Extreme response of Dynamic Umbilicals in Random Sea

R. Yasseri (1), S. Yasseri (2) and Dr B. Wang (1)

(1) Brunel University Uxbridge, Middlesex, UK, (2) Safe-Sight Technology, Surrey, UK

Abstract: Umbilical systems provide power and control (electricity, hydraulic power, chemical injection) to subsea oil and gas equipment. Installations into increasingly deeper water place greater demands upon the structural components in terms of strength. 3D finite element analysis is an applicable technique by which to assess the strain and stress distribution and the interactions between components in such complex structures. The true geometry is respected and most of the simplifications of usual approaches can be dropped. However finite element models developed this way are complex to build and can reach a large size, the model construction and the simulation must be adapted in order to remain practical. It is posed to create a model using pipe element for the global analysis and then generate sub-models to determine the local behaviour. This paper addresses the global analyses of an umbilical in an extreme wave condition employing Abaqus/Aqua.

1. Introduction

Umbilicals belong to a class of offshore structure known as flexible pipes. They all are line-like structures; namely one of their dimensions (the cross-section) is vastly smaller than their length and hence they are flexible, and may undergo large displacement without straining. The factor that differentiates umbilicals from each other is the composition of their cross sections. Flexible pipes are made of several layers of steel and thermo plastics, while control umbilicals are a number of small tubes, electrical cables and fiber optic bundled together within a sheath cover (Figure 1)

Figure 1 Examples of umbilicals

Components are generally bundled together helically which adds to the overall strength and flexibility. In multi-layered umbilicals the layers are usually contra rotated. Umbilicals are not bonded together, but kept apart using plastic fillers. Helical winding makes the response which is known as stick-slip behaviour (ISO-13628-5 2009). When loadings are not large enough to overcome the shear friction at the contact points, the components will stick together. The shear resistance at the interfaces are governed by the friction coefficient, and the reaction forces at the interfaces generated by the tension and torsion exerted on the umbilical. When the interface shearing resistance is exceeded then components slip and move from the compressive side towards the tensile side of the umbilical

2. Performance Requirements

A performance specification establishes functional requirements under various operating conditions. Compliance with performance requirements can be measured by analytical methods (the purpose of this paper) or standard test methods with defined acceptance criteria. There are several codes of practice giving recommendations on the design of umbilicals. The most popular among them are ISO 13628-5, DNV FS-OS-F101, API 17E and NORSOK Standard. For example ISO-13628-5 recommends the following load combination:

- **Normal operation**: This applies to the permanent operational state of the umbilical, taking into consideration functional and environmental loads.
- **Abnormal operation**: This applies to the permanent operational state of the umbilical taking into account functional, environmental and accidental loads.
- **Temporary conditions**: This applies to temporary conditions, such as installation, retrieval, pressure testing and other intermediate conditions prior to permanent operation.

ISO-13628-5 requires the fatigue life to be studied under the following conditions:

- Direct wave loading as well as wave induced host motion.
- Slow drift vessel motions including variation of mean position
- VIV response of the umbilical under steady current conditions
- Cyclic loading during fabrication and installation
- Cyclic loading due to operation of the umbilical.

In general, similar failure modes as for the pipelines is observed for the static umbilical and failure mode similar to deep-water riser for the dynamic umbilical and hence recommendations of pipeline and rise codes are pertinent.

3. The Wave Environment

3.1 Random Wave

Generally a regular wave (defined by its height and period) is used for the design of dynamically insensitive offshore structure. Such wave is known as the “design” wave, which has a 100-year return period. For dynamically sensitive structures, the dynamic nature of structure must be considered. For practical purposes, the random sea is considered as a collection of large number of wavelets of different heights, periods and directions, combining in random phase (Barltrop & Adam, 1998). Ocean waves could be assumed consisting of an infinite number of sinusoidal wavelets with different frequencies and directions. The distribution of energy of these wavelets when plotted against frequency and direction is called the *wave spectrum.* More precisely the wave energy distribution with respect to frequency alone, irrespective of wave direction, is called the *frequency spectrum* whereas the energy distribution expressed as a function of both frequency and direction is called the *directional wave spectrum*. Figure 2 gives an example of an irregular wave profile constructed by adding five sinusoidal wave components of different heights and periods.

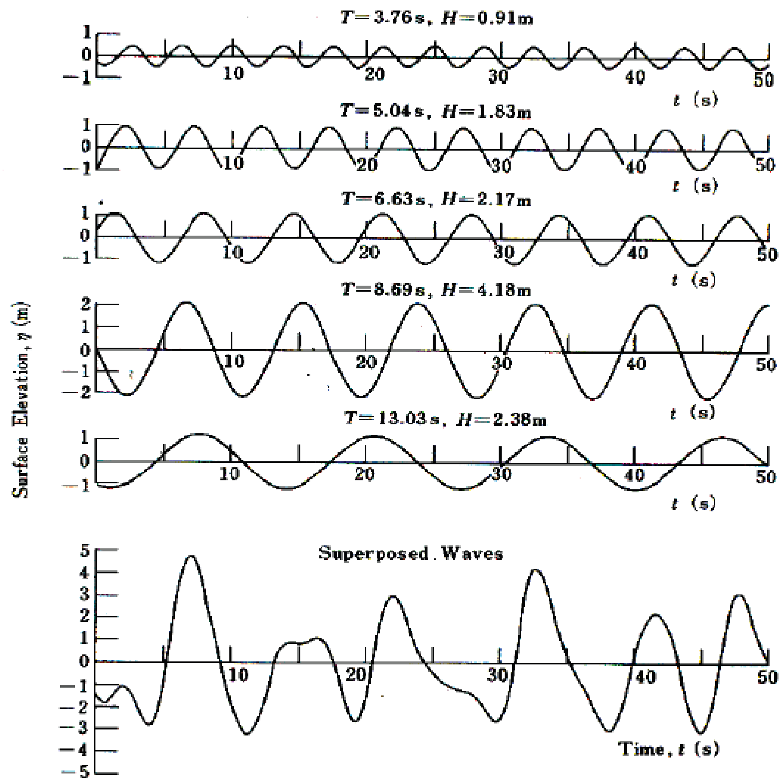


Figure2: Random Sea as a summation of wavelets (From Goda, 2000)

The random nature of the ocean surface can only be described statistically. The statistical properties of random waves in a sea may be assumed to be approximately constant for short periods of say one to three hours. During this time, the sea state may be modelled by a frequency spectrum of water elevation. There are few frequency spectra proposed for various ocean waves including JONASWAP (Hasselmann et al., 1973) and the Pierson & Moskowitz (1964). A summary of these spectra can be found in Goda (1990) and Ochi (1998).

The sea-state is characterized by significant wave height and mean zero-crossing period, as defined below, and sometimes peak period (T_p)- (Barltrop, 1998). The mean zero up-crossing periods denoted by T_z is another characteristic of a sea state. The customary practice is to utilize either the zero-up-crossing or zero-down-crossing for defining random waves. These two methods are described by Goda (2000).

The significant wave height denoted by H_s, or sometimes by $H_{1/3}$, is commonly used to describe the representative height for a sea state. Most observed and recorded wave data are presented in the form of H_s and also most energy spectrum analysis are expressed in terms of H_s. In practice the period is often routinely estimated from $T_z = \sqrt{m_0/m_2}$ (when frequency in Hz), or $T_z = 2\pi\sqrt{m_0/m_2}$ (when frequency in rps). Here m_0 and m_2 are the zeroth and second wave spectral moments- the proof of the formula can be found in many books including Ochi (1998) and Goda (2000).

1.1 Pierson-Moskowitz Energy Density Spectrum

Pierson-Moskowitz (PM) energy density spectrum is wildly used for characterizing waves in the open sea (Barltrop and Adams 1998). The PM formulation was developed from the analysis of the measured data obtained by wave recorders in North Atlantic. The analysis was carried out only on selected wave records considered to have been acquired in fully developed seas (A sea state in which waves have reached its maximum energy, (Ochi, 1998)). The following formula of the spectrum (Barltrop & Adams, 1989), which depends on the sea–state representing parameters i.e. H_s and T_z , has been used in this study to decompose a sea-state into several sinusoidal wave components. The decomposition procedure will be described in the next section.

$$S(f_j) = \left(\frac{A}{f_j^5}\right) e^{-\left(B/f_j^4\right)} \quad for\ 0 < f_j < \infty \qquad (1)$$

$S(f_j)$ Energy density of the wave components $((m^2/H_z)$

$A = \frac{H_S^2}{4\pi T_Z^4}$, $B = \frac{1}{\pi T_Z^4}$

f_j Frequency of j^{th} wave component (H_z) ,

H_s signifcant wave hight (m),

T_z mean zero-crossing period of a sea state (s).

Zeroth, first, and second spectral moments are obtained from (Ochi, 1998):

$m_0 = \frac{A}{4B}$, $m_1 = \frac{0.306A}{B^{3}/_{4}}$ and $m_2 = \frac{\sqrt{\pi}}{4}\frac{A}{\sqrt{B}}$.

1.2 Decomposition of a Sea State

ABAQUS/AQUA has the option to use wave theories including Stokes and Airy waves. Linear Airy wave theory is generally used when the ratio of wave height to water depth is less than 0.03, provided that the water is deep i.e. ratio of water depth to wavelength is greater than 20 (ABAQUS, 2014). The software requires the sea state to be decomposed into a number of regular waves when Airy theory is used.

Table 1: A sample of Decomposition of a sea-state characteristic by Hs=1, Tz=3

Amplitude (m)	Period (s)	Phase Angle (deg)	Amplitude (m)	Period (s)	Phase Angle (deg)
0.0000	27.43	342.0465	0.0320	1.71	146.0542
0.0000	13.72	83.2099	0.0276	1.61	336.7691
0.0000	9.14	218.4633	0.0240	1.52	330.0856
0.0135	6.86	174.9537	0.0210	1.44	147.6973
0.1006	5.49	320.8676	0.0185	1.37	321.7138
0.1603	4.57	274.3549	0.0164	1.31	20.8409
0.1619	.3.92	164.3284	0.0146	1.25	127.0325
0.1404	3.43	6.6613	0.0131	1.19	292.7399
0.1159	3.05	295.7066	0.0118	1.14	3.5501
0.0944	2.74	160.0932	0.0107	1.10	50.0007
0.0770	2.49	221.5557	0.0097	1.06	72.9955
0.0634	2.29	285.0973	0.0088	1.02	71.5398
0.0527	2.11	331.8527	0.0080	0.98	217.3653
0.0442	1.96	265.7546	0.0073	0.95	97.9877
0.0374	1.83	63.4558	0.0068	0.91	71.5731

It was assumed the Pierson-Moskowitz spectral formulation represents the sea-state. Each sea-state was decomposed into 30 sinusoidal components having its own amplitude, frequency and phase angle (Table 1). The phase angles were generated randomly between 0 and 360 degrees. Then for each sea-state the range of frequency (bandwidth), i.e. zero to where the spectrum approaches zero, was determined and divided into 30 subintervals. The frequency of each subinterval end point was selected as each component frequency. Then, given the frequency of the component, its amplitude was calculated using the following formula (Goda, 2000):

$$a_i = \sqrt{2S(f_i) \times \Delta f_i} \ , \qquad (2)$$

Where:

a_i = the amplitude of i^{th} component,

f = the frequency of i^{th} component,

$S(f_i)$ = energy density given by Eq. (6),

Δf_i = $(f_{i+1} - f_{i-1})/2$.

4. Global-Local Analysis

Analysis of umbilicals using solids or shells elements leads to a prohibitively large model. Thus, the analysis is carried-out in two levels, namely global and local, as shown in Figure 3.

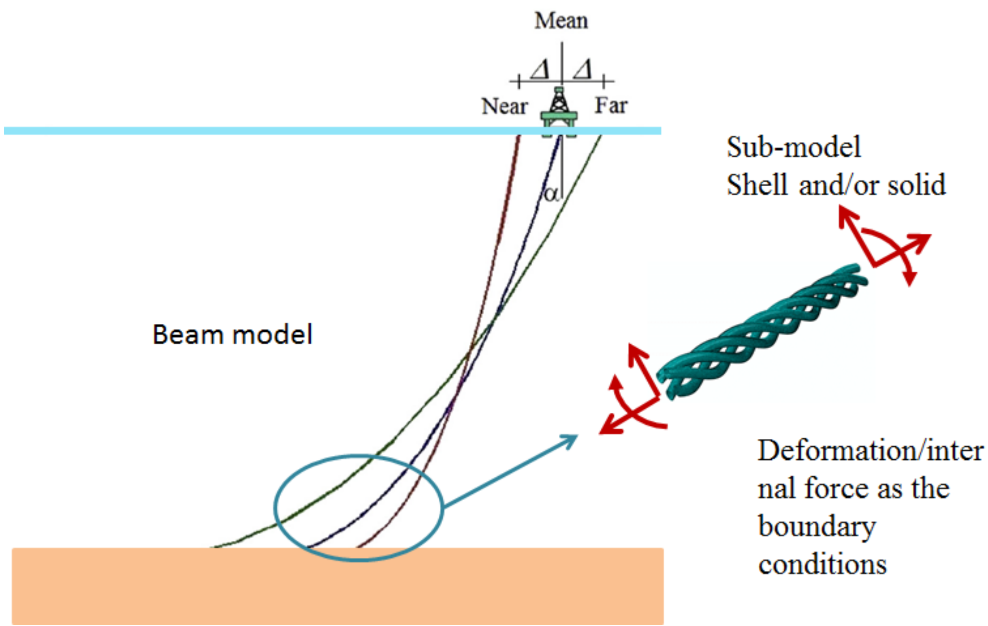


Figure 3: Global model and the sub-mode

In this approach, the global analysis of the umbilical is carried-out using pipe elements (Pipe32). These elements will capture the dynamic and nonlinear effects in a simple and efficient manner. It is necessary that the equivalent mechanical properties (*EA*, *EI*, *and GJ*) of the umbilical are correctly determined. These can be obtained either by testing or a finite element model of a length of the umbilical. These are then verified my manual calculations.

The global analysis yields the displacements and stresses resultants (axial force, bending and torsional moments) along the umbilical's length. These results are good enough to check the umbilical strength under extreme conditions. However, more detailed information is required for the fatigue life determination. Thus, the stress resultants calculated in global analysis are used as input for local analyses (sub-modelling). The critical sections are at the touch down zone, and the point where the umbilical is connected to the vessel; and perhaps at the mid-height buoy if it is used- The example used here is of free hanging type, which does not use a mid-height buoy. The local analysis is carried-out using a mixture of solid and shell finite element, as these elements allow the computation of stresses and strains for each component, as required by the fatigue analysis procedure using S-N curves.

Various ideas for the modeling of the touchdown zone (TDZ) were explored in the literature. A rigid seabed can give high levels of conservatism when compared to an elastic seabed. In the TDZ where the riser meets the sea bottom, the catenary shape of the umbilical will impose high stresses. This is further aggravated by the motions of the vessel. The vessel motion is a function of sea state. The vessel motion causes the umbilical to move in different directions, and the touchdown zone to vary in time. The restraints by the sea floor will cause large fatigue damage in this area. When the size of the surface structure is comparable to the length of wave, the pressure on the structure may alter the wave field in the vicinity of the structure. In the calculation of wave forces, it is then necessary to account for the diffraction of the waves from the surface of the structure and the radiation of the wave from the structure if it moves (Ochi, 1998).

5. Strength Limit State

5.1 Make-up of the example umbilical

Figure 4 shows the cross section of the example umbilical. The umbilical is installed in 500m water and connected to an FPSO. The far end of the umbilical is connected to a subsea cluster about 8 kilometres away. The umbilical make-up is the same along the length, except the about 1000m (the dynamic part), which is connected to the vessel, has extra armour to achieve the required strength and fatigue life. Table 2 and Table 3 give particulars of the example umbilical.

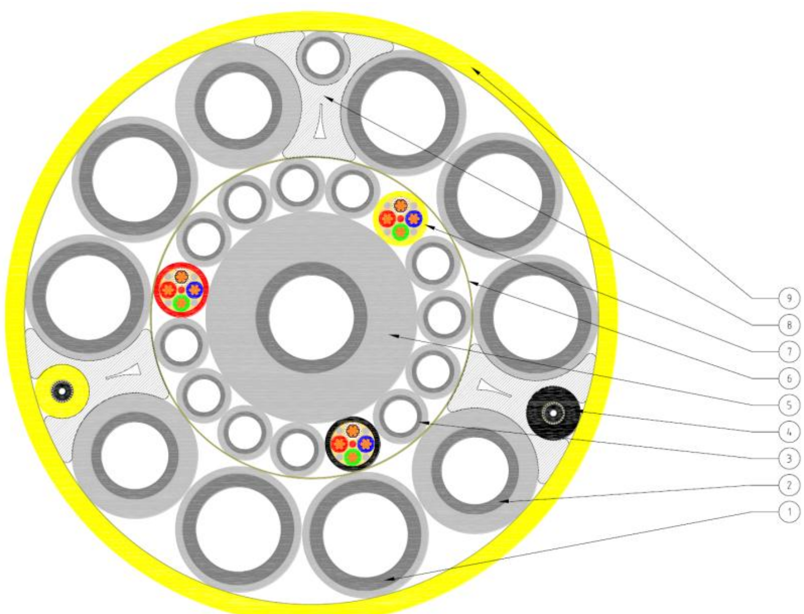


Figure 4: General configuration of the example umbilical

Table 2: Mechanical properties of components within the example umbilical

Parameter	Parameter	Unit
MHT (utilisation factor of 100% SMYS)	1 996	[KN]
Min. breaking load (No bending, 100% UTS)	3 593	[KN]
MBR (elastic limit)	6,69	[m]
Axial stiffness	1 376	[MN]
Bending stiffness	243	[kNm2]
Torsion stiffness	275	[kNm2]

Table3: gives typical data needed for the design.

Item	QTY	Description	Nominal thickness (mm)	Nominal Diameter (mm)
1	8	1.25” SD steel tube, 900 bar , sheathed	5.08	42.16
2	3	1” SD Steel tube, 900 bar, sheathed	3.85	33.1
3	13	½” SD steel Tube, 900 bar, Sheathed	1.77	16.24
4	2	Fibber Optic Element, 24 SM fibbers, armoured		20.2
5	1	Centre tube sheath		18.
6		Wrapping	0.32	
7	3	Electrical Qua 16mm^2, 1kV		
8	3	Profiled Filler		
9	1	HDP Outer Sheath	6.8	~230

5.2 Operating conditions

There are spare tubes inside each umbilical which are used when a working tube is damaged. However, during installation all tubes are pressurized to a pressure just above the pressure commensurate with the ware depth in order to prevent collapse under external pressure. Fluid inside each umbilical is the same as the fluid for the designated function. However, during operation the pressure inside the spare tubes are kept by sealing them. The pressure of other umbilicals are increased t its functional level.

5.3 Sea States (Metocean loads)

The wave scatter table gives the joint probability of significant wave height and wave zero crossing periods. The rows give the different wave height classes and the columns the zero crossing period classes. The probability is shown as parts per thousand; therefore a value of 78 represents a probability of 0.078, or 7.8%.

The P-M wave height spectrum with parameters related to open seas and North Atlantic wave scatter diagram has been employed in this study. A condensed wave scatter diagram as shown in Table 4 is used for this study. The last column is the percentage of persistence of each sea state in a year. It should be noted that the probabilities displayed have been rounded to the nearest part per thousand. As a result, the tabulated values may not always total exactly 1000.

Table 4: Wave scatter diagram used in this study

Sea-State Definition		**Sea State Occurrence (%)**
T_z sec	**H_s m**	
1.95	0.3	7.2
3.34	0.88	22.2
4.88	1.88	28.7
6.42	3.25	15.5
7.96	5.00	18.7
9.75	7.50	6.1
12.07	11.50	1.2
13.32	14.0	0.2
14.5	14.8	0.01

5.4 Drag, inertia and added mass coefficients

The Morison equation is a semi-empirical equation for the inline force on a body in oscillatory flow. The Morison equation is the sum of two force components: an inertia force in phase with the local flow acceleration and a drag force proportional to the (signed) square of the instantaneous flow velocity. The inertia force is of the functional form as found in potential flow theory, while the drag force has the form as found for a body placed in a steady flow. These two force components, inertia and drag, are simply added to describe the force in an oscillatory flow. The Morison equation contains two empirical hydrodynamic coefficients — an inertia coefficient and a drag coefficient — which are determined from experimental data.

An umbilical is a slender structure; hence Morison's equation is applicable. The basic assumption of Morrison method is that the diameter of cylinder D compared with wavelength L is small, D/L<0.2, hence the cylinder cannot affect the wave field. The hydrodynamic coefficients used for the riser are summarized in Table 5.

Table 5: Hydrodynamic Coefficients

Hydrodynamic Coefficients	**Value**
Drag Coefficient, Normal	0.7
Drag Coefficient, Axial	0.0
Added Mass, Normal	1.0
Added mass, Axial	0.0

5.5 Analysis Procedure

The umbilical–seabed interaction is frequently modelled by non-linear springs and dashpots at nodes in contact with the seabed. In this study Abaqus' facility for modelling of rigid surface with different friction coefficient for horizontal and vertical direction was used. The contact definition is the general contact in Abaqus. The seabed was modelled using Abaqus's rigid Element (R3L4). The length of seabed is 2500m and 2000m of the umbilical was modelled. After establishing contact with seabed and equilibrium under the self-weight, one end of the umbilical lifted to the sea surface by applying the displacement and angle with the vertical as the boundary condition. For the global model P32 was used and elements length was about 0.5m. Figure5 shows the outline of the model. For further details can be found in Yasseri et al. (2014). Analysis steps are as follows:

Step 1: Umbilical was initially modelled as straight beam on the rigid seabed. The vessel end was assigned simple support and the anchor point was fixed. The submerged weight was applied to the umbilical.

Step 2: The umbilical end was lifted to the nominal attachment point so that the target inclination of 72 degree was achieved.

Step 3: The collection of waves was applied using AQUA. At the same time and the vessel RAO was applied at the nominal attachment point.

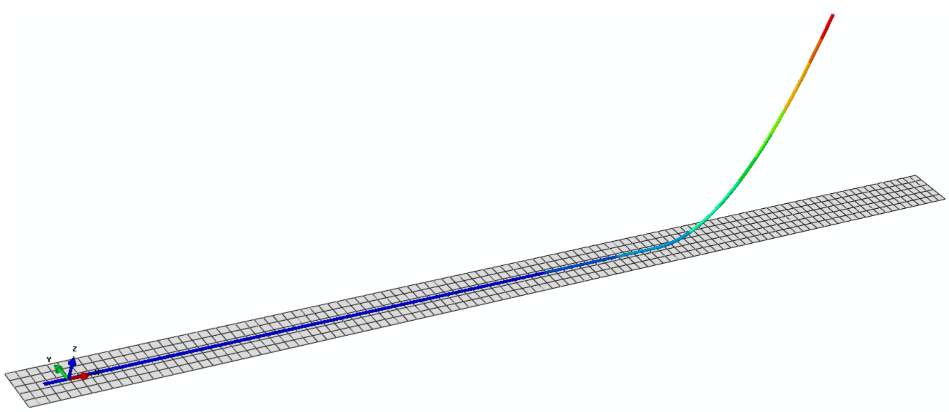


Figure 5: An outline of the model

The configuration mainly depends on the water depth, weight of umbilical location of the surface vessel and top tension. Software packages are available to study a most suitable configuration. Using the selected configuration as the input, Abaqus is used to predict both the dynamic behaviour and the limits of the service life of the system.

To ensure the integrity of the umbilicals, the extreme environmental must be analysed and all Von-Mises stresses are kept below the allowable limit (generally 0.66% of the material's proof stress). Such analyses must account for the dynamical property of the umbilicals. For the static part, the on-bottom stability and spanning is of concern- these are not studied in this dissertation. A sea state of H_s=14.8m and T_z=14.5 sec has a return period about 100 years (probability of occurrence of 0.01).

As discussed earlier the analysis starts with applying the self-weight and the internal pressure which is maintained during reeling. The internal pressure was set to 70 bar, which is generally slightly above the hydrostatic pressure. The next step is taking the near end of the umbilical to the vessel connection by applying the correct coordinates and angle. The last step is applying the hydrodynamic load (current and wave) and performing a time domain dynamic analysis. The analyses ran for 3584 seconds with a fixed time increment of 1 second, generating 10240 increments; which divisible by 1024.

The maximum Von Mises stress must be determined and if it is above the allowable limit, the umbilical must be resized. Resizing can be done in several ways depending how severely the system is failing. A simple method is to increase the wall thickness of the tubes. Sometimes the outer sheaths can be made of high grade steel (e.g. super duplex stainless steel). For very deep water this is not practical, hence armour layers are added which encompasses all components.

The maximum stress depends on the wave excitation, since the umbilical's response is non-linear. Generally there are few candidates for the location of maximum stresses, which can be found by inspection.

Since the umbilical response is non-linear the position of the maximum stress depends on the wave excitation. The time history of stresses at a number of the elements were obtained and examined to ensure that the member with maximum response is picked up.

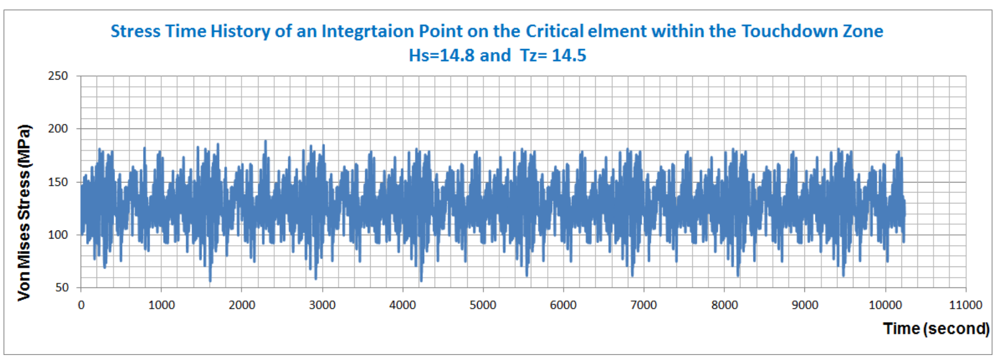


Figure 6: Stress Time History for Hs= 14.8 m Tz= 14.5s at an integration point within the touchdown zone

Figure 6 shows a typical stress time history at an integration point, on the critical element within the touchdown zone, as a result of applying the sea-sate characterized by *Hs* =14.8 m & *Tz* = 14.5

s. Using 1 second fixed 10240 von Mises stress values were obtained for each integration point by ABAQUS/AQUA for the sea-state loading as well as the self-weight, internal pressure and buoyancy effects.

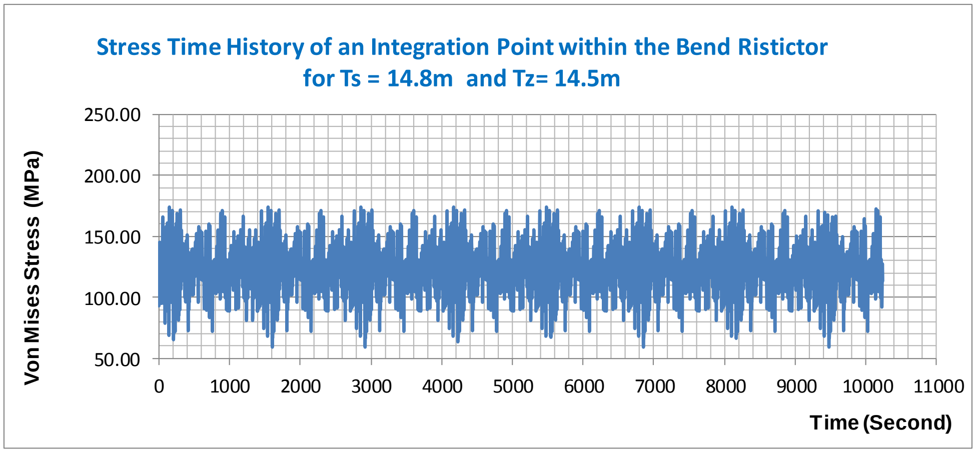


Figure 7: Stress Time History for Hs= 14.8 m Tz= 14.5s at an integration point within the bend restrictor

The mean and standard deviation of these data were computed and the most likely extreme amplitude of stress cycles after h =3 hours, using a long-term extreme prediction due to Barltrop and Adams (1991), was calculated from Eq. (5) for all elements in the previously defined subset "*Max*":

$$S_e = \bar{S} + \sigma\sqrt{2ln\frac{3600h}{T}} \qquad (5)$$

Here:

S_e =most likely extreme stress after h hours (MPa)

$\bar{S}$ = the mean of the stress time history (MPa),

σ =standard deviation of the stress time history of an element (MPa),

h =time (in hours); in the present study h =3

T =mean zero-crossing period for the stress time history related to an integration point of an element; in this study T = 300/N where

The most probable maximum Von Mises stress which occurs during h = 3 hours, and is obtained from Eq. (5) for the critical element. In other words it is the maximum of all of the values obtained. Table 6 gives Von Mises stresses calculated by various approaches including Eq. (5). It can be seen that all values are below 70% of the material yield, thus acceptable.

N total number of zero up-crossings in the stress time history

Table 6: Summary of results for two critical points on the umbilical

Within the following area:	Mean (MPa)	Standard Deviation (MPa)	RMS (MPa)	Maximum of the time history (MPa)	Mean plus 3 times standard deviation (MPa)	According to Equation 7.1 (MPa)
TDZ	129	21.94	130.87	188.36	194.85	208.45
Bend Restrictor	124	20.97	125.61	174.1	186.75	192.11

6. Fatigue Limit State

6.1 Background

Fatigue life determination of dynamic umbilicals is more involved, due to their non-linearity and dynamic sensitivity as well as the complexity of the cross section. For this reason analyses must be in the time domain dynamic analyses considering interlayer friction.

Deterministic fatigue analysis is the simplest approach to evaluate the fatigue life. This approach uses an S-N diagram, which in turn requires breaking down stress variation into a number of ranges and determining the number of their reparations. Sheehan et al. (2005) compared the deterministic and probabilistic methods for various riser configurations and concluded that the deterministic approach is sufficiently accurate provided blocking of the sea state is not too crude, and the deterministic fatigue analysis was performed using a realistic wave scatter diagram.

One way of implementation of this method is to define the environment in the form of wave scatter diagram giving the wave height, wave period and number of each wave in a year. This should account for all sea states and all direction of loading. To make this approach manageable, the wave scatter diagram is divided into a number of blocks; each block represented by a single wave which has the total cycle of all waves. RAO is obtained by analysing the system for each of these blocks. To simply further, the response is linearized for each sea sates by assuming that the response is proportional to the wave height and it is constant for each block. The effect of the second order motions can be accounted for as part of the first order fatigue by considering appropriate vessel offsets within the linearization (API-RP-2RD 1998). The total fatigue damages are obtained using Miner's rule (API-RP-2RD 1998).

In this study, the design sea states are defined as a number collection of waves with significant wave height and zero crossing period. It is assumed the sea state is governed by P-M spectra. Each sea state is then decomposed into 30 regular waves with given period and amplitude. A random phase is assigned to each of these waves.

6.2 Local Analysis

Scatter diagram as shown in **Table 4** contains 9 sea states, which requires 9 global analyses. The analysis methodology is exactly the same as described in the previous section. The next step is to determine maximum principal stresses on the components. For this purpose eight sub-models were produced; one for the touchdown zone, one for the bend restrictor zone and four for the rest of the umbilical. The differences between the last six models are minimal. Except for the sub-model which has the bend restrictor, the rest have different curvature. Thus, using the six sum-models 50 analyses were performed, using a configuration which best represented a section of the umbilical.

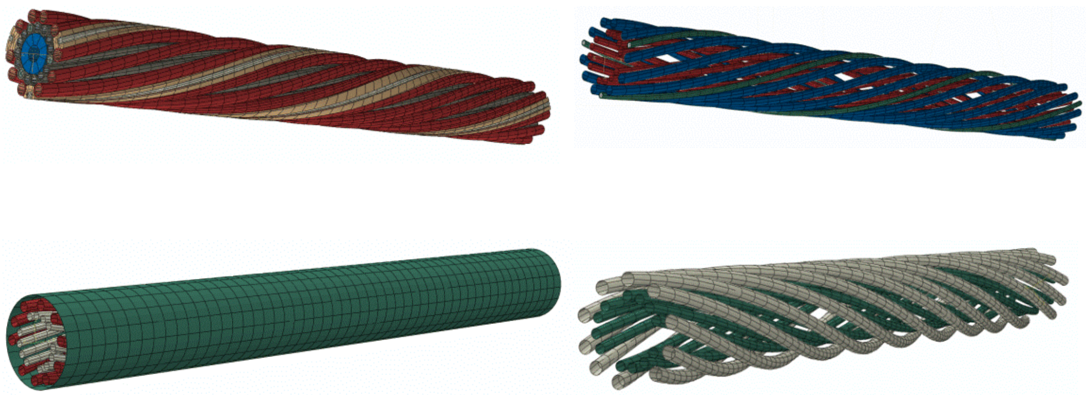


Figure 8: Components of the local model

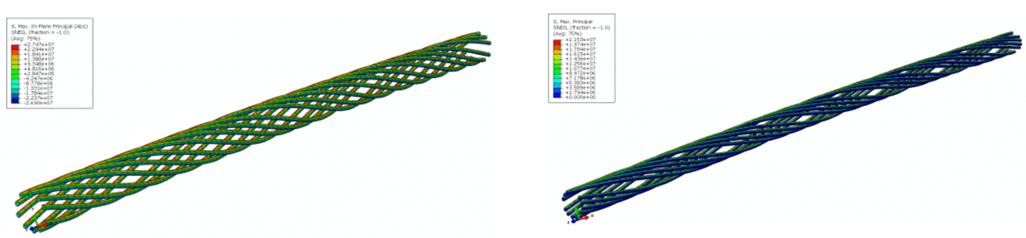


Figure 9: Maximum principal stress for the inner tubes - One frame of time domain analysis for Hs=0.88 and Tz=3.3

A length of 5.6m was chosen, which lead to about 250,000 elements, as the size of tubes is small hence small elements were needed to model the geometry correctly. Load transfer from the global to sub-models was automatically performed by the software.

In order to simplify the process, another approximation was made here. Generally, in fatigue analyses one should take the principle stress which is normal to the weld, i.e. not always the maximum principal stress is normal to the direction of crack opening. In this study, the maximum principal stress irrespective of its direction was used; hence results reported here is somewhat conservative. Figure 8.3 1 show details of meshing. Figure 8.3 2 and Figure 8.3 3 both show plots of maximum principal stresses for the inner and outer tubes. These are just one frame of time domain analysis showing maximum principal stresses.

6.3 Fatigue Calculation Procedure

Determining the fatigue life requires three pieces of data, which are:

- S-N curve, applicable to the detail and the environment (e.g. sea water, if there is Cathodic protection, residual stresses, type of details, material type and so on). All codes of practice have a list of such curves covering every condition
- Stress rage and
- the number of cycles

Various methods were devised to answer the last two bullet points, which vary in sophistication, thus conservatism.

The response to random sea is a random stress S(t), which is not only made up of a peak alone between two passages by zero, but also several peaks appear in between, which makes difficult to determine the number of cycles. An example for the random stress data is shown in Figure 10

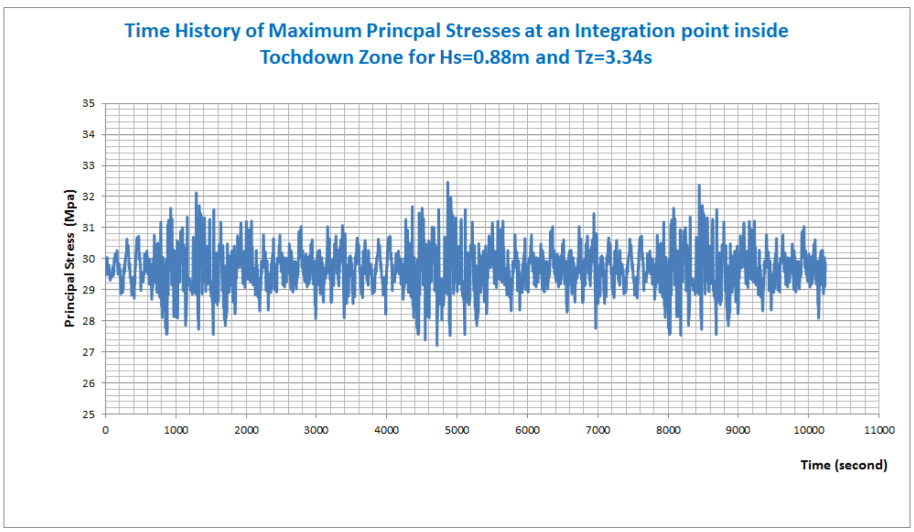


Figure 10: Principal stress history of a point on an outer tube for one sea state

The counting of peak stresses makes it possible to construct a histogram of the peaks of the random stress. This can be used directly with the Miner rule, or can be transformed into a stress spectrum. The stress spectrum is thus a representation of the statistical distribution of the characteristic amplitudes of the random stress as a function of time.

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

$$N = aS^{-k} \qquad (6)$$

where,

S =the stress range including the effects of stress concentrations

N =the allowable number of cycles for the stress range

a, k are the parameters defining the curves

The calculation of the wave fatigue damage in this study is based on X' curve as specified in API RP 2A; however, E S-N curve as recommended by UK-HSE could be used:

$$N = \begin{cases} 2.5 \times 10^{13}(SCF \times \Delta\sigma)^{-3.74} & API\ X' - Curve \\ 1.04 \times 10^{12}(SCF \times \Delta\sigma)^{-3.0} & HSE\ E - Curve \end{cases} \qquad (7)$$

N is the permissible number of cycles for a stress range $\Delta\sigma$ MPa, SCF is the stress concentration factor which is assumed to be 1.3. Results reported here are based on the HSE E curve.

Fatigue occurs as a result of stress or strain fluctuations, which are known as cycles. The significant aspects of these are the ranges of stress in the cycle and also their mean stress. The range and mean information is usually extracted from the time history using a procedure known as 'Rainflow Cycle Counting'.

Each cycle will induce a certain amount of fatigue damage on the component. The total damage caused by the stress time history can therefore be obtained by summing the damage caused by each cycle. This approach is known as the Miner accumulated damage

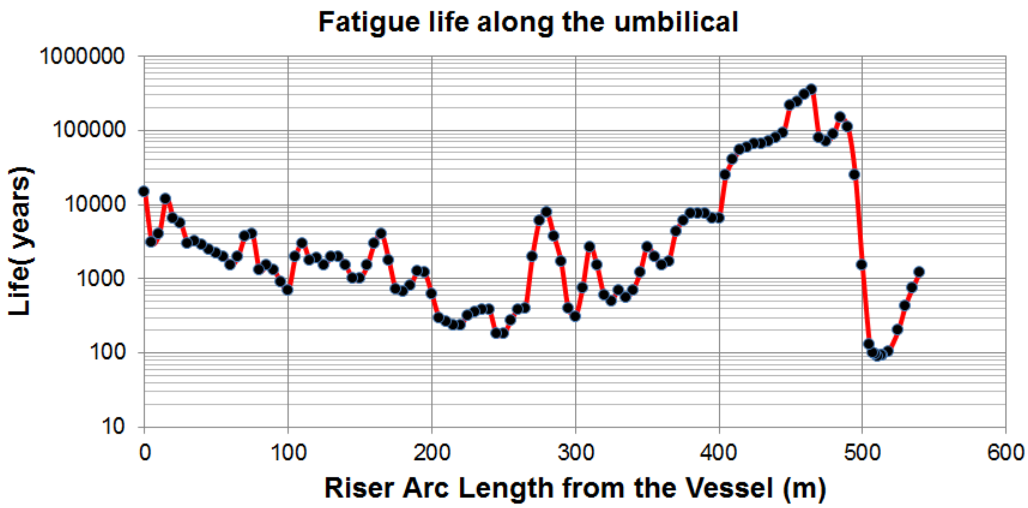
The damage caused by each cycle is calculated by reference to the material life curve, in this case the S-N curve. The SN curve shows the number of cycles to failure, N_f, for a given stress range, S. The total damage caused by N number of cycles is therefore obtained as the ratio of cycles to the number of cycles to failure. The Minor rule can therefore be expressed as Eq. (8)

$$d_J = \ Accumulated\ Damage\ for\ the\ sea\ sate\ J = \sum_i \frac{N_i}{N_f} \qquad (8)$$

where, N_i is the number of cycles with a particular stress range and mean; i is a ranging variable covering all the possible range and mean combinations; and N_f is the number of cycles to failure for a particular stress range and mean.

Then d_J is multiplied by its probity to occur during one year to determine the damage due to the sensate J. Summing all damages for all sea sate gives the total damage. The inverse of it is the fatigue life.

The fatigue life of an umbilical requires a large number of dynamic analyses as explained earlier. Such analyses should be consistent in representation of all environmental loads imposed to the structure. For each seastate the stress field over the component has to be determined. The slip between adjacent components can be ignored as the softer material used between components mitigate the effect of fretting and wear.



Fatigue 11: lives along the umbilical length

A typical fatigue life distribution plot, for one outer tube, along the umbilical length is given in Figure 11. This figure give a composite results for various vessel ordination, soil condition, hydrodynamic coefficient and point around the cross section (8 points were chosen). This study used the Rainflow algorithm in the commercial software MATLAB code developed by Nieslony. The fatigue damage is highest in touch down zone, followed by the connection point at the FPSO.

7. Concluding Remarks

In this study Abaqus/Aqua was used for performing the time domain dynamic analyses of marine control umbilicals. The wave environment is generally expressed in terms of significant wave height and its zero crossing periods and the wave energy is expressed in terms of wave spectra, e.g. Person-Moskowitz spectra which is used here. The sea states are decomposed into several waves with given period and amplitude but with random phase angles. Using the Airy waves, these decomposed waves were entered in the analyses input file together with the water depth and the hydrodynamic coefficients.

The analysis method adopted here is termed global-local analyses. That is, the entire umbilical is analyzed using beam elements of 0.5m and time domain analyses performed for a three hour sea state. In the next step, local models (sub-models) various were created and displacement and forces from the global model were applied at the terminal points. There are generally a few locations where the Von Mises stress is at its maximum. Performing statistical analyses on the time history records the maximum stresses are determined, which must be below the allowable value.

Using the industry software, which is designed for the deep water risers, for the design of umbilical requires approximation of the behavior of the cross section, since complex cross section of umbilical cannot be modelled in standard software produced for risers design. The advantage of industry standard software is due to its purpose built design; some of preparatory work (e.g. wave decomposition) is not required. But the advantage of Abaqus is the relationship between sub-model and the global one is automatic, which is very important when performing the fatigue analyses (Yasseri, 2014).

8. References

1. Abaqus 6.12, Simulia Dassault Systems.
2. ANSI/API Specification for Subsea Umbilicals Specification 17E 4th ed., 2010, Effective Date: April 1, 2011
3. Barltrop, N. D. P., and Adams, A. J.,199, ".Dynamics of Fixed Marine" , Structures, Butterworth–Heinemann, Oxford
4. DNV-RP-F401, 2012, Electrical Power Cables in Subsea Applications FEBRUARY 2012
5. DNV-RP-F109, 2010, On-Bottom Stability Design of Submarine Pipelines
6. Faltinsen, O.M., 2005, Hydrodynamics of High-Speed Marine Vehicles. Cambridge University Press.
7. ISO 13628-5:2009 Design and Operation of Subsea Umbilicals, Part 5.
8. Li, J., Wang, H., Zhang, K. & You, X., 2013. FEM Model and Mechanical Behavior of Flexible Risers. International Conference on Fracture and Strength of Solids.
9. Martins, C.A. and Pesce, C.P., 2002, Simplified Procedure to Assess the Fatigue-Life of Flexible Risers, 12th ISOPE 2002, and Japan.
10. Nieslony, A., Rainflow Counting Algorithm, MATLAB File Exchange. Accessed on 22/12/2013, http://www.mathworks.co.uk/matlabcentral/fileexchange/authors/7825
11. Norsok Standard, Common Requirements, Subsea Production Control Umbilical U-CR-006Rev. 1, January 1995 Specification for Subsea Umbilicals
12. Yasseri, S.F., Bahai, H., Bazargan, H., and Aminzadeh, A., (2010), "Prediction of safe sea-state using finite element method and artificial neural networks", Ocean Engineering 37, 200–207.
13. Yasseri, R.F., Yasseri, S.F., Wang, B, 2014, "Integrity of Subsea Control Umbilicals", OMAE2014-23778, 34th OMAE conference 2014