THE COMPLEXITIES OF FATIGUE ANALYSIS FOR DEEPWATER RISERS

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ABSTRACT

Riser systems are dynamic, fatigue sensitive structures, that are usually regarded as the most challenging aspect of a deepwater development. There are many complex issues involved with the design and analysis of deepwater riser systems.

Riser long-term fatigue performance is an important design consideration. Overly conservative design approaches can be costly, whilst less sophisticated analysis methods may not be truly representative, with the possibility of non-conservatism and catastrophic failure.

The aim of the paper is to increase confidence in deepwater riser systems, concentrating on riser fatigue analysis, particularly of steel catenary risers. Current areas of uncertainty will be addressed, and the effect of different vessels, motion characteristics, geographical locations and analysis techniques will be discussed, with the aid of example cases.

INTRODUCTION

Exploration is moving into water depths of over 2000m in the Gulf of Mexico and West Africa, and over 1000m in the harsher areas West of Shetland and Voring Basin. The resulting deepwater developments are constantly pushing riser technology to the limit and there is a growing belief that riser systems based on steel pipe, rather than flexible, offer the best technical and commercial solutions.

Steel risers can take many forms, examples of which are top tensioned, hybrid and catenary riser configurations. Each riser type, and the variants on these, can provide deepwater development solutions. Of these solutions, catenary risers are considered an enabling technology, allowing large diameter export or production from remote wells. However, in terms of fatigue, steel catenary risers are very sensitive to environmental loading. A simple catenary riser and a buoyant wave catenary riser are shown in Figure 1.

Correctly calculating riser fatigue is a complex problem. First order loading and vessel motions, low frequency second order vessel motions, vessel springing and vibration due to vortex shedding can all contribute towards the long-term fatigue damage of a riser system. The interaction of all these loads and motions must be assessed thoroughly to avoid unrealistic results.

This paper concentrates on the fatigue analysis of catenary riser systems under first order and second order loading. A considerable amount of experimental and analytical work has been conducted in recent years to develop catenary riser systems. A designers perspective is given of the issues and available methods of fatigue analysis, current developments, and the effects of different vessels and geographical locations.

SN Curves and Crack Growth

The most common approach for the assessment of steel riser fatigue is the stress-cycle (S-N) approach. The equation used to determine riser fatigue lives is defined as follows:

$$N = a\,S^{-k}$$

where,

S	is the stress range including the effects of stress concentrations
N	is the allowable number of cycles for the stress range
a, k	are the parameters defining the curves

The parameters defining the fatigue curves are given in Table 1. These curves allow a designer to calculate fatigue damage using a predicted level of stress response. Usually a single sided girth weld is classified as F2, and double sided welds dressed flush are defined as C class. However, it is widely believed that the F2 curve is conservative in predicting the fatigue performance of single sided girth welds, and with better welding practices and quality assurance programs that an E class or higher can be achieved. Testing work is currently being conducted within a number of JIP's to confirm this belief [5].

Although the focus of this paper is the S-N approach, fatigue crack growth is also an important design consideration. Fracture mechanics can be used to predict the life of a joint through crack growth, assuming a certain initial defect and residual stress.

Critical Fatigue Locations

The slender cable-like structure of deepwater steel catenary risers are fatigue sensitive. In addition to this, some form of floating vessel is required in deepwater environments. Floating vessels come in many forms each with its own motion characteristics, for instance tension leg platform (TLP) first order motions are relatively sedate whilst FPSO first order motions can be very severe. All vessel motions are applied to the riser at the point of attachment to the vessel. This is the first critical fatigue region on the riser - directly below the attachment point. The applied motion at the top of the riser is transferred down the riser length and converted to bending directly above the point at which the riser touches down onto the seabed. This is the second critical region on the riser - the touch down point (TDP). A typical fatigue distribution plot along the riser length is given in Figure 2. The eight directions in Figure 2 are different circumferential locations around the pipe.

The critical touch down point region invariably sees the worst fatigue damage. Even when conservatism is minimised through a rigorous analysis approach the touch down point fatigue life can still be critical. However, there are technical solutions which will be proposed later.

Low frequency vessel motions are commonly considered insignificant in terms of fatigue due to their very long period in comparison to wave loading. However, this can be a dangerous assumption to make. In fact, with some vessels the low frequency motions can cause the highest quantities of damage, whilst with other vessels, the low frequency vessel drift can spread the touch down point fatigue damage from first order effects. This could be described as the help or hindrance effect of low frequency vessel motions. Figures 3 and 4 demonstrate this concept for a Spar and semi-submersible respectively. Low frequency motions help improve riser fatigue with a semi-submersible and hinder the riser fatigue with a Spar.

The seabed properties are also critical for fatigue calculation. A rigid seabed can give high levels of conservatism when compared to an elastic seabed. Using a rigid seabed may be realistic though as the seabed will consolidate with time. Also, other phenomena may occur which will be detrimental to riser fatigue such as suction of soft clay, entrenchment and back filling of the trench.

Long-Term Data

There are some basic requirements for long-term fatigue calculation. As a minimum, wave loading must be defined by a Hs-Tp (or Hs-Tz) scatter diagram. Definition of wave loading by individual waves is not satisfactory for catenary riser response due to the dependency of platform motion on seastate period. The vessel response in terms of both first order and low frequency motions across the long-term scatter diagram is also required.

Safety Factors

The fatigue damage from each seastate in the scatter diagram can be combined using Miners rule, which allows cumulative damage summation. Once the long-term fatigue damage is calculated, a factor of safety must be applied. A factor of 10 is used for a component of major importance to structural integrity and inaccessible for inspection, and 3 is used for a component that is accessible for inspection and maintenance [2]. Catenary risers are not accessible for inspection and so a factor of 10 is required. A factor of 10 may seem excessive, it has been an industry standard for many years, in which time the tools and approaches used for calculating riser fatigue have improved significantly. So why is it not reduced?

Due to the nature of the S-N curves, using an F2 fatigue detail, a 26% increase in the stress range doubles the fatigue damage, or doubling the stress range results in 8 times more fatigue damage. This is even more significant with C class welds where the slope (k value in Table 1) is 3.5. Catenary risers are attached to dynamic floating vessels in very deep water. There are uncertainties regarding the soil/riser interaction and catenary riser technology is still in its infancy. There are probably enough complexities and uncertainties, especially taking the magnification of stress increases into account, to warrant a factor of safety of 10.

Extreme Storm Response

Although this paper covers fatigue it is important to understand why simple catenary risers are not acceptable with some vessel types and in some geographical locations. As discussed above, the vessel motions are transferred directly to the riser. In extreme storm events the vessel motions may be severe enough to cause compression and buckling in the touch down point region of a simple catenary riser. This is most common with large wave induced vessel motions in the harsher environments, such as an FPSO in the Gulf of Mexico or a semi-submersible in the West of Shetland. In most cases where SCR's do not work, buoyant wave catenary risers can provide a steel riser solution an example of which is given in Figure 1.

The buoyant wave riser is similar to the simple catenary riser except that it has an additional suspended length supported by a buoyant section. This forms an arch prior to the touch down point on the seabed. The extra compliancy of the buoyant wave riser absorbs the large motions that are applied at the top of the riser.

Different Vessels and Motion Characteristics

A wide range of tethered and moored production vessel designs have evolved over recent years, including TLPs, Spars, FPSO's, deep draught floater's, semi-submersibles, and their derivatives. Each vessel type has its own distinct motion characteristics that affect the riser response and fatigue damage in different ways. Differences in steel catenary riser fatigue can be due to differing riser attachment location, low frequency motions and first order motions.

The cyclic hydrodynamic loading from waves induces bending stress fluctuations at the top of the riser. Placing the riser at a point below the wave zone will reduce the load variations and fatigue damage. This is most easily achieved with deep draught vessels such as a Spar. The other factor is the lever arm, which is the distance from the vessel motion origin to the riser attachment point. Five degrees of vessel pitch with a 20 metre horizontal lever arm would result in approximately 1.7 metres of heave. Increasing the lever arm increases the motion at the riser attachment point and the resulting fatigue damage.

Low frequency motions are very much dependant on the mooring system used. Typically, taut leg mooring increases the natural frequency and reduces the amplitude of low frequency motions in comparison to catenary mooring. Although a slacker mooring system increases the low frequency motion amplitude, in cases where the first order motions result in high levels of damage this can actually help improve the riser touch down point fatigue life, spreading the damage across a longer length of riser.

Horizontal vessel translations (e.g. surge) are the predominant fatigue contributor from low frequency motions. However, in some cases other low frequency motions can be significant. Deep draught floaters such as a Spar can pitch with amplitudes over 5 degrees and harmonic periods of 200-300 seconds. They can also bob up and down like a cork, i.e. heave, with similar periods to the low frequency pitch. Deep draught floaters are not the only vessel type where low frequency motions other than surge are present. An example is the low frequency yaw of TLP's.

First order motions are described by vessel response amplitude operators (RAO's). The RAO's in combination with the attachment point location relative to the vessel motion origin are critical in defining the riser fatigue response. The contribution to fatigue damage of the vessel RAO's is defined as one of three categories: small, significant and severe, and the contributions summarised as follows:

- TLP – Surge response is significant whilst the heave and pitch contribution is small.
- Spar or deep draught floater – All first order motion contributions are small.
- Semi-submersible – All first order motion contributions are significant except for yaw.
- FPSO – Ship shape FPSO first order motions are significant. If turret moored with the risers attached near the bow the effect of pitch induced heave is severe. Alternatively,

if spread moored and the risers are attached closer to the centre of gravity the pitch motion contribution ranges from significant to small depending on the lever arm distance.

The long-term fatigue life along the lengths of buoyant wave catenary attached to an FPSO and a simple catenary riser attached to a semi-submersible are shown in Figures 5 and 6 respectively. Although these risers are not directly comparable it can be seen that the fatigue life in the upper region of the buoyant wave catenary with an FPSO is much more severe than that of the simple catenary with a semi-submersible. At the attachment point of the buoyant wave riser over 80% of the fatigue damage is from the tension contribution compared to approximately 15% for the semi-submersible. This is the result of the severe pitch contribution that causes large amplitude heave at the attachment point. Also, the compliancy of the buoyant wave spreads the fatigue along the riser length, with high levels of fatigue damage in the buoyant arch and sag.

Geographical Locations

Catenary riser fatigue damage is dependant upon the environmental loading conditions. The more severe environments will result in higher levels of riser fatigue damage.

Environmental loading West of Shetland is very severe, with an average significant wave height per year of over 3.0 metres (9.8 feet). Also, the extreme waves can be over 30 metres (98 feet) which mean that simple catenary risers can only be used with vessels that have very small levels of heave and pitch. Spars or similar deep draughter floaters and TLPs are examples. Buoyant wave risers are feasible with the more dynamic vessels such as semi-submersibes and FPSO's. However, even with the more sedate vessels such as Spars and TLPs high levels of riser fatigue are seen in the West of Shetland because of the severe year round weather conditions.

In comparison to the West of Shetland, Gulf of Mexico and Brazil environmental loading is relatively sedate. The extreme waves seen during hurricane events in the Gulf of Mexico can be over 23 metres (75 feet) but they are not as severe as the storm seas seen in the West of Shetland. Long-term wave loading is even less severe, with a typical average significant wave height per year of 1.2 metres (3.9 feet). The resulting riser fatigue damage is much lower than in the West of Shetland.

In terms of fatigue, West Africa is one of the best locations for reducing simple catenary riser fatigue. The weather is highly directional with most of the environmental loading coming from the South. This allows spread moored FPSO's to be used. The risers can then be placed close to the FPSO centre of gravity thus reducing the dynamic lever arm. Also, because of the directionality, the riser spread can be designed such that in-line loading, which induces the highest level of fatigue damage, can be minimised.

Low temperature wells or ultra deep water can result in the need for high levels of thermal insulation. This can make the pipe close to neutrally buoyant and be detrimental to its extreme storm response, resulting in compression and buckling in the touch down point region. This is the case for catenary risers West Africa. Hence, pipe in pipe configurations or alternative riser configurations may be necessary for West African developments. If an acceptable extreme storm response can be achieved the steel catenary riser fatigue damage will be small in the West Africa environment.

ANALYSIS TECHNIQUES

Frequency Domain vs Time Domain Analysis

Riser fatigue from first order loads and motions and low frequency motions may be determined using either time or frequency domain analysis methods. Time domain analysis requires a significant amount of computational effort whilst frequency domain requires much less. The shape of a catenary riser is non-linear and non-linearities in riser response are amplified because of this. Analysis techniques that are acceptable for vertical top tensioned risers may not be for catenary risers. When using frequency domain analysis to calculate catenary riser fatigue, validation should be conducted with time domain analysis.

Based on time or frequency domain analysis, the fatigue damage can be calculated with assumptions regarding the statistical nature of the response. The Rayleigh distribution is often used to define stress peaks, and assumes a stationary narrow banded process. The riser response under first order motions and loading may be more broad banded than this in the upper region of the riser and in the touch down point region. Using time domain analyses, the nature of the response and the appropriateness of statistical assumptions used to determine fatigue damage can be assessed.

Combining First Order and Low Frequency Fatigue

The touch down point of a catenary riser is very sensitive to both first order and low frequency motions. Failure to evaluate both of these effects can be either conservative or unconservative depending on the magnitude of the first order motions, Figures 3 and 4. The question is how is this achieved? Simply adding the damage resulting separately from first order loading and low frequency loading is not correct.

Two different methods can be used to combine the two fatigue damage contributors. Low frequency and high frequency (first order) processes can be combined using statistics [3], or the low frequency and first order effects can both be described in combination using random sea time domain analyses, and the fatigue damage calculated directly from the response time traces using stress cycle counting.

There are various stress cycle counting approaches, such as simple range counting, range pair or rainflow counting [4]. Simple range counting is suitable for harmonic stress responses with little variation in the stress range amplitudes. However, when both low frequency and high frequency stress responses are present, simple range counting does not take account of the total stress variation due to the two processes.

Rainflow counting is generally considered the optimum stress cycle counting method when the response is characterised by both low frequency and high frequency processes. The statistical nature of the riser response is not required when using rainflow counting or similar stress cycle counting algorithms. Hence, the usual uncertainties regarding the definition of the statistical approaches for fatigue damage calculation are not present.

Simplification with Linearisation

Linearisation can be used to reduce the number of analysis runs required for fatigue damage calculation. Linearisation is the process by which the fluctuation of stresses along the riser length in one loading condition is assumed to be related to that of another loading condition. For example, a riser positioned on a line of vessel symmetry, with loading defined by a 100 seastate scatter diagram, such as those for the West of Shetland, and 8 compass points, would require 800 random sea analyses if linearisation is to be avoided.

Linearisation can be conducted by lumping the seastates, loading directions or by assuming riser response is proportional to wave height. If using linearisation, it should be demonstrated that the chosen approach errs on the side of conservatism.

Simplification through linearisation may not be required for some environments. The long-term seastate scatter diagrams for the Gulf of Mexico and West Africa are small enough to allow time domain random sea analysis on every seastate in the scatter diagram to be used.

Analysis Approach Recommendations

Whichever analysis method is adopted, there are some general riser modelling features which should be implemented. Element discretisation must be sufficiently refined that peaks in damage are not missed. Typically element lengths from 1 to 3 metres are required, in the critical touch down point region. When assessing multiple directions of loading the distribution of fatigue damage around the riser circumference should be calculated in order that the maximum damage is not missed. For catenary risers in particular, which have no heave compensation, the dynamic variations in both riser tension and bending should be considered in combination.

Typically, the design life of a catenary riser is around 20 years, in which time many things can change, such as production fluid and seabed properties. Sensitivity analyses should be conducted to quantify and bound the effect of changes in operational conditions, directional effects and uncertainties in design parameters.

VALIDATION/TEST PROGRAMMES

A considerable amount of experimental work and analytical development has been conducted in recent years to develop catenary riser systems. This work is helping to relieve a lot of the uncertainties in SCR design and analysis. Joint industry projects such as the STRIDE (Steel Risers for Deepwater Environments) JIP and HCR (Highly Compliant Risers) JIP are tackling a number of SCR issues.

The STRIDE JIP was established in 1997 by 2H Offshore Engineering with the key objective of better understanding catenary riser issues. The JIP scope covers the following activities:

- Riser basic sizing and parametric studies
- Global analysis methods
- Codes and Standards
- Installation methods
- VIV analysis and testing
- Touch down point analysis methods and testing
- Material assessment and fabrication requirements

All of these issues have a knock-on effect on riser fatigue. However, the touch down point analysis methods and testing, and material assessment and fabrication requirements are the most critical.

Touch down point testing has been conducted within STRIDE to validate the existing mathematical models used for TDP response prediction. It is also focussing on the seabed, tackling the problems of riser entrenchment, seabed consolidation, and suction from soft clays, all of which can contribute to higher levels of fatigue damage.

Calculation of fatigue damage relies on the quality of the welds. As part of STRIDE a material testing program is currently being conducted by the welding institute (TWI). Its aim is to investigate the effect of plastic deformation (reeling for installation) on the fatigue performance of welded joints, and also to determine a database of single-sided girth weld fatigue performance.

The HCR JIP was established by PMB engineering with the key objective of better understanding the dynamic behaviour of risers, particularly near the seabed, and to verify existing analytical models. Scaled testing has been conducted with a simple catenary, bouyant wave catenary and combined vertical axis riser.

CONCLUSIONS

Catenary riser fatigue calculation is a complex problem. All vessel motions and environmental loads must be taken into account in a representative way for all expected conditions. Catenary riser fatigue is highly sensitive to vessel type and geographical location. Time domain, random sea analysis is the optimum fatigue analysis approach because it accounts for the non-linearities in the riser response. Low frequency motions and first order motions and loading must be evaluated together using either statistical combination or stress cycle counting algorithms such as Rainflow counting. The element refinement in the critical regions should be high. Lengths of 1 to 3 metres at the touch down point are required so that fatigue damage peaks are not missed.

However, even when a detailed fatigue analysis is conducted the fatigue life in the critical regions may be unacceptable. The high fatigue regions tend to be very localised and this means that there are some relatively simple engineering solutions such as:

- Insertion of a high quality weld section in the touch down point region.
- Periodically changing the touch down point position by pulling out or inserting extra lengths of riser at the top.
- Reduction of stress concentration factors through better welding practices.
- If seabed suction shows itself to be a problem, an artificial seabed such as matting or grouting could be a solution.
- A buoyant wave may change its own TDP position over time through degradation of the buoyancy modules.

There are currently 4 simple catenary installations, with more planned in Brazil and the Gulf of Mexico in the near future. In the long term, feedback from these installations may help to relieve the uncertainties and concerns regarding catenary risers.

REFERENCES

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[5] Dickerson, T.L., Pisarski, H.G., Maddox, S.J. and Razmjoo, G.R. – "Guidance on Fatigue and Fracture Aspects of Welded Joints in Catenary Risers". TWI Report 621699/1/97, June 1997.

Material	**Fatigue Detail**	**a**		**k**
		Ksi	**MPa**	
Steel	C	4.92×10^{11}	4.266×10^{13}	3.5
Steel	D	4.64×10^{9}	1.513×10^{12}	3
Steel	E	3.16×10^{9}	1.047×10^{12}	3
Steel	F2	1.31×10^{9}	4.266×10^{11}	3

Table 1 – Parameters Defining Fatigue Curves

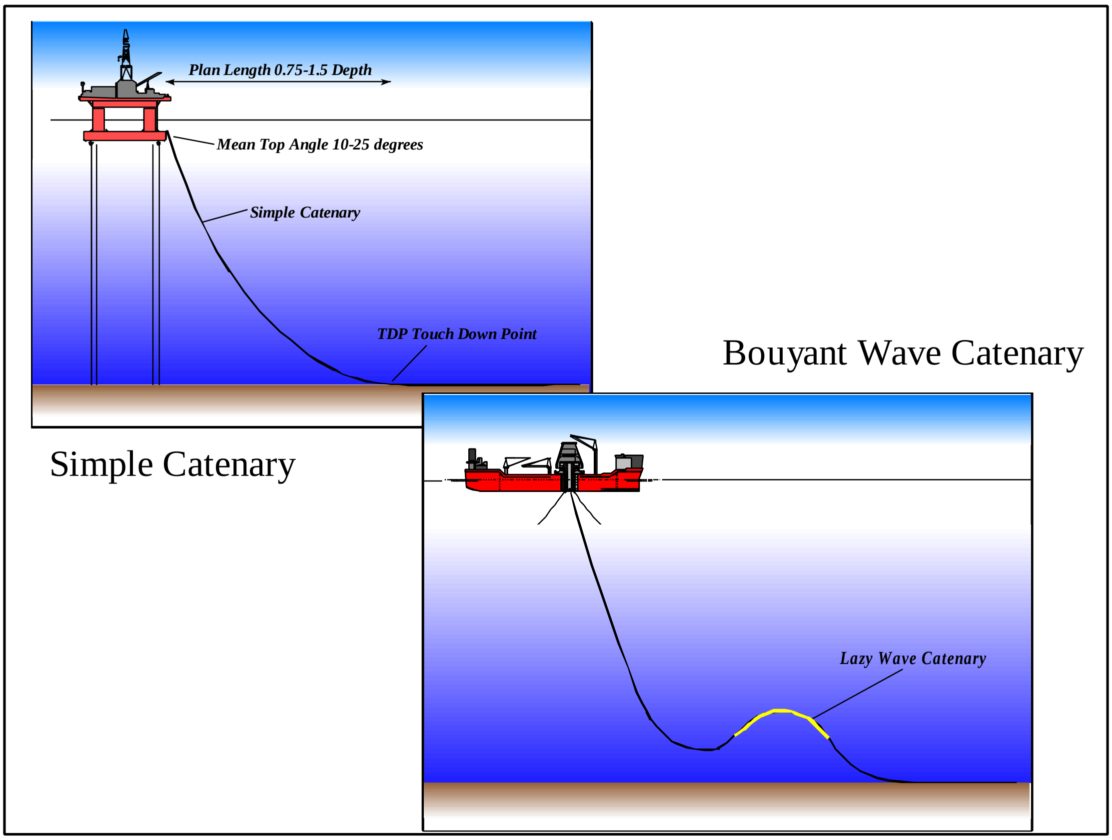

Figure 1 – Simple Catenary and Buoyant Wave Catenary Risers

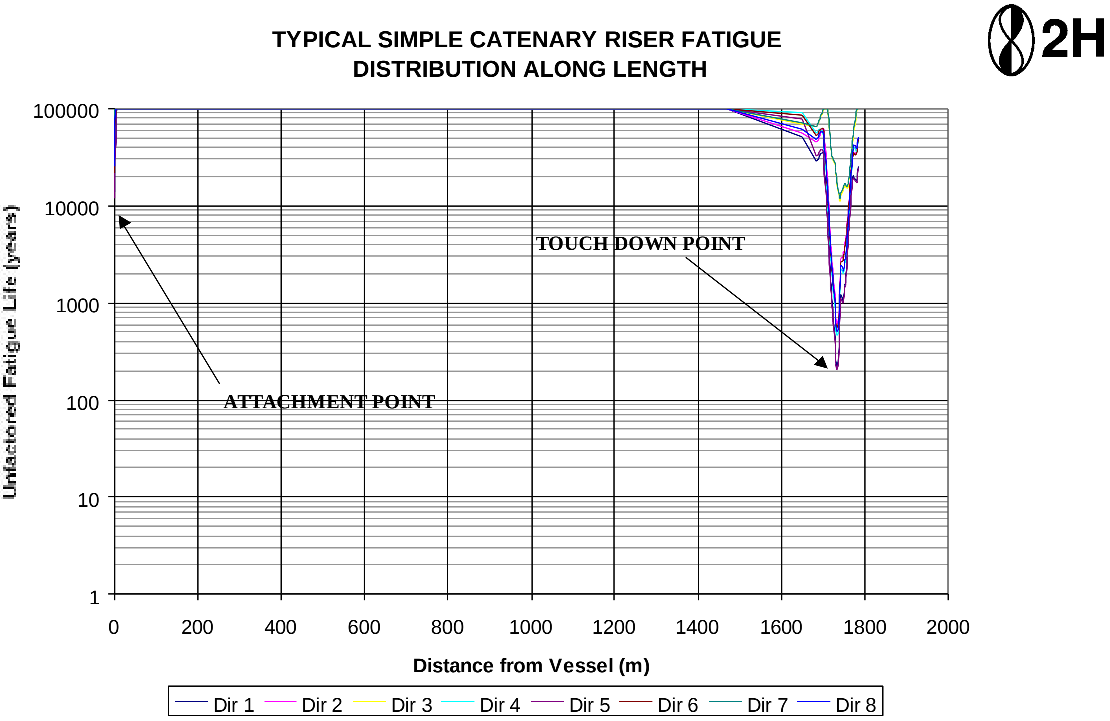

Figure 2 – Example Simple Catenary Riser Fatigue Life Distribution

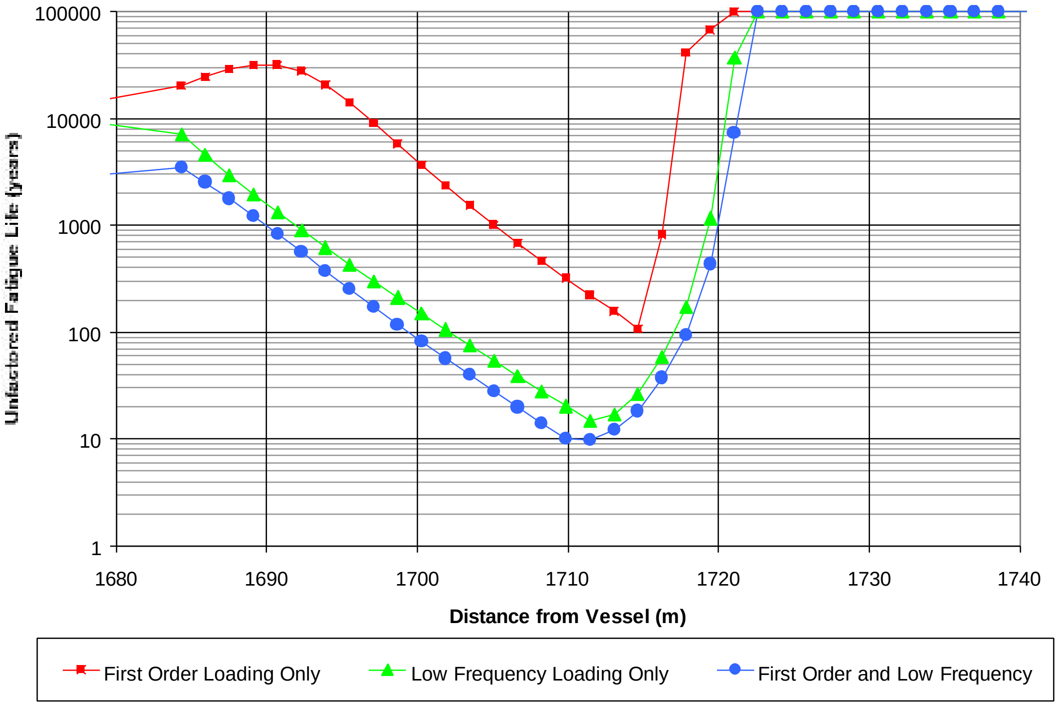

Figure 3 – Simple Catenary Riser Fatigue with Spar for Single Seastate Taking Different Motions into Account

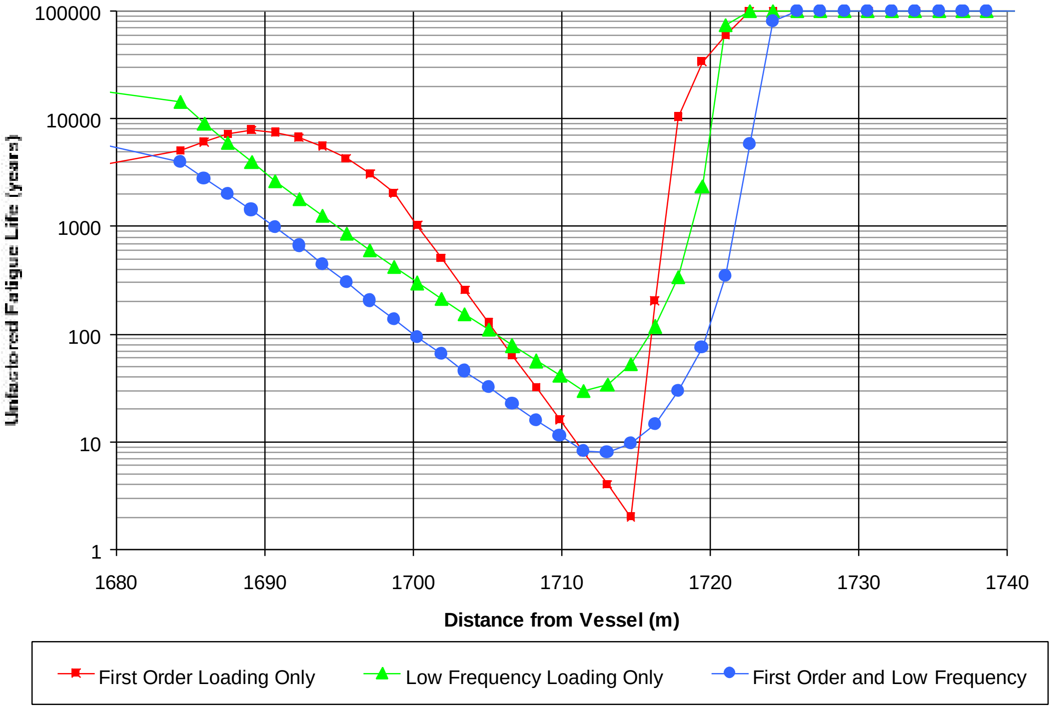

Figure 4 – Simple Catenary Riser Fatigue with Semi for Single Seastate Taking Different Motions into Account

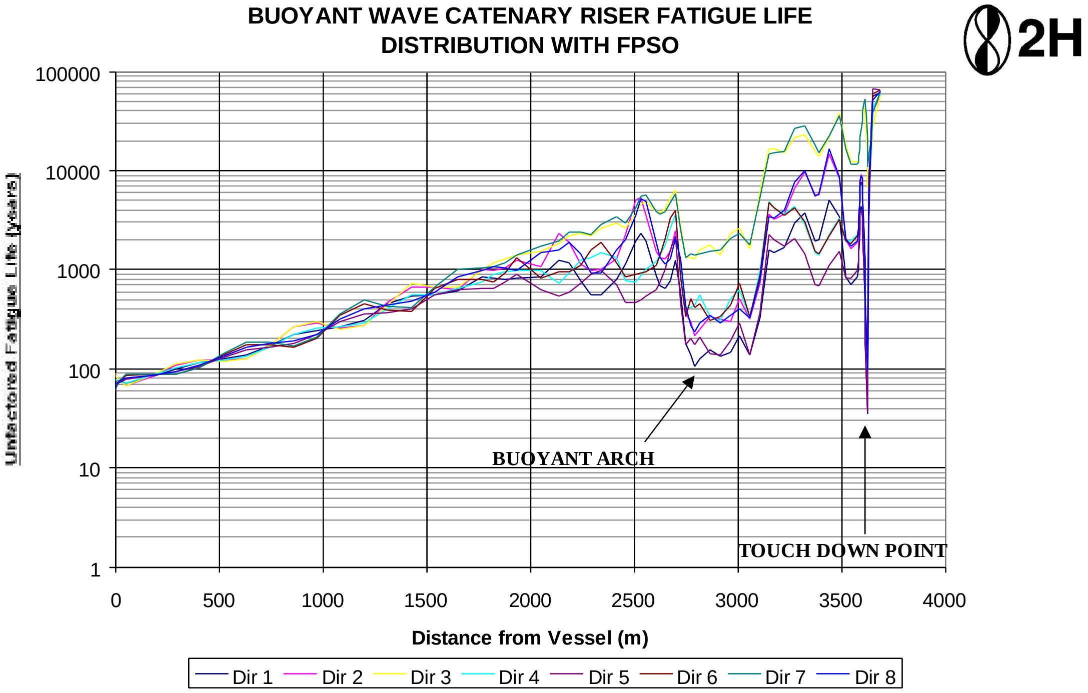

Figure 5 – Example Bouyant Wave Riser Fatigue Life Distribution with FPSO

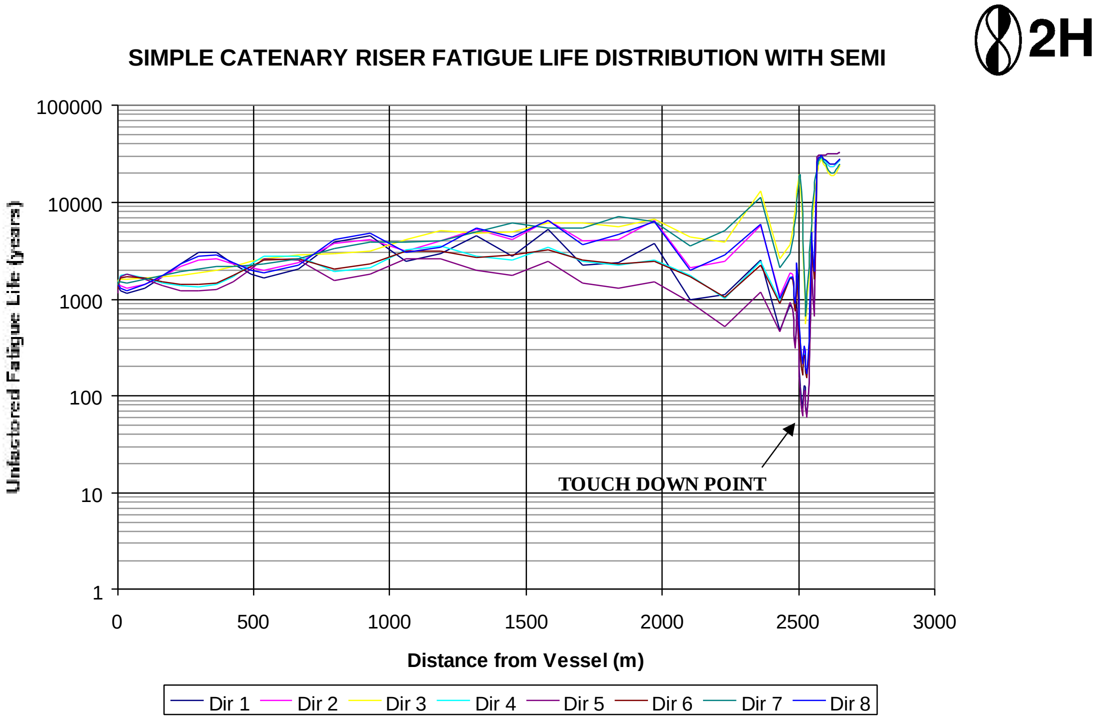

Figure 6 – Example Simple Catenary Riser Fatigue Life Distribution with Semi