RISK-BASED STRUCTURAL ANALYSIS OF FRADE UMBILICAL CABLES

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Abstract. *The main purpose of this paper is to present the risk-based approach applied in the dynamic and fatigue analyses of subsea umbilical cables for Frade field development. Umbilicals are composite cables used for offshore oil exploitation with components of power, signal/control and hydraulic functions. The ones that are object of this paper are composed by steel tubes and were designed for use in the Frade Field, which is located in 1100-1250 meters water depth approximately 120 kilometers from the Brazilian coast in the prolific Campos Basin. Dynamic and fatigue analyses of Frade umbilicals were initially performed using a free-hanging catenary (FHC) configuration subjected to extreme conditions modeled according to API 17E standard. After this first cycle of analyses this configuration presented adverse results with infringement of the umbilical's allowable bending radius and compressive loads at the touch down region. These results led to the evaluation of a so called "wavy-wave" configuration (WWC) which utilizes buoyancy modules close to the umbilical's touch down point so as to reduce compression on the seabed since this configuration is less sensitive to the floating unit heave motion. Besides being more complex, the "wavy-wave configuration" has additional costs due to the buoyancy modules themselves and also because of the installation procedures and time spent in that operation. Then, Frade umbilicals were installed in a free-hanging configuration after using a risk-based approach whose assumptions and results are presented and discussed in this paper*

Keywords*: umbilical cables, structural analysis, Frade field*

1. INTRODUCTION

The Frade Field is located in 1100-1250 meters of water depth approximately 120km from the Brazilian coast in Campos Basin. The dynamic risers for subsea development consist of 12 production, two water injection, three gas lift, one gas import/export, and four umbilicals. The umbilicals supplied by Oceaneering International, Inc. are used for actuation of subsea control valves and the injection of chemicals as can be seen by the cross section components shown in Fig. 1. Each umbilical passed through the turret of an FPSO, moored in a water depth of 1065 meters, before descending to the seabed in a free-hanging catenary configuration.

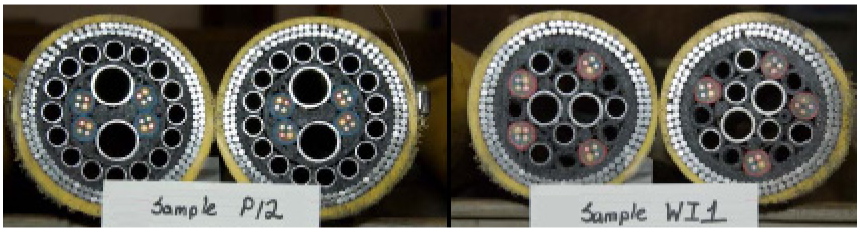

Figure 1. Cross Section of Production (P12) and Water Injection (WI1) Umbilicals

Compression and high curvature events at the touchdown point induced by the vessel motions are the main issues that makes an umbilical design in deep water challenging using steel tubing, and these phenomena are particularly found in free-hanging catenaries. One of the most important tasks during the project was to develop the acceptance criteria for extreme and fatigue events because a prescriptive rule approach was not successful. For extreme events, the main task shifted then to determine the non-linear stress in the tubing by using an equivalent Knapp (1988) strain. Consequently, for extreme events the acceptance criterion was the strain, and not the stress or the minimum bending radius defined in the data sheets.

For fatigue, mean-minus-two-standard-deviation and mean curves were applied and safety factors were measured against both curves as a sensitivity analysis. All fatigue cases whether regular or irregular, factored the results using a so called gradient factoring technique to compute the fatigue damage of the umbilical cross section.

This paper has a similar approach to that presented at OTC by Clarkston *et al*. (2009) but with the focus on describing with details the challenges surpassed during the dynamic analysis of the project.

Dynamic analysis in the context of this paper is taken to mean an analysis performed aided by a software tool, OrcaFlex version 9.1 (2008), covering extreme event and fatigue performance.

The umbilicals have been recently delivered; the peak oil production rate is expected in 2010 with first production set for the second quarter of 2009.

2. ENVIRONMENTAL INPUTS

The Frade facilities consist of subsea production wells tied back to a turret type FPSO which is therefore free to rotate around the centerline of the turret. As the seabed topography is sloped and undulating the four umbilicals have varying water depths at their connection points, which are indicated in Fig. 2.

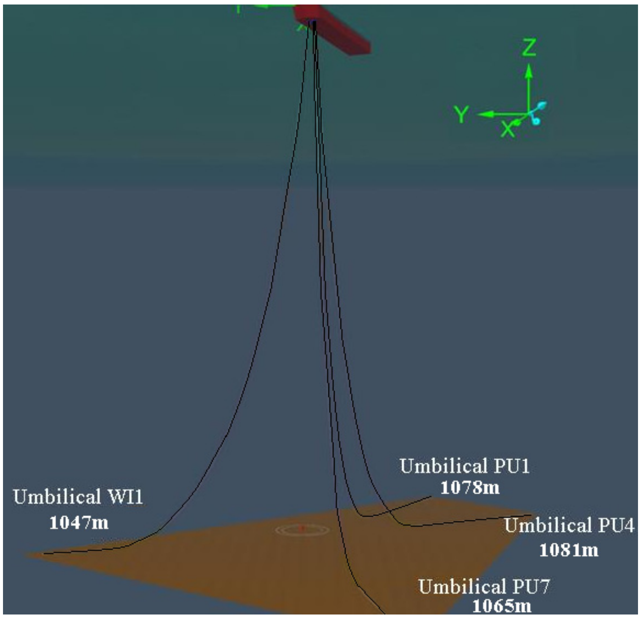

Figure 2. Model showing operational water depth of each umbilical

The seabed was modeled using a cubic polynomial fitting method. The end points of the umbilicals were extrapolated a further distance (50m) to ensure that in all conditions the umbilical would stay within the model. This method of interpolating within the model was used to provide smooth transitions and to aid with convergence.

As there was little information on seabed stiffness it had to be examined during the dynamic analysis to ensure that a conservative (yet realistic) approach was adopted in the selection of its characteristics. Figure 3 shows that ZZ stress in the super duplex tubes increases as seabed stiffness increases. However by the time 60kNm^2 has been reached the gradient is significantly smaller. At 100 kNm^2 the stress has leveled out, justifying the choice of this value as input parameter. This topic is seen as very important since softer seabed “absorbs” energy during umbilical touchdown impact and therefore less stress is imparted to the umbilical components.

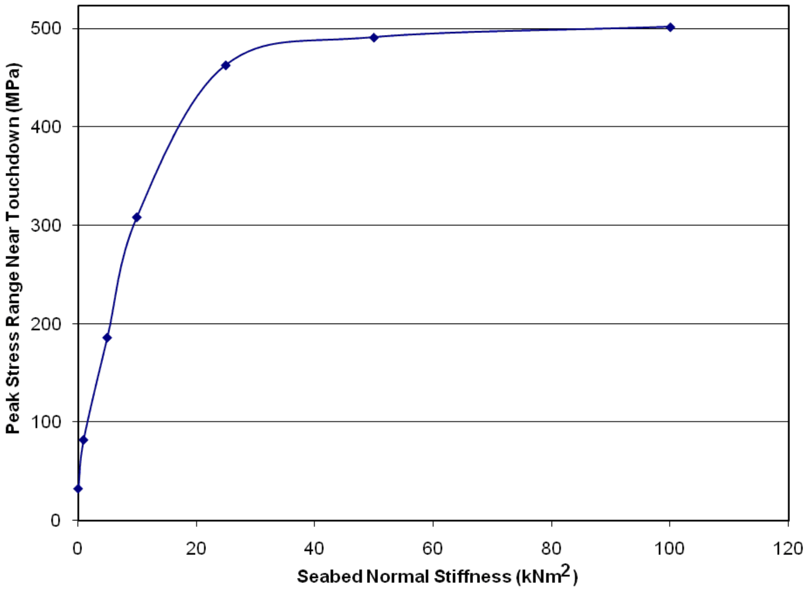

Figure 3. Effect of Seabed Stiffness on Stress in 0.5 inch Super Duplex Tubes

2.1. Extreme Waves

It is stated within the Metocean data (Tab. 1) of Frade field that the wind and swell waves are correlated. Therefore, it was possible to use in the main analysis an irregular wave approach based on a double peaked Ochi-Hubble spectrum (Ma *et al*, 2004). H_{s1} and H_{s2} are collinear and in the table below, the column θ_w-θ_h means the direction where the wind comes from minus the direction where the wave comes from. Moreover, the wind direction (from) is the same of the vessel heading.

Table 1. Extract from Metocean Design Data – Wave parameters

Return Period (years)	H_{s1} (m)	T_{p1} (s)	γ_1	H_{s2} (m)	T_{p2} (s)	γ_2	θ_w-θ_h (°)	Wind Speed (m/s)
1	3.9	11.0 - 16.0	1.5 - 4.0	2.5	9.0	1.5	-14	14.7
10	5.8	12.0 - 15.0	1.5 - 2.5	2.0	9.0	1.5	-9	17.0
100	7.0	12.0 - 15.0	1.5 - 2.5	2.0	9.0	1.5	-9	19.2

H_{s1} = Significant wave height for swells
H_{s2} = Significant wave height for local waves
T_{p1} = Peak period for swells
T_{p2} = Peak period for local waves
γ_1 = spectral peakedness factor for swells
γ_2 = spectral peakedness factor for local waves
θ_w = direction of the wind (from)
θ_h = direction of the waves (from)

OrcaFlex enables the user to input multiple wave types at different directions so that the effect of swell and wind waves could be investigated.

It is important that all transience in the system, caused by the energy input at the start of a simulation, has died out before the extreme event passed through the system. It was found that transience dies away after a typical 25 second period therefore this was selected as the build up time.

Eleven seeds were selected for use and as well as harmonics they were based on a probabilistic distribution. For the extreme models a run time of 100 seconds was selected, considering that the extreme wave event occurs at the mid-point of the 100 seconds. This extreme wave event was selected by inputting the statistical 100-year data and then running three 1.5-hour storms with the same seed and with different time periods. The highest wave from the storms was selected and that 100-second section of data was also selected. An example of this wave time history is in Fig. 4.

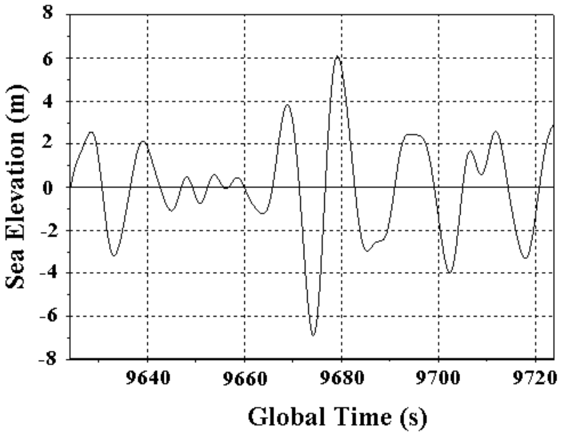

Figure 4. Typical Wave Time History Selection

2.2. Fatigue Waves

The fatigue wave selection was also made based upon the Metocean data, however several modifications were made. The swell and wind wave heading values have been obtained by selecting the worst case (minimum, maximum or mean) which reflected the closest to beam seas condition.

After performing the fatigue cases, the majority of the umbilical damage was found to be produced by a small number of cases (around 10 cases). These cases were studied using the same irregular wave approach outlined for extreme analysis. The bulk of the cases which produce little or insignificant damage was then treated using a regular wave approach based on a stream function wave. The H_s and T_z value were converted from Ochi-Hubble to stream function using the following equations, which represent a weighted average of wave height and period:

$$H = \sqrt{H_{s1}^2 + H_{s2}^2} \tag{1}$$

$$T = \frac{H_{s1} * T_{p1} + H_{s2} * T_{p2}}{H_{s1} + H_{s2}} \tag{2}$$

$$T_z = 6 * H^{0.3} \tag{3}$$

where
H = Wave height used for regular wave
T = Period used for regular wave
T_z = Zero crossing period used to compute number of cycles

Equation 3 is an empirical relation presented in the former DNV classification note for environmental conditions, number 30.5 which was superseded by DNV-RP-C205 practice (DNV, 2008).

3. UMBILICALS

Used for actuation of subsea control valves and injection of chemicals, the umbilicals are fully described in Tab.2.

Table 2. Umbilicals Physical Characteristics

Description	**P12**	**WI1**
Design Life (years)	18	18
Outside Diameter OD (m)	0.1415	0.1277
Linear Nominal Weight in Seawater (N/m)	242	185
Maximum Allowable Tension (kN)	696.4	634.8
Maximum Allowable Compression (kN)	25.0	25.0
Estimated Axial Stiffness at 23°C (MN)	615	462
Bend Stiffness at 23°C (kN.m^2)	26.1	14.8
Bend Stiffness at 4°C to be used from 100m above seabed on (kN.m^2)	31.1	18.2
Length of Dynamic Section from Hang-off to Subsea Termination (m)	PU-1: 4423 PU-4: 3597 PU-7: 4214	WU1:1750
Dynamic Minimum Bend Radius (m)	10.2	7.8

The umbilicals themselves were modeled with marine growth, using the data from the Engineering Science Data Unit (ESDU, 1980) to construct a set of drag coefficients that varied with Reynolds number. The input variables to this are roughness and outside diameter. Using the outside diameter of the umbilicals with marine growth added, a set of variable drag figures that more accurately predict the drag scenario in the field were calculated. An example of this is presented in Fig. 5.

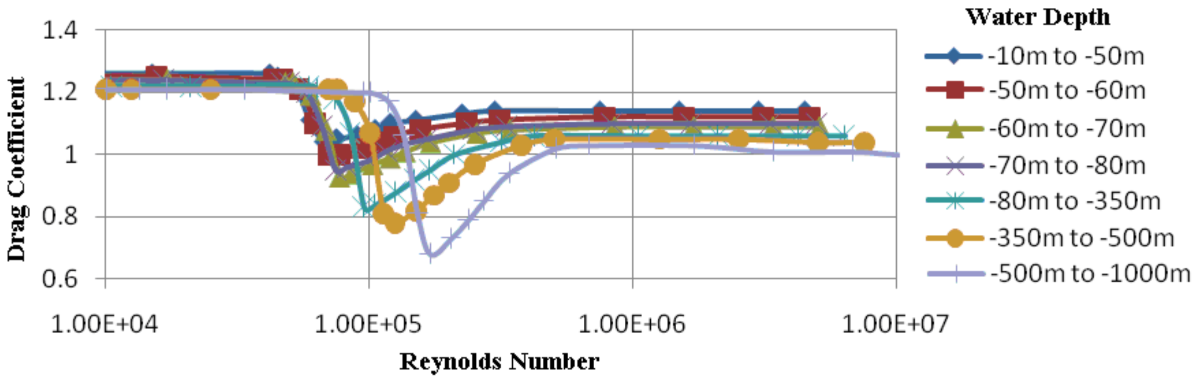

Figure 5. Variance of Drag Coefficient with Reynolds Number for a Cylinder "far" from a Boundary

Compression acceptance of the umbilicals has been revised from the Oceaneering International, Inc. traditional figure of 5kN to 25kN due to specific tests performed in order to evaluate the axial compression limits. It is often found in umbilical analysis particularly with free hanging catenaries that a compressive wave travels back up the umbilical from the touchdown point.

This is because the umbilical is massively axially stiff in comparison to its bend stiffness. As the umbilical is "speared" into the seabed by the action of the FPSO above it tends to suffer from local buckling and one of the manifestations of this is a compression event followed by a relieving local buckle. Subsea umbilicals standard (API 17E, 2003) do not provide specific guidance for levels of compression, nor how it develops and its consequences. As a solution, Chevron carried out compression tests (Fig. 6) to better understand the umbilical behavior, as well as to ascertain a safe level of acceptable compression for the Frade design. Samples of each umbilical were subjected to compressive loads up to 98.1kN.

Figure 6. Compressive Testing of Umbilicals (test setup)

On test, the umbilicals were configured so that their diameters were measured at a central position. The armor birdcage buckling under compressive load could lead to displacement of armor wires and a weakening of the bundle strength. The results from these tests demonstrated that a safety factor of 4 existed over the worst case compression seen in the umbilicals (25kN) showing that the effect in the armor layer was negligible.

The effect of a stiffness increase in the touchdown region improves curvature output and hence bending stress is significantly reduced across the umbilical bundle. Then, to account for differences on bending stiffness due to the variation of Young's modulus of polyethylene from ambient (23 ºC) to seabed temperature (4ºC), the percentage difference was input to the umbilical design software and the change in stiffness was calculated and used in sensitivity analysis.

4. EXTREME EVENT ANALYSIS

The Frade umbilicals include super duplex (S32750) tubes within the component bundle. Part of the analysis was to consider potential non-linear stress / strain behavior of the tubes under various loading conditions.

The maximum tensions seen in the umbilicals are significantly below the minimum breaking loads. Peak values for the P12 umbilical was found to be 677kN against a minimum break. load of 2017kN while peak values for WI1 were of 523kN against a minimum break load of 1775kN.

The point of minimum bending radius (MBR) for each umbilical is at touchdown, being the lowest for P12 with 3.2m, while for WI1 the MBR was 3.8m.

The key assessment of curvature is the strain induced within the super duplex tubes during this extreme event. To correctly assess this variable the umbilical model within OrcaFlex needed to be modified to reflect the behavior of the tube to be considered. To do this, the equivalent Knapp (1988) strain was taken for the super duplex tubes.

$$\varepsilon_{\max}(\alpha, R_s) = \sqrt{[\varepsilon_a(\alpha, R_s) + \varepsilon_b(\alpha, R_s)]^2 + 3\gamma(\alpha, R_s)^2} \tag{4}$$

where

ε_{max} = total strain
α = lay angle of steel tubes
R_s = radius from umbilical bend center to the umbilical center axis
ε_a = axial strain
ε_b = bending strain
γ = shear strain

This strain was plotted against curvature, $1/R_s$, in the umbilical and for a radius of 3.2m the strain was found to be 0.3%. From tests conducted by the super duplex supplier, the materials bending stress is seen to be approximately linear at the maximum strain found, as can be seen in Fig. 7, therefore it was concluded that the material was still in the elastic region.

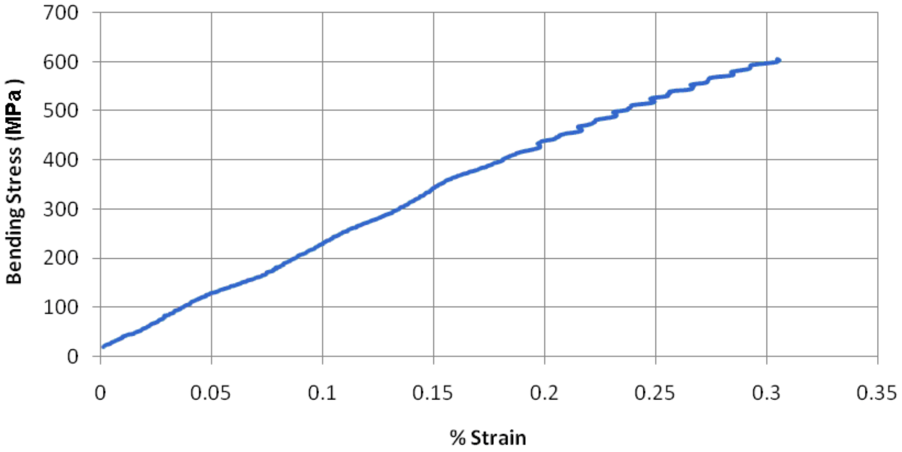

Figure 7. Strain x Maximum Stress for Super Duplex Steel

5. HANG OFF ANALYSIS

At the hang off point the umbilicals are protected by a BSR (Bend Strain Reliever or also called Bend Stiffener), this component was designed at an early part of the project and by the time the risk-based analysis started the items were already at an advanced state of manufacturing.

The extreme analysis to this point had focused upon the touchdown area but it was felt that the hang off zone should be analyzed to ensure that the BSRs were performing as per the requirements.

A pinned or “no moment” analysis was undertaken and plots of end load against end EZ angle (the angle apart from declination neutral axis) were taken. These plots showed that the performance of the BSRs was exceeded and excessive angles were produced, as can be seen in Fig.8.

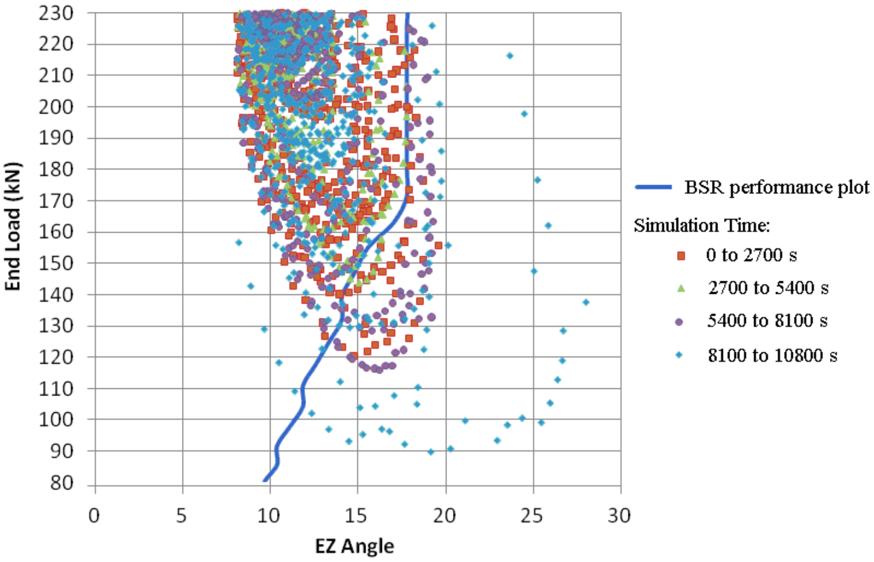

Figure 8. End Load x EZ Angle Plot (example of breach)

In addition to the breaches in the performance envelope, curvature limits were breached in the region of the BSR just after the tip of the component. Finally, the shear forces at the root of the BSR were also found to be breached in some cases analyzed.

The BSR performance limit was derived from the minimum umbilical bend radius, as presented in Tab.2. This MBR was obtained based on the curvature limit of the steel tubes. The curvature issue was dealt with by considering the bending strain in the components and comparing this strain to the stress strain curve of the super duplex material. As this was also part of the extreme analysis the values could be compared and it was proved that a curvature no worse than that of the touchdown zone was found. Then, it was reasonable to conclude that the super duplex tubes would also be operating in theirs elastic region also at the hang off.

In order to evaluate the impact of BSR breaches on system behavior, an assessment of the time during a typical 3-hour storm in which the BSR performance envelope was breached was made.

Results showed that the combinations EZ angle/end load for umbilical WI1 breach the envelope for a total time of 10.05 seconds in this 3-hour 100-year storm. As a percentage of total simulation time this represents 0.093% in breach. The same analysis was performed for the umbilical PU7 (worst P12 case) which was found to be in breach for a total time of 28.2 seconds during storm. As a percentage of total simulation time this was 0.26% of time in breach.

It can therefore be seen that the breaches in envelope were extremely small in comparison to the 100-year 3-hour storm and consequently the risk of umbilical or BSR failure due to these loads has low probability.

The failure mode would either be a rupture of the tubes due to overbending or a failure of the BSR at the joint between polyurethane and steel insert. In previous paragraphs it was shown that the steel tubes are still operating within their elastic region at the maximum curvature event, however, to ensure that the BSR would operate as expected a local finite element analysis of each BSR was conducted. This analysis demonstrated that the stress levels at high angles were well within the capabilities of the actual BSR material itself as can be seen at Fig. 9 which shows the worst case results. The maximum equivalent von Mises stress corresponds to a strain of 10% in the polyurethane which is typically the limit for this component under extreme environmental conditions.

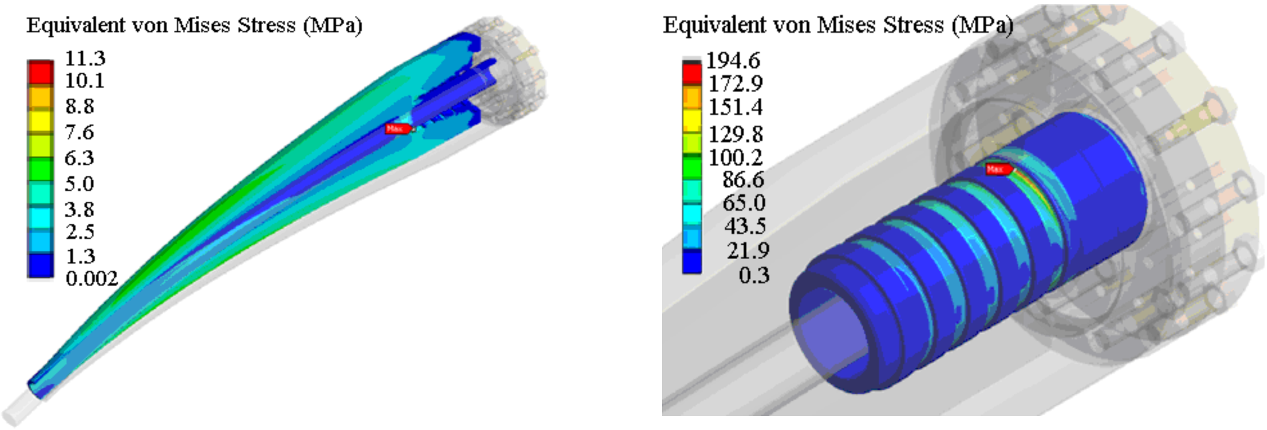

Figure 9. BSR von Mises Stress Plot: BSR body and insert

6. FATIGUE ANALYSIS

As discussed in section 2.2, the bulk of the fatigue analysis was conducted using regular wave analysis. Simulation files of five wave periods long (two periods for build up and three periods for steady state) were used to estimate fatigue damage. Cycles were calculated based on the service life of 18 years. The period used was T_z, which was calculated as previously mentioned. In summary, the number of cycles was calculated using the seconds during service life multiplied by the annual occurrence of the load case divided by T_z:, i.e.,

$$N = \frac{365 * 24 * 3600 * 18 * (occurrence)}{T_z} \tag{5}$$

For the ten critical cases of the scatter diagram, irregular wave approach was used to estimate fatigue damage through simulation files of 1.5-hour storm time (25 seconds for build up and 5400 seconds for steady state). The seeds were checked for convergence against 3-hour simulations and the results for standard deviation of sea surface elevation were compared. The checking seed standard deviation was 0.612 with a mean up-crossing period of 8.6 seconds. The selected seed standard deviation was calculated to be 0.613 and the mean up-crossing period was of 8.7 seconds. This was considered to be an acceptable signal of convergence.

All fatigue cases whether regular or irregular were run and then a post processing operation was carried out to effectively factor the results depending on component selected, which was achieved by using the gradient factoring technique explained below.

By default, an umbilical in OrcaFlex is represented as a series of beam elements with a circular section and outer diameter (d_o). However, its fatigue life is determined by the analysis of its internal components, such as steel tubes, armor wires and signal cables. The gradient technique correlates the global stresses to the stresses found in the internal components, helically wound, based on the local stresses relationships derived by Knapp (1988). Therefore, to calculate stresses for a particular umbilical component the relationships of bending stress/curvature and axial stress/applied tension must be factored against those for the circular section used in the model. This is achieved by inputing stress loading factors in OrcaFlex which are presented in Eq. 6 and 7.

$$B_\kappa = \sigma_{Knapp} \frac{\pi d_0^3}{32EI} \tag{6}$$

$$T_\kappa = T_{Knapp} \frac{\pi d_0^2}{4} \tag{7}$$

where EI is equivalent to the bend stiffness of the umbilical, B_κ is the bend stress factor, T_κ is the tension factor , σ_{Knapp} and T_{Knapp} are the bend stress and the axial tension, respectively, calculated by Knapp (1988) equations.

Once these factors have been obtained, fatigue damage is produced for each component. When studying regular fatigue cases the minimum and maximum values of stress over the last simulated wave cycle define a stress range. The associated single-occurrence load case damage value is then given by D(κS) where κ is the stress concentration factor and S is the Stress range.

When irregular techniques are used the rainflow cycle counting method is deployed. This gives a number of stress ranges for half cycles. The associated single-occurrence load case damage value is then given by $\frac{1}{2}\sum D(\kappa S_i)$ where the summation is over all the half cycles.

DNV-RP-C203 (2008) design S-N curves for super duplex tubing were used to estimate fatigue damage. Final results showed that the fatigue life for the production umbilicals were above the service life of 18 years, but presented a safety factor below 10, which is usually the typical value used for design according to API 17E (2003). It is important to stress that API 17E (2003) does not specify the method or safety factor to be used for fatigue performance. For this project, the acceptance criterion regarding the safety factor was of 3, or 54 years of fatigue life considering the mean S-N curve, because the umbilicals present functional redundancy in all tubing lines and also a complete spare umbilical was supplied. The fatigue results were used on planning for spares and replacement.

The worst case fatigue damage occurs in the 1-in tubes of the P12 umbilical type and the ¾-in tubes of the WI1 umbilical type. A comparison of the fatigue life obtained by using the mean S-N curve (Lotsberg and Fredheim, 2009) and the mean-minus-two-standard-deviation curve (DNV-RP-C203, 2008) is presented on Tab. 3. The 1-in tube in the PU4 umbilical produces the lowest life-span.

Table 3. Fatigue life comparison

Umbilical	Fatigue Life (years) – mean-minus-two-standard-deviation curve	Safety factor	Fatigue Life (years) - mean curve	Safety Factor
PU1 (1” tube)	58.4	3.3	76.2	4.2
PU4 (1” tube)	47.7	2.7	64.1	3.6
PU7 (1” tube)	84.7	4.7	108.1	6.0
WU1 (¾” tube)	252	14	392.0	21.7

7. CONCLUSIONS

By careful selection of input parameters and interpretation of results from a risk-based analysis it is possible to significantly change the outcome of a dynamic analysis. Traditional dynamic analysis has evolved through the years to become a largely deterministic field. However by changing assessment criteria away from determinism and adding risk into the selection equation it is possible to make significant savings in project time and cost.

It has become very clear that it is vital to include as much reliable test data as is available. Live testing of material samples has led to significant changes in the input array for the Frade umbilicals.

Bending stiffness increases in the umbilical sheaths were seen to increase as the temperature decreases, this data is often discounted in analysis but in this instance it was used to determine if any improvements in compression or curvature in the touchdown area and indeed performance improvements were seen.

Acceptance of compression within the umbilical structure was also tested and as a result the acceptable compression figure was changed from 5kN to 25kN. Once again the previously seen “excessive” compression may have led to configuration change.

The production of stress / strain data for super duplex tubes led to the finding that even at low bending radius the umbilicals were operating at a bending stress that still put the material in the elastic region. In traditional analysis, the datasheet value would have been adhered to and configuration changes may have proved necessary.

In this respect configuration change would have meant the deployment of buoyancy models and these items would have added significant capital cost to the project in terms of item value and installation time.

To process the data a factoring technique was taken which enabled fatigue analysis to be conducted as a process. In fact, the most recent versions of the OrcaFlex software have modifications in place which allows the use of the gradient technique. By utilizing this facility fatigue analysis processing time was significantly reduced.

The BSR design technique provides for an operational envelope which is based upon a linear strut model. As well as quantifying the amount of time the system was breaching this envelope, by the use of finite element analysis the non-linearities inherent in the system but ignored by the BSR design software proved that under extreme load the BSR performance was within its own material capabilities.

One important recommendation is that analyses should use different values for the axial stiffness whether it is for tension or compression. The factor difference will produce lower values of compression on the seabed because the compressive wave is less severe, and could discard solutions that otherwise would be feasible.

During umbilical design this risk-based approach enabled the planning for spares and replacement, besides the design of cross section with redundancy in all low and high pressure tubing lines so if a tube fails during operations, the same hydraulic function can be re-routed to a spare tube.

8. ACKNOWLEDGEMENTS

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