Table 1. Semi-log S-N relationships

Designation	a	b
SN1	0.861	0.01
SN2	1	0.02
SN3	1	0.03
SN4	1	0.04
SN5	1	0.05

Ref [13] proposed the use of a non-dimensional scalar quantity to take the mean stress effect into account, based on the observation that S-N curves for different R ratios can collapse into a master curve if the scalar quantity replaces the commonly used normalized maximum stress. The S-N relationship used in this work is in the form of the following power law relationship.

$$2N = \frac{1}{(\Sigma^*)^{n^*}} \tag{3}$$

where Σ^* is effective normalized stress based on Tsai-Hill criterion, and the value of the exponent n^* is 11.9 for carbon-epoxy. Note that this representation is different from those for metals in that it has only one material constant. This S-N relationship is used in addition to the previous semi-log relationships, and again, a parametric study with various n^* values is performed.

The past composite riser research identified the steel liner as the weakest element which limits the capacities of the entire riser. This may also apply to fatigue, since the liner is connected to the end fittings by welding. In this study, two design S-N curves, DNV-C and E, are employed to estimate the fatigue life of the weld. The DNV-C curve is used for welds that are dressed flush, and the E curve is for welds made at site and not machined [14]. These curves are associated with 97.6 % probability of survival.

After all sets of n_i's and N_i's are calculated, cumulative damage is estimated. There are numerous non-linear cumulative damage models which take loading sequence into consideration. However, for wave loading, no definitive sequence can be specified. For this reason, Miner's rule is used in this study. Miner's rule is the well-known linear cumulative damage model expressed as follows [15]:

$$D = \sum_i \frac{n_i}{N_i} \tag{4}$$

For design purposes, it is typically assumed that fatigue failure occurs when $D = 1$. This procedure is performed for all short term sea states and finally the total damage per unit time is obtained by summing up the damage values of the individual sea states. Expected fatigue life is obtained simply by inverting the total damage.

5 Results

5.1 Semi-log S-N relationships

The SN1 curve shows extremely high fatigue resistance with the degradation constant b being only 0.01. As shown in Table 2, this S-N relationship results in a practically infinite fatigue life. The value of b for typical carbon-epoxy composites used for offshore applications ranges from 0.02 to 0.03, and 0.04 is a fairly conservative value [16]. Therefore, the composite riser is expected to exceed the fatigue requirements. Every S-N relationship in Table 2 estimates that the top sustains more fatigue damage. Although the bottom experiences greater bending moment, in terms of both mean and RMS, the top undergoes incomparably large mean axial tension, which appears to be the reason for severer damage at the top.

Table 2. Fatigue life estimates by semi-log S-N relationships (years)

	Bottom	Top
SN1	2.7×10^{29}	3.1×10^{28}
SN2	1.5×10^{14}	6.3×10^{13}
SN3	1.1×10^{7}	7.7×10^{6}
SN4	3205	2693
SN5	24	23

For the outermost layer of the composite riser, the normalized maximum stress S for individual stress level ranges from 0.02 to 0.09, which is associated with extremely high cycles (> 10^{18}). Therefore, it can be expected that the slightest difference in b would greatly affect the fatigue life estimate, and the results in Table 2 show the sensitivity of the predicted life to the constant b.

Figs. 3 and 4 show the contribution of each sea state to the total damage at the bottom and top of the composite riser, respectively. At both locations, the first several sea states are responsible for most of the damage, regardless of the amount of total damage. Generally speaking, the lower sea states feature smaller and shorter waves with higher probability of occurrence. The results indicate that the number of stress cycles is the most dominant factor in the damage estimation by the semi-log S-N relationships.

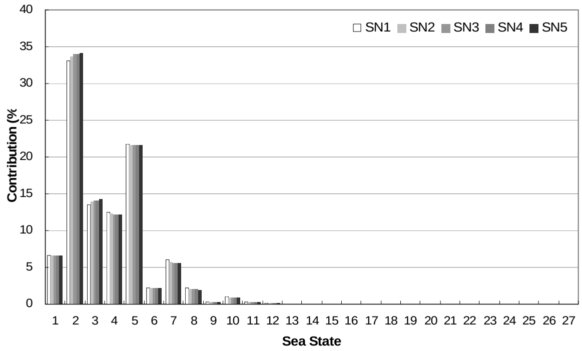

Fig. 3. Damage contribution of each sea state at the bottom of the composite riser: semi-log S-N relationships

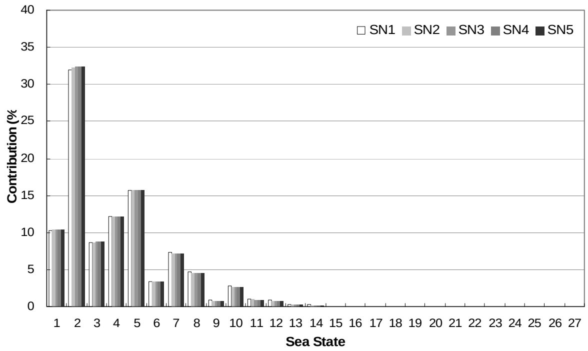

Fig. 4. Damage contribution of each sea state at the top of the composite riser: semi-log S-N relationships

5.2 Power law S-N relationships

Since the exponent n^* is related with the slope in the log-log scale, the predicted fatigue life is less sensitive to changes in the slope than the prediction by the previous semi-log representation is. Table 3 presents the fatigue life estimates from selected power law relationships. Again, the fatigue life estimates are near infinite unless the exponent is drastically changed from the published value.

Table 3. Fatigue life estimates by power law S-N relationships (years)

	Bottom	Top
n^* = 11.9	5.3×10^{20}	2.1×10^{20}
n^* = 11	1.4×10^{19}	4.9×10^{18}
n^* = 10	2.3×10^{17}	7.3×10^{16}
n^* = 5	4.2×10^{7}	1.3×10^{7}
n^* = 3	121	197

Unlike the semi-log representation, power law S-N relationships vary in the estimated contribution of each sea state, as shown in Figs. 5 and 6. In the first three relationships, fatigue damage occurs exclusively by the higher sea states where larger waves are predominant and the probability of occurrence is relatively low. When n^* = 5 and 3, lower sea states contribute to the fatigue damage. There is far less resemblance between Figs. 5 and 6 than there is between Figs. 3 and 4. Another interesting observation is that the fatigue life is higher at the top only in the case of n^* = 3.

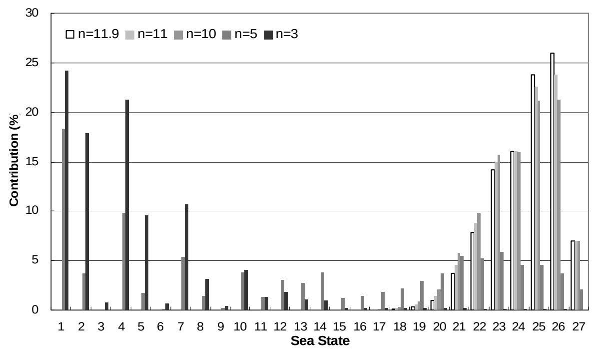

Fig. 5. Damage contribution of each sea state at the bottom of the composite riser: power law S-N relationships

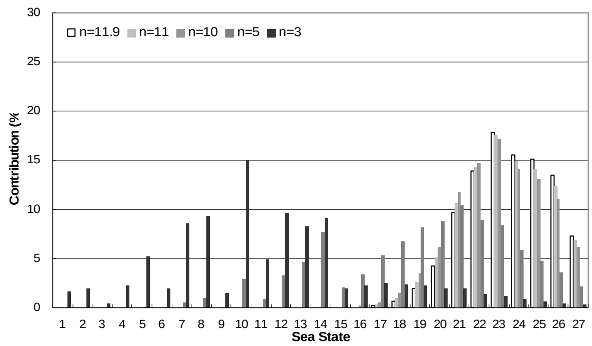

Fig. 6. Damage contribution of each sea state at the top of the composite riser: power law S-N relationships

5.3 Steel liner weld fatigue

The estimated lives by two established S-N curves for welded sections are presented in Table 4. Both curves predict acceptable fatigue lives of the welds. Note that the bottom location shows severer fatigue damage at the weld, and hence shorter fatigue life. Figs. 7 and 8 show the damage contributions from the sea states.

Table 4. Fatigue life estimates for liner welds (years)

	Bottom	Top
DNV-C	7.7×10^4	8.7×10^4
DNV-E	4.1×10^3	6.7×10^3

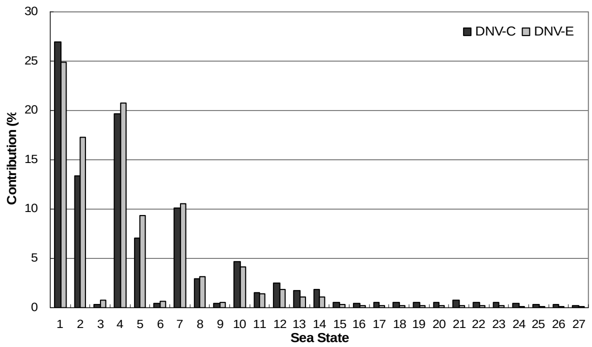

Fig. 7. Damage contribution of each sea state to the liner weld fatigue at the bottom of the composite riser

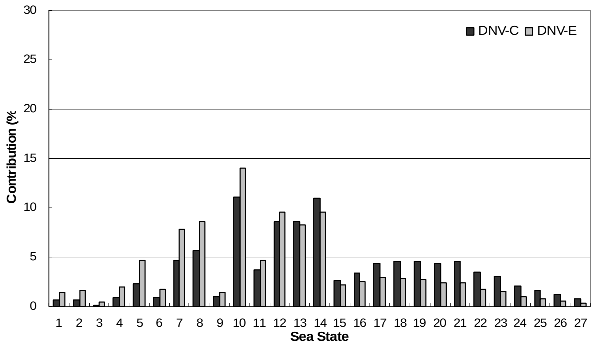

Fig. 8. Damage contribution of each sea state to the liner weld fatigue at the top of the composite riser

6 Summary and discussion

Variation of wave-induced stress which is irregular in reality is converted into multiple regular stress cycles through Rayleigh probability density function. A number of S-N curves were used to estimate the probable range of the fatigue lives of the composite riser at two major locations. The calculated results were highly sensitive to the material constants of the S-N relationships. Provided that the material possesses moderate fatigue properties, the composite riser will have an extremely long fatigue life.

In the stress histogram for a sea state, individual stress level is shown to be extremely small, usually associated with number of cycles far greater than billions. Therefore, it is important to construct an S-N curve that faithfully represents high number of cycles range. Also, the representation form, semi-log or log-log, must fit the high cycles range. It was shown that different S-N curves not only yield different fatigue life estimates, but also present different predictions as to the predominant sea characteristics that are responsible for most of the damage.

References

[1] Sparks, C. “Lightweight composite production risers for a deep water tension leg platform”. *Proceedings of the 5th International Symposium OMAE*, Tokyo, Japan, pp 86-93, 1986.

[2] Baldwin, D., Newhouse, N., Lo, K.. and Burden, R. “Composite production riser design”. *Offshore Technology Conference*, Houston, TX, OTC 8431, 1997.

[3] Karayka, M., Wu, S., Wang, S., Lu, X. and Ganguly, P. “Composite production riser dynamics and its effects on tensioners, stress joints, and size of deep water tension leg platforms”. *Offshore Technology Conference*, Houston, TX, OTC 8666, 1998.

[4] Salama, M. “Lightweight materials for deepwater offshore structures”. *Offshore Technology Conference*, Houston, TX, OTC 5185, 1986.

[5] Salama, M. “Some challenges and innovations for deepwater developments”. *Offshore Technology Conference*, Houston, TX, OTC 8455, 1997.

[6] Kim, W., Ochoa, O., Ward, E. and Miller, C. “Structural response of composite production risers”. *Composite Materials for Offshore Operations – 4*, Houston, TX, 2005.

[7] Halverson H., Curtin W. and Reifsnider K. “Fatigue life of individual composite specimens based on intrinsic fatigue behavior”. *International Journal of Fatigue*, Vol 19, No. 5, pp 369-377, 1996.

[8] Harris B., Reiter H., Adam T., Dickson R. and Fernando G. “Fatigue behavior of carbon fibre reinforced plastics”. *Composites*, Vol 21, No. 3, pp 232-242, 1990.

[9] Green A. and Pratt P. “The axial fatigue behavior of unidirectional type IIIs carbon fibre-epoxy composites”. *Composites*, Vol 5, No. 2, pp 63-66, 1974.

[10] Lee J., Daniel I. and Yaniv G. “Fatigue life prediction of cross-ply composite laminates”. *Composite Materials: Fatigue and Fracture, Second Volume,*

ASTM STP 1012. American Society of Testing and Materials, pp 19-28, 1989.

[11] Lorenzo L. and Hahn H. "Fatigue failure mechanisms in unidirectional composites". *Composite Materials: Fatigue and Fracture, ASTM STP 907.* American Society of Testing and Materials, pp 210-232, 1986.

[12] Sims D. and Brogdon V. "Fatigue behavior of composites under different loading modes". *Fatigue of Filamentary Composite Materials, ASTM STP 636.* American Society of Testing and Materials, pp 185-205, 1977.

[13] Kawai M. "A phenomenological model for off-axis fatigue behavior of unidirectional polymer matrix composites under different stress ratios". *Composites Part A: Applied Science and Manufacturing,* Vol 35, No. 7-8, pp 955-963.

[14] DNV-RP-C203. "*Fatigue design of offshore steel structures*". Det Norske Veritas, 2005.

[15] Miner M. "Cumulative damage in fatigue". *Journal of Applied Mechanics.* Vol 12, pp 159-164, 1945.

[16] Lo K. *Personal Communication,* Houston, TX, 2006.