Understanding Fatigue for Deepwater Mooring Systems – The Footprint of Fatigue

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West Africa deepwater systems typically include a taut-moored FPSO with flowlines connected to an offloading buoy at some distance from the vessel. In these systems, the flowlines and sometimes other risers exert a large horizontal pull on the FPSO which must be countered by some of the mooring legs in order to keep the FPSO on station. These systems tend to have mooring chain components governed by fatigue. Increasing the anchor to vessel distance from what is commonly specified in these taut-moored systems significantly increases the fatigue life of the mooring chain. The chain fatigue life for seven systems is computed for three mooring guidelines, including one that will become effective in early 2005. Data on fatigue life factors of safety for these analyses is reviewed.

Introduction

It has become common practice for deepwater West Africa projects to include a spread moored FPSO with an offloading buoy two kilometers away, with the vessel and buoy connected by a set of flowlines that transfer oil from the FPSO to the buoy for export. These flowlines are under high tension, and typically have a large horizontal tension component at the vessel and buoy ends, acting to pull the two together. The magnitude that is typical for this horizontal tension component ranges between 100 and 200 tonnes per flowline, with most projects requiring two or more flowlines between the vessel and the buoy.

Another typical feature of these spread moored projects are that they are taut-moored systems whose footprint on the seabed is limited to an anchor to vessel distance equal to the water depth at the site. This distance limitation is a result of the desire to have the maximum seabed area available for pipeline and riser routings and that the vessel offsets of a taut-moored system are small enough to accommodate various riser designs for deep water.

The combination of taut-moored systems with flowlines inducing large horizontal loads on the FPSO has inadvertently resulted in producing fatigue problems in the mooring chain for those mooring legs that are countering the large external loads. This fatigue problem is greatly exacerbated by limiting the anchor to vessel distance to an amount equal to the water depth.

It has been our experience that most FEED studies, which are used to develop the mooring layout pattern, do not take the loading from flowlines and risers into account and do not include a fatigue assessment. Therefore, fatigue issues often show up late in the detailed design phase.

This paper will show how increasing the allowable vessel to anchor distance can greatly improve the fatigue life of the mooring chain in the higher tension legs. A number of case studies are presented for comparison. The ultimate goal of this research is to enable the field layout designers to understand the effect on the mooring system of large asymmetrical loads and to adapt their field layouts to adequately account for fatigue issues.

Another goal of this paper is to provide a comparison of the fatigue analysis results from three mooring guidelines (new and future API RP 2SK and POSMOOR). Each guideline has its own required factor of safety for the fatigue life. This is especially important to consider once the new API RP 2SK guideline is in effect, which has a more conservative T-N curve but a lower required fatigue life factor of safety.

Case Study Descriptions

Seven different taut-moored systems have been designed and analyzed for both maximum line loads and fatigue life estimates of the mooring chain components. These systems have been designed based on common attributes of deepwater West Africa systems in terms of FPSO size, environmental conditions, and typical governing constraints.

All cases are chain / wire / chain systems in 1000 meters of water with twelve mooring legs. The mooring legs are in four groups of three, one group at each corner of the vessel. All chain is studless and all wire is sheathed spiral strand. It was assumed that all chain and wire sizes are the same for all mooring leg groups. The vessel heading was “South”, which was assumed to be into the middle of the sector from which swell arrives. Mooring legs 1, 2, and 3 were oriented towards the southeast, 4,5, and 6 to the northeast, 7, 8, and 9 to the northwest, and 10, 11, and 12 toward the southwest, at plan angles of 55, 60, and 65 degrees from the vessel centerline.

Each of the seven mooring systems have been designed to meet certain vessel offset criteria and safety factors, and then evaluated for fatigue life. Each system is described in terms of the chain size needed for strength and the size needed to meet fatigue requirements of the current API RP 2SK guideline.

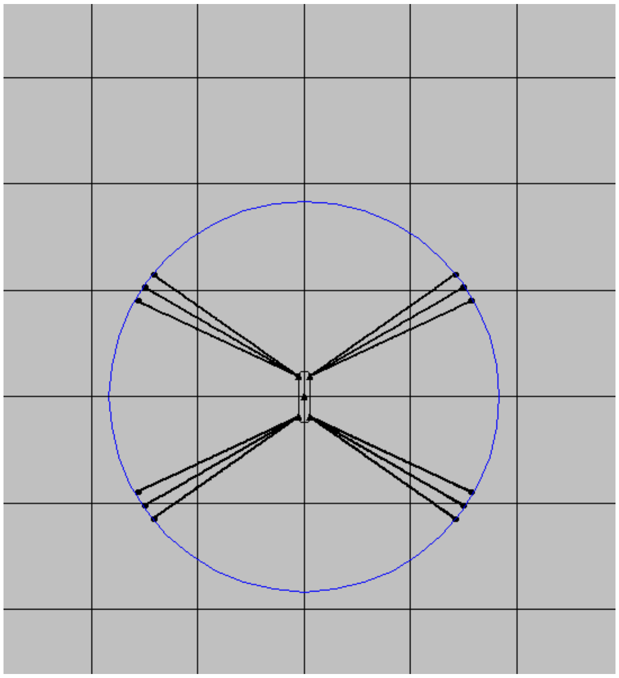
The mooring design for vessel offset and maximum line load used a simplified approach, since the purpose of this part of the analyses was to get approximate sizing only. Therefore, only the intact mooring system was analyzed.

The vessel offset criteria used was a maximum offset of 5% of water depth, which is 50 meters. The safety factors were based on the API RP 2SK guidelines, for which an intact mooring system must have a minimum factor of safety of 1.67. The fatigue analysis for each system was used to calculate the estimated fatigue life based on three guidelines, with fatigue life estimates of the chain obtained both for chain sized by strength and chain sized by fatigue.

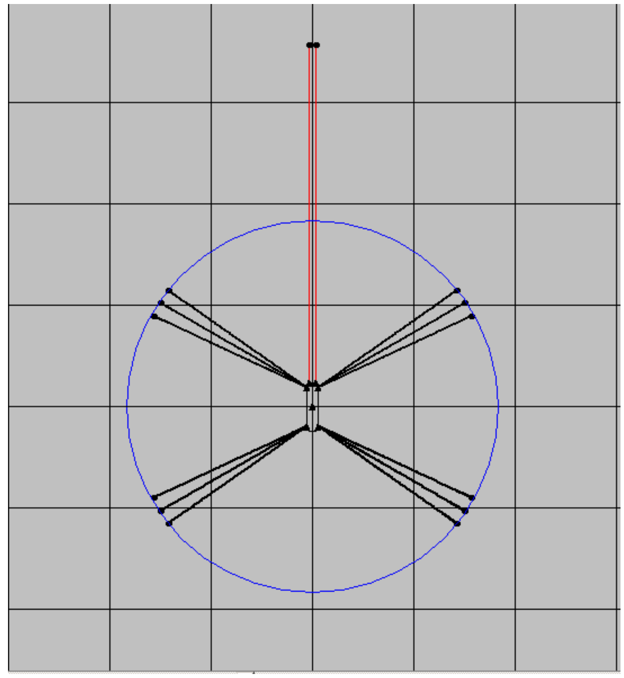
The seven cases are:

- Case 1: An FPSO without an offloading buoy in the system, and therefore no flowlines. This system constraint was to have the anchor to fairlead distances (endpoint separation, or EPS) equal to the water depth (WD). This system is considered the Base Case without Flowlines.
- Case 2: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth. This system is considered the Base Case with Flowlines.
- Case 3: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth plus 10%.
- Case 4: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth plus 20%.
- Case 5: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth plus 30%.
- Case 6: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth plus 40%.
- Case 7: An FPSO with flowlines connected to an offloading buoy, and whose mooring legs were constrained to anchor to fairlead distances equal to the water depth. The flowlines were oriented into the predominant swell. This case is considered to be an inverse of Case 2.

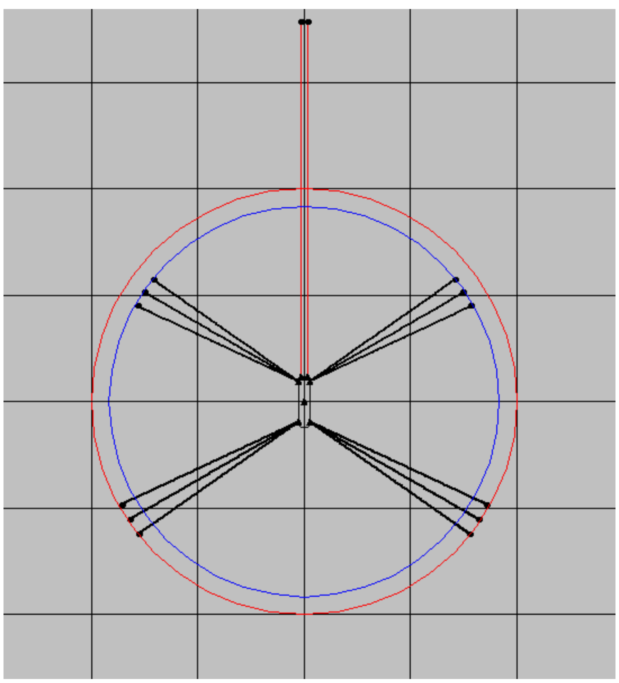
These seven cases are illustrated in Figures 1a and 1b. Note that only the mooring legs away from the flowlines have increased EPS values, while the mooring legs toward the flowlines are kept at an EPS value equal to the water depth (WD).



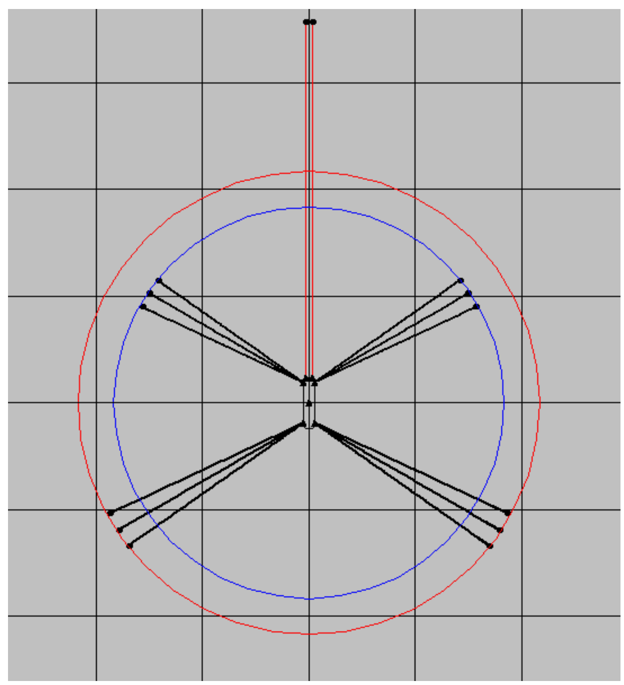
Case 1 (Base Case without Flowlines)



Case 2 (Base Case with Flowlines)

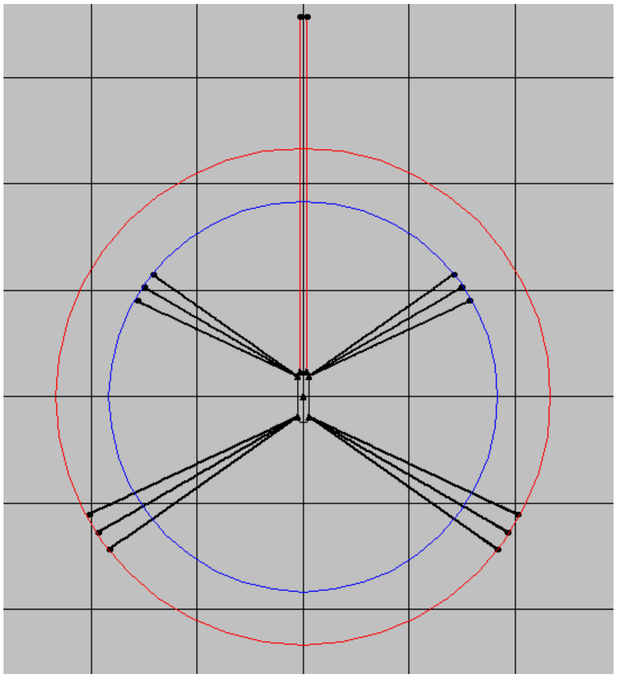


Case 3 (EPS = WD + 10%)

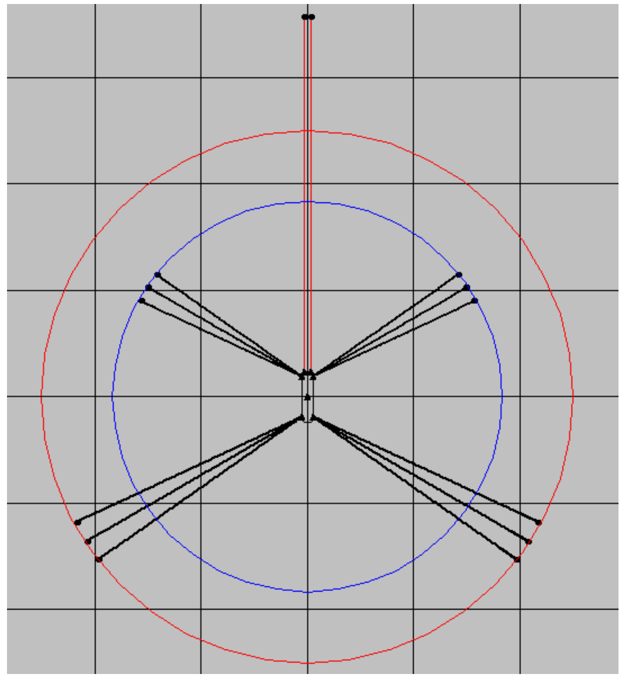


Case 4 (EPS = WD + 20%)

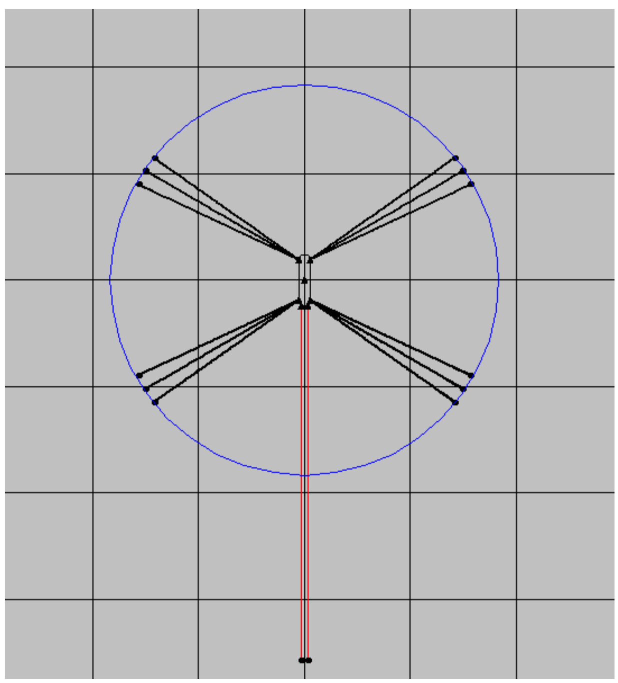
Figure 1a. Analysis case layouts (Cases 1 to 4) showing vessel and flowline orientations, mooring leg plan angles, and radius of endpoint separation (EPS). Case 1 is the base case, without flowlines, where the EPS is equal to the water depth (WD) for all mooring legs. Cases 3 and 4 show increasing EPS values for the mooring legs away from the flowlines only. All layouts show FPSO-centered circles as visual markers for EPS values.



Case 5 (EPS = WD + 30%)



Case 6 (EPS = WD + 40%)



Case 7 (EPS = WD, Flowlines into Swell)

Figure 1b. Analysis case layouts (Cases 5 to 7) showing vessel and flowline orientations, mooring leg plan angles, and radius of endpoint separation (EPS). Cases 5 and 6 show increasing EPS values for the mooring legs away from the flowlines only. Case 7 has all EPS values equal to the WD, with the flowlines oriented into the swell. All layouts show FPSO-centered circles as visual markers for EPS values.

Environment

The metocean conditions offshore most West African countries are generally described by swell extremes, wind squall extremes, and current extremes. The mooring system must be designed to have acceptable mooring line safety factors and vessel offsets in these extreme conditions. The day to day conditions are dominated by swells and seas, with many sites exhibiting bimodal seastates. Fatigue seastates are represented by numerous combinations of swell wave height and period with occurrence percentages for each seastate.

The swell usually arrives at the site from about a 45 degree sector, with the vessel oriented into the midpoint of that sector. The significant wave height of the 100-year return period swell ranges from around 3 to 4 meters, with peak periods of the swell ranging from 13 to 18 seconds. The wind, current, and sea associated with these swell events are typically mild. The swell conditions often govern the maximum line loads of the mooring legs towards the sector from which the swell arrives.

The extreme wind events, typically referred to as squalls because they arrive suddenly and disappear quickly, are characterized by high speed gusts of wind that change rapidly in direction. The 100-year return period squalls generally have five second gusts ranging from 20 to 40 meters per second. Some regions offshore West Africa are prone to squall events from any direction, while other regions have common sectors from which the squalls arrive. The squall events tend to govern the maximum vessel offsets, mostly because the typical FPSO in West Africa has a very large topsides area, and gusts tend to arrive from a beam-on direction. The squall events often govern the maximum line loads in mooring legs in off-swell directions, but also sometimes govern line loads of mooring legs into the swell.

The extreme currents conditions are usually described as varying with magnitude and direction for the entire water depth. These conditions rarely govern any mooring line loads or vessel offsets in the deepwater systems described in this paper.

The day to day conditions are used for fatigue analyses, and are usually presented as significant wave height and period matrices with associated percentages of occurrence. Sometimes bimodal (swell plus sea) seastates are given for fatigue. The swell component contributes much more to the fatigue damage in a mooring line than does the sea component, in part because the swell wave heights tend to be larger than the sea wave heights, and because the swell periods induce larger low frequency offsets of the vessel than do the periods associated with the sea. The wind and current associated with the fatigue seastates are usually mild.

The direction of the swell component is an important factor in determining the fatigue life estimates. Generally, three different swell directions, one straight on to the vessel and then on either side, are used for the fatigue analysis.

The analyses performed for this paper used only the 100-year return period squall events to size the mooring system components and determine the maximum vessel offsets. The squall winds were assumed to come from all directions. The only vessel load case analyzed was the ballast condition. A one-hour wind speed of about 21 m/s (40 knots) was used with the NPD wind spectrum to represent these squalls. The associated current was just less than a meter (1.5 knots), and the associated swell was a 1.5 meter significant wave height with a peak period of 14.0 seconds. No sea conditions were be modeled. The wind and current were assumed to be from the same direction, while the swell was assumed to arrive from a 45 degree sector (from the middle and from either boundary). Table 1 lists the analysis case numbers and the directions from which the swell, wind, and current arrive.

This extremal data set has been constructed from a variety of West African metocean sources and is not meant to represent any specific location, but to be representative of the area in general. These extremal conditions were used to design each mooring system for all seven cases based on the intact mooring system having safety factors of 1.67 at a minimum and with vessel offsets kept to less than 5% of the water depth (50 meters).

The fatigue seastates are listed in Table 2. The seastates were selected from a broader set of fatigue seastates from one West African site. Their number was reduced and the percent of occurrences adjusted so that 70% of the swell arrived head-on to the vessel and 15% each arrived at plus and minus 15 degrees from head-on. The number was reduced to 33 individual cases, which makes for a total of 99 fatigue seastates for all three swell directions. The associated wind was about 6 m/s (12 knots, one-hour wind speed for the NPD wind spectrum) and the associated current was 0.26 m/s (0.5 knots). It was assumed that there was no wind generated sea.

Table 1. Environmental Directions Analyzed for Squall Extremes.

Case #	Swell From:	Wind & Current From:	Case #	Swell From:	Wind & Current From:	Case #	Swell From:	Wind & Current From:
1	S	S	17	SSE	S	33	SSW	S
2	S	SSE	18	SSE	SSE	34	SSW	SSE
3	S	SE	19	SSE	SE	35	SSW	SE
4	S	ESE	20	SSE	ESE	36	SSW	ESE
5	S	E	21	SSE	E	37	SSW	E
6	S	ENE	22	SSE	ENE	38	SSW	ENE
7	S	NE	23	SSE	NE	39	SSW	NE
8	S	NNE	24	SSE	NNE	40	SSW	NNE
9	S	N	25	SSE	N	41	SSW	N
10	S	NNW	26	SSE	NNW	42	SSW	NNW
11	S	NW	27	SSE	NW	43	SSW	NW
12	S	WNW	28	SSE	WNW	44	SSW	WNW
13	S	W	29	SSE	W	45	SSW	W
14	S	WSW	30	SSE	WSW	46	SSW	WSW
15	S	SW	31	SSE	SW	47	SSW	SW
16	S	SSW	32	SSE	SSW	48	SSW	SSW

Table 2. Fatigue Seastate Definitions, from Three Directions.

Swell Hs, m	Swell Tp, s	Wind From:	Current From:	Fatigue Case #	% Occur. From South	Fatigue Case #	% Occur. From S – 15 deg	Fatigue Case #	% Occur. From S + 15 deg
1.5	7.0	SE	SE	1	2.0320	34	0.4354	67	0.4354
2.0	7.0	SW	S	2	0.7039	35	0.1508	68	0.1508
2.5	7.0	S	W	3	0.0250	36	0.0053	69	0.0053
1.5	9.0	SE	N	4	9.3709	37	2.0081	70	2.0081
2.0	9.0	SW	NE	5	4.2386	38	0.9083	71	0.9083
2.5	9.0	S	W	6	0.2946	39	0.0631	72	0.0631
1.5	11.0	SE	S	7	9.8402	40	2.1086	73	2.1086
2.0	11.0	SW	W	8	11.5627	41	2.4777	74	2.4777
2.5	11.0	S	NW	9	1.9870	42	0.4258	75	0.4258
3.0	11.0	SE	N	10	0.2496	43	0.0535	76	0.0535
1.5	13.0	SW	SE	11	8.8168	44	1.8893	77	1.8893
2.0	13.0	S	S	12	7.9930	45	1.7128	78	1.7128
2.5	13.0	SE	W	13	1.9171	46	0.4108	79	0.4108
3.0	13.0	SW	NW	14	0.4343	47	0.0931	80	0.0931
3.5	13.0	S	N	15	0.1298	48	0.0278	81	0.0278
4.0	13.0	SE	NE	16	0.0250	49	0.0053	82	0.0053
1.5	15.0	SW	SE	17	2.4963	50	0.5349	83	0.5349
2.0	15.0	S	S	18	3.0954	51	0.6633	84	0.6633
2.5	15.0	SE	W	19	1.4079	52	0.3017	85	0.3017
3.0	15.0	SW	NW	20	0.3844	53	0.0824	86	0.0824
3.5	15.0	S	N	21	0.0899	54	0.0193	87	0.0193
4.0	15.0	SE	NE	22	0.0150	55	0.0032	88	0.0032
1.5	17.0	SW	SE	23	0.8637	56	0.1851	89	0.1851
2.0	17.0	S	S	24	1.0035	57	0.2150	90	0.2150
2.5	17.0	SE	W	25	0.4493	58	0.0963	91	0.0963
3.0	17.0	SW	NW	26	0.1298	59	0.0278	92	0.0278
3.5	17.0	S	N	27	0.0399	60	0.0086	93	0.0086
4.0	17.0	SE	NE	28	0.0449	61	0.0096	94	0.0096
1.5	19.0	SW	SE	29	0.0749	62	0.0160	95	0.0160
2.0	19.0	S	S	30	0.2197	63	0.0471	96	0.0471
2.5	19.0	SE	W	31	0.0399	64	0.0086	97	0.0086
1.5	21.0	SW	N	32	0.0150	65	0.0032	98	0.0032
2.0	21.0	S	NE	33	0.0100	66	0.0021	99	0.0021
Total:					**70.000%**		**15.000%**		**15.000%**

Additional Assumptions

Vessel

The vessel used for all analyses was nearly 300 meters long and just over 60 meters wide. Vessel particulars, RAOs, and wind and current coefficients from a particular vessel were all used based on an FMC SOFEC project from West Africa. Only the ballast condition was used, for both extremal and fatigue analyses.

Flowlines

The flowlines to the offloading buoy were modeled directly for all analyses. It was assumed that two flowlines, on either side of the vessel centerline and off the stern (except for Case 7), connect to a buoy 2 km away. These flowlines were modeled based on properties of an FMC SOFEC West Africa project. These particular flowlines each exert 130 tonnes of horizontal load on the FPSO, pulling it towards the buoy. The buoy end of the flowlines was assumed to be fixed 2 km away. It should be noted that the change in horizontal load of each line at the FPSO is slight when vessel and buoy offsets are accounted for.

The flowlines between the FPSO and buoy vary among the West Africa projects to date. They may be flexible lines or steel pipe, and their diameter varies. Even their shape in the water column varies by project. However, all are noted to have high horizontal tension components at the end connections. It is important for this study to capture the effect of these high external forces on the FPSO, while the nature of the exact load is not important. If higher flowline loads had been assumed, then short fatigue life estimates would have been calculated. Conversely, if lower flowline loads had been assumed, longer fatigue life estimates would have been calculated. It is the relative comparison of fatigue life calculations in this paper that are important to understand.

Analysis Software

The mooring system design for the extremal cases and the fatigue analyses will use the program Moorsim™, part of the Seasoft mooring analysis package [1]. This is a frequency domain analysis program. This computer program simulates the highly nonlinear dynamics of a spread-moored vessel with multi-element mooring lines. It has been designed to provide a complete, wave-basin-type simulation. It provides detailed mooring line performance data for a particular vessel/mooring line combination under specifiable water depth and environmental conditions. Physical mooring line characteristics, including mass, elastic and hydrodynamic properties of each element of a multi-element mooring line, are fully specifiable.

The mooring line load calculation is fully dynamic and utilizes a proprietary algorithm for the fast and efficient calculation of nonlinear dynamic loads. Long-period oscillations of the system are also characterized and contributions to long-period motions from low-frequency components of variable wind and wave-drift force are computed.

The simulation comprises three distinct phases of calculation: "Static", "low-frequency" (typical periods of oscillation of 1 to 4 minutes) and "high-frequency" or "wave-frequency" (typical periods of oscillation of 3 to 20 seconds).

Utilizing the input wind and current coefficients, Moorsim™ determines the mean offsets and orientation of the vessel and the mean wind, wave and current loads acting on the vessel, which are all reported in a static equilibrium summary.

After the mean loads and vessel offsets have been determined, a low-frequency dynamic analysis is then performed about the mean position. This phase of the analysis takes into account the assumed vessel characteristics, mooring system composition and environmental conditions in the calculation of system damping and low-frequency motions for surge, sway and yaw. Based on the low-frequency analysis of surge, sway and yaw; the significant, maximum and minimum mooring line loads are developed for each mooring line.

In order to determine the maximum and minimum low-frequency system forces (longitudinal, transverse and vertical forces and moments) it is necessary to have a "snapshot" of all line loads for the relevant vessel offsets and orientations. In Moorsim^{TM}, this is accomplished by determining the vessel offset/orientation corresponding to both the maximum and minimum potential energy points of the mooring system.

Having computed system mean and low-frequency motions and loads, the final phase of the analysis involves computation of wave-frequency induced motions and loads. In the computation of wave-frequency line loads, both quasi-static loading (which are a function of mooring line static force-deflection properties) and nonlinear dynamic loading are accounted for. For each and every mooring line in the system, wave-frequency loads are computed at its mean plus significant low-frequency offset or mean plus maximum low-frequency offset. The wave-frequency analysis calls on the program Shipsim^{TM}, described below, to obtain information about the vessel motions in the waves.

Resultant horizontal and vertical wave-frequency vessel motions at the chain stopper locations have been computed using our ship motions computer program Shipsim^{TM}. These unmoored vessel motions have been calculated for the mean relative vessel heading with respect to waves determined from Moorsim^{TM} analysis.

Shipsim^{TM} is a general purpose six degree-of-freedom wave-frequency vessel motions program specifically enhanced for displacement-hull vessels with relatively large block coefficients. Vessels in this category include drillships, barges and tankers.

Shipsim^{TM} utilizes an efficient algorithm for calculating wave-frequency forces and moments which permits accurate simulation using as input only gross hydrostatic and mass properties. Non-linear effects, particularly for roll, are fully simulated, leading to realistic roll response predictions that depend on details of bilge geometry. A wide range of environmental conditions is accommodated. Accelerations, velocities and displacements at any point on the vessel can be computed.

Design Life and Fatigue Life Safety Factors

Typical deepwater West Africa projects also have a long design life, about 20 years, and are often specifically required to have a safety factor of 10 on the calculated fatigue life. Therefore, it was assumed that the mooring chain would have a minimum fatigue life of 200 years. This minimum life was based on the current API RP 2SK guidelines, which is also commonly used for these deepwater West African systems. Fatigue life estimates were also calculated based on the API RP 2SK guidelines that will become effective sometime in early 2005 and for the DNV POSMOOR guidelines for purposes of comparison.

Fatigue Analyses

The fatigue analyses were performed by applying the 99 fatigue seastates to the ballast loaded vessel condition. Three sets of fatigue life calculations were made for each set of analysis cases. These are the API RP 2SK guidelines [2] currently in effect (March, 1997), the API RP 2SK guidelines [3] that will become effective sometime in the early part of 2005, and the DNV POSMOOR guidelines [4]. All calculations were based on the simple summation method, which sum all low frequency and wave frequency damage computations from the RMS low frequency and RMS wave frequency tension variations.

The fatigue damage using the API guidelines is computed from the following equation:

$$D = N * (2^{1/2} * R_{rms})^{M} * \Gamma(1 + M / 2) / K.$$

R_{rms} is the ratio of the tension range to the reference breaking strength, N is the number of cycles, M is the slope of the T-N curve, and K is the intercept of the T-N curve. This damage computation was performed for each LF and WF tension range for all 99 seastates and summed separately for all 12 mooring legs.

For the current API RP 2SK guidelines, the values for M and K are M=3.36 and K=370 for chain (studless or studlink). The reference breaking strength is the assumed strength of ORQ grade chain after half of the wear and corrosion allowance is applied. The required factor of safety on fatigue life for areas that cannot be inspected is 10.

The above equation is still used in the next generation API RP 2SK guidelines, but the M and K values and the required safety factors change. The values for M and K are M=3.00 and K=316 for studless chain. The reference breaking strength is the assumed strength of R3 grade chain after half of the wear and corrosion allowance is applied. The required factor of safety on fatigue life is 3.

The DNV POSMOOR guideline has fatigue calculations based on stresses in the chain. The equation for damage for each seastate is:

$$d_{NBi} = v_{0i} * T_i * (2 * 2^{1/2} * \sigma_{Si})^{m} * \Gamma(1 + m / 2) / a_D.$$

Here σ_{Si} is the standard deviation of the stress, $v_{0i}*T_i$ is the number of cycles, m is the slope of the S-N curve, and a_D is the intercept of the S-N curve. This damage computation was performed for each LF and WF tension range for all 99 seastates and summed separately for all 12 mooring legs. The values for m and a_D for studless chain are m=3.0 and a_D=6.0E10. The area used for the stress calculation is based on a chain diameter after half the wear and corrosion allowance is applied, and multiplied by two for both sides of the link. The POSMOOR code does not have a specific safety factor to apply to the fatigue life. Rather, it is based on a ratio of tensions in adjacent mooring lines. However, this safety factor is 8 at the most.

Results

The results of all the analyses are summarized in this paper individually on seven pages of tables, one page per mooring case, with each page labeled at the bottom by case number. Each summary page contains a table at the top of the page that indicates the mooring leg pretensions (the tension in each leg with zero environment applied), the fairlead to anchor distance (EPS), and the maximum mooring line load from the 48 cases of extreme squall analyses. Embedded within this table is an offset graph showing the maximum offset position of the vessel midships for all 48 cases. Each graph shows the maximum allowable offset envelope of 50 meters (5% of water depth) and 48 discreet data points. For most of the graphs presented, at the small scale on each page, the data points plot nearly on top of each other for cases that vary only by swell direction. (See Table 1, where 16 different wind and current directions are analyzed for 3 different swell directions.)

Each summary page also contains a table at the bottom of the page that indicates the results of the fatigue analysis. Case 1 shows fatigue life calculations for both the chain at the fairlead and chain at the anchor end, while all other cases show fatigue analysis results for only the chain at the anchor, but calculated for two different sizes of chain.

Between the summary tables for each case is a description of the mooring component sizes needed for both the chain and the wire rope. A wire rope size is estimated based solely on the intact mooring system analysis of the squall extremes, as presented in the table at the top of each page. Wire rope sizes were estimated from Bridon Xtreme sheathed spiral strand, and used standard sizes available to obtain something close to the 1.67 safety factor required. The equivalent chain size needed to match the strength of the wire is also listed, based on R4 chain. Fatigue calculations are presented for the strength-sized chain on the left side of each fatigue summary table, while the fatigue life estimates shown on the right side of each summary table (except for Case 1) are for the smallest size chain that passes the fatigue requirements of the current API RP 2SK guidelines.

Case 1, the Base Case without Flowlines, has component sizes entirely governed by strength. The vessel offsets shown are close to the allowable limit, and all mooring legs see maximum loads within a similar range. The R4 chain needed to meet the strength requirements easily exceeds the required minimum fatigue life for all three types of fatigue life calculations. Note that the fatigue life estimate of the chain at the anchor end is slightly less than that at the fairlead, and that the legs into the swells (1-3 and 10-12) have the lowest fatigue life. (All other cases will list the fatigue life estimates only at the anchor end.) Note that the mooring leg pretensions are at 12% of the wire minimum break load (MBL).

The approximate total weight of the chain and wire components is based on a total of 150 meters of chain per leg and 1300 meters of wire per leg, for total lengths of 1800 meters of chain and 15,600 meters of wire. (This total chain length will be used for all other case comparisons, but the wire lengths will change for cases with increased EPS values.) The total chain and wire weight of Case 1 is:

Chain: 1800 m * 206.9 kg/m * 1 t/1000 kg = 372 tonnes,
Wire: 15,600 m * 39.9 kg/m * 1 t/1000 kg = 622 tonnes.

The addition of the flowlines for the remaining cases dramatically alters the mooring system. The vessel offsets will not efficiently use the allowable limits, and the maximum mooring line loads will be very different by groups, making some legs over designed for both strength and fatigue. Understanding the difference between Case 1 and all other cases is important to understanding why a FEED study that does not include flowline and riser loads is an inadequate representation of the mooring system for design layouts.

Case 2, the Base Case with Flowlines, has the wire governed by strength and the chain governed by fatigue. Note the asymmetry in pretensions for the mooring legs opposing the flowlines (legs 1-3 and 10-12) and those on the same side of the vessel as the flowlines. This is because the mooring leg tensions were adjusted to keep the FPSO near its defined location. If the flowlines are added to an identical mooring system as in Case 1 without any tension adjustments, the externally applied load from the flowlines causes the vessel to move 48 meters closer to the buoy, almost the entire offset limit. While some projects might allow for an intermediate amount of static offset due to this applied load, this study has been undertaken with the assumption that the vessel needs to be positioned near its target location, and so Cases 2-7 have mooring leg tension adjustments to keep the vessel within a few meters of its target.

Case 2 has larger maximum line loads than Case 1 and requires bigger wire. Furthermore, the chain sized equivalently for strength has a miserably low fatigue life estimate of less than 30 years, and requires much larger chain (although of lesser grade than R4) to have a minimum 200 year fatigue life based on current API RP 2SK guidelines. Note the mooring leg pretensions are about 20% of the wire MBL in the higher tension legs. The total chain and wire weight for this system (based on the same lengths as Case 1) is:

Chain: 1800 m * 525 kg/m * 1 t/1000 kg = 945 tonnes, (573 tonnes more than Case 1!)
Wire: 15,600 m * 49.6 kg/m * 1 t/1000 kg = 774 tonnes. (152 tonnes more than Case 1!)

In addition to the extra chain and wire weight, the suction piles would be larger since they would have to be designed for a bigger load, the pull-in equipment on the FPSO would need to have a much larger capacity, the chain stoppers and fairleads would increase in size and weight, and the installation equipment, such as wildcat wheels to handle chain, cranes to lift wire rope reels, etc., would all need to be bigger or have larger capacities. And this just for a system with a chain size that barely meets the fatigue requirements, let alone one that has as comfortable margins as Case 1.

Case 2 is in our opinion an example of mooring system design constraints taken to an extreme. For example, if the seabed placement and routing of pipelines, risers, and umbilicals really required that the mooring leg endpoint separations be restricted to a distance equal to the water depth, adding an additional mooring leg to each of the groups into the swell would greatly improve the fatigue life of those mooring legs and would help reduce the required wire size since the maximum loads would be shared among more legs. This option would require additional cost in day rates for offshore installation since two more piles would be installed and hooked up to the vessel, and might not be the most cost effective solution, but would nonetheless be preferable from a mooring design standpoint.

Other changes that could be made to the mooring system to accommodate the flowline loads would include adjusting the mooring leg plan angles and increasing the anchor endpoint separation (EPS) distances if allowed by the field layout. This paper will focus only on changing the EPS distance, which often appears to be acceptable from project field layouts we have seen.

The Case 2 fatigue life calculations for the 162 mm studless chain (based on 158 mm chain after corrosion and wear allowances) meets the safety factor of 10 required by the current API RP 2SK guidelines. Using the API RP 2SK guideline that will become effective next year (third edition), the safety factor is not quite the required value of 3. The chain size increase to accommodate this factor of safety would not be large. However, if this hypothetical project were supposed to satisfy both the third edition API RP 2SK and a safety factor of 10, the chain size would have to increase dramatically over the 162mm chain.

The Case 2 fatigue life calculations for the POSMOOR guidelines for the 162 mm chain do not meet the maximum fatigue life safety factor of 8 as given in POSMOOR. (20 years * 8 = 160 years.) This requirement on this hypothetical system would also require significantly larger chain than 162mm.

Too emphasize this point, a company should take care when specifying a fatigue life factor of safety, if different from their chosen guideline requirement, as this could cause the chain size to increase remarkably beyond what the guideline requires.

Cases 3 through 6 have the mooring legs into the swell successively increase EPS values by 10% of water depth increments to assess the resulting fatigue life estimates of the mooring chain. With each increase in EPS allowed, the minimum fatigue life of 200 years is attained with smaller and smaller chain. In fact, Case 6 illustrates an example for which the chain size required to meet the fatigue life is not quite strong enough to give a 1.67 factor of safety on the intact mooring system throughout its 20 year design life.

The total chain and wire weights for Cases 3 through 6 are listed below.

Case 3

Chain: 1800 m * 408.8 kg/m * 1 t/1000 kg = 736 tonnes,
Wire: (6*1300+6*1365) m * 47.6 kg/m * 1 t/1000 kg = 761 tonnes.
Pretension about 19% of the wire MBL in higher tension lines.

Case 4

Chain: 1800 m * 343 kg/m * 1 t/1000 kg = 617 tonnes,
Wire: (6*1300+6*1440) m * 44.9 kg/m * 1 t/1000 kg = 738 tonnes.
Pretension about 21% of the wire MBL in higher tension lines.

Case 5

Chain: 1800 m * 274 kg/m * 1 t/1000 kg = 493 tonnes,
Wire: (6*1300+6*1525) m * 42.2 kg/m * 1 t/1000 kg = 715 tonnes.
Pretension about 21% of the wire MBL in higher tension lines.

Case 6

Chain: 1800 m * 229 kg/m * 1 t/1000 kg = 412 tonnes,
Wire: (6*1300+6*1600) m * 39.9 kg/m * 1 t/1000 kg = 694 tonnes.
Pretension about 22% of the wire MBL in higher tension lines.

Figure 2 is a bar graph showing the total chain and wire weights for Cases 1-6. The weights are indicative of a cost difference, with additional cost impact due to larger chain stoppers and fairleads, different pull-in capacity requirements, and larger piles as the design loads increase.

Case 7 has been included in the study to illustrate that it is not just the fact that the mooring legs into the swell are prone to fatigue problems. Case 7 is a sort of inverted example of Case 2, as the pretensions indicate, but with the flowlines 180 degrees away from their orientation in Case 2. For Case 7, the mooring legs 4 through 9 balance the applied loads from the flowlines, and although they are lines that slacken in swell, their tension ranges in fatigue seastates still produce enough damage that chain sizes are governed by fatigue.

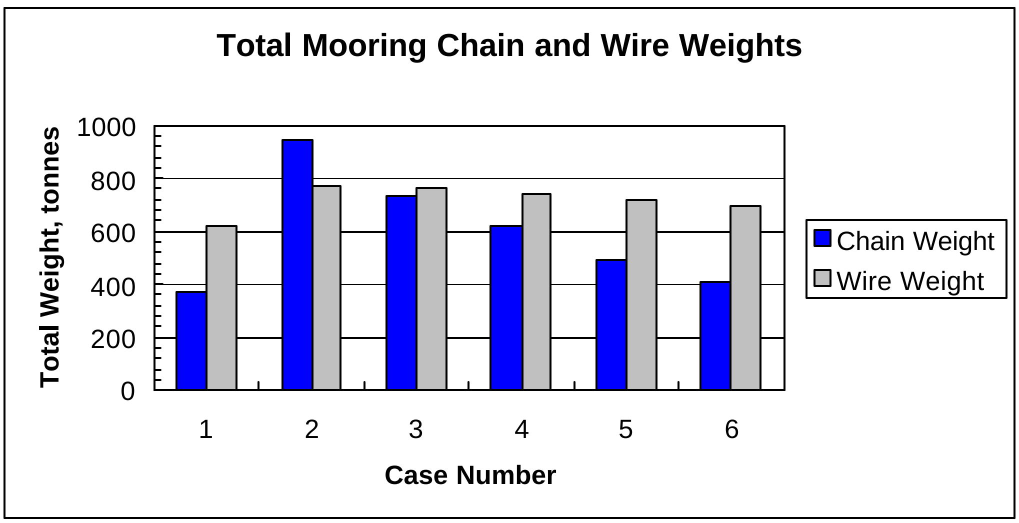
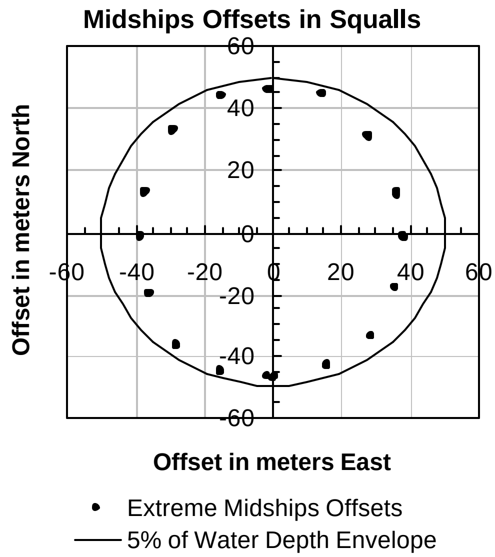


Figure 2. Bar chart showing the total chain and wire weights required for Cases 1 through 6 in order to meet the current API RP 2SK guidelines.

Table 3. Summary Results for Case 1 (Base Case System with No Flowlines).

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	107	1000	531
2	107	1000	493
3	107	1000	459
4	107	1000	432
5	107	1000	485
6	107	1000	537
7	107	1000	504
8	107	1000	463
9	107	1000	414
10	107	1000	459
11	107	1000	467
12	107	1000	500



Estimated Size for Sheathed Spiral Strand Wire Rope:
892 tonne MBL (SF 1.68), 90 mm plus jacket
Equivalent Chain Size: 103 mm studless R4 chain
1060 tonne BS new
918 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
Fatigue calculations based on 99 mm chain (0.4 mm/yr for half the design life)

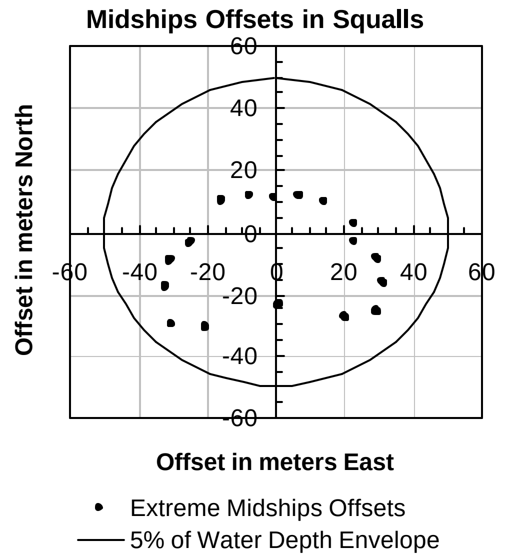
Table 4. Estimated Chain Fatigue Life Using Three Sets of T-N or S-N Curves.

Mooring Leg #	Fatigue Life at Fairlead (years)			Fatigue Life at Anchor (years)		
	API RP 2SK March ‘97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March ‘97	API RP 2SK Early 2005	POSMOOR June 2001
1	2239	526	380	2218	521	376
2	2374	555	401	2345	548	396
3	2526	587	424	2489	579	418
4	14713	2941	2125	14943	2979	2152
5	16179	3190	2304	16614	3261	2356
6	17673	3442	2486	18376	3555	2568
7	17746	3441	2485	18934	3617	2612
8	16525	3232	2335	17374	3358	2425
9	15342	3027	2186	15912	3112	2248
10	2685	606	438	2673	602	435
11	2504	570	412	2502	567	409
12	2339	537	388	2347	535	386
Based on Chain:	99 mm ORQ 761 tonnes	99 mm R3 804 tonnes	99 mm diameter	99 mm ORQ 761 tonnes	99 mm R3 804 tonnes	99 mm diameter

Case 1

Table 5. Summary Results for Case 2 (Base Case System with Flowlines).

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	221	1000	654
2	221	1000	641
3	221	1000	655
4	110	1000	270
5	110	1000	275
6	110	1000	276
7	110	1000	248
8	110	1000	250
9	110	1000	248
10	221	1000	634
11	221	1000	623
12	221	1000	622



Estimated Size for Sheathed Spiral Strand Wire Rope:
1106 tonne MBL (SF 1.69), 100 mm plus jacket
Equivalent Chain Size for Strength: 114 mm studless R4 chain
1266 tonne BS new
1115 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
Fatigue calculations based on 110 mm chain (0.4 mm/yr for half the design life)
Chain Size Needed to meet Fatigue Requirements:
162 mm Studless ORQ or 162 mm Studless R3
Fatigue calculation based on 158 mm chain (0.4 mm/yr for half the design life)

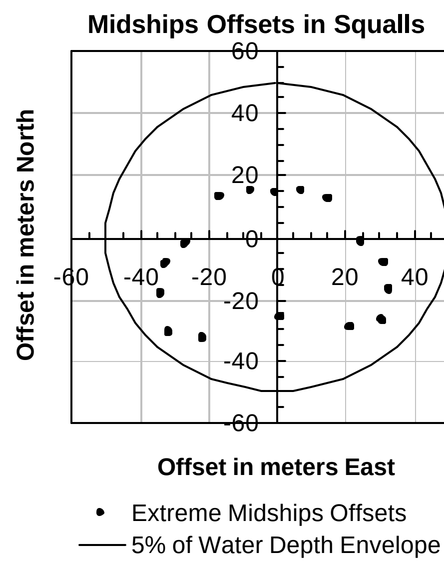
Table 6. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	27	9	7	215	58	64
2	28	9	7	217	59	65
3	28	9	8	219	60	66
4	118640	18951	15004	935340	119755	131763
5	123815	19642	15551	976136	124120	136566
6	128615	20271	16049	1013984	128098	140943
7	128708	20279	16055	1014714	128146	140996
8	123969	19633	15544	977354	124061	136502
9	119304	19014	15054	940571	120155	132204
10	28	9	7	217	59	65
11	27	9	7	215	58	64
12	27	9	7	212	57	63
Based on Chain:	110mmORQ 911 tonnes	110mm R3 963 tonnes	110 mm diameter	158mmORQ 1685 tonnes	158 mm R3 1780 tonnes	158 mm diameter

Case 2

Table 7. Summary Results for Case 3 System with Flowlines EPS increased 10%.

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	204	1100	620
2	204	1100	601
3	204	1100	615
4	110	1000	281
5	110	1000	287
6	110	1000	289
7	110	1000	260
8	110	1000	261
9	110	1000	259
10	204	1100	602
11	204	1100	593
12	204	1100	589



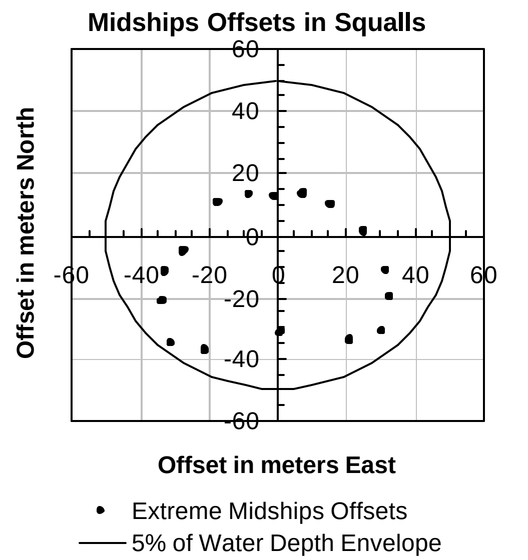
Estimated Size for Sheathed Spiral Strand Wire Rope:
    1065 tonne MBL (SF 1.72), 98 mm plus jacket
Equivalent Chain Size for Strength: 110 mm studless R4 chain
    1190 tonne BS new
    1042 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
    Fatigue calculations based on 106 mm chain (0.4 mm/yr for half the design life)
Chain Size Needed to meet Fatigue Requirements:
    143 mm Studless ORQ or 143 mm Studless R3
    Fatigue calculation based on 139 mm chain (0.4 mm/yr for half the design life)

Table 8. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	44	14	21	211	58	109
2	46	15	22	218	60	113
3	47	15	23	225	62	116
4	99363	16160	23925	473825	65183	121647
5	103356	16706	24733	492864	67386	125758
6	106896	17182	25439	509744	69307	129345
7	107056	17189	25449	510508	69334	129395
8	103360	16693	24715	492882	67335	125663
9	99510	16166	23934	474524	65208	121694
10	47	15	23	224	62	115
11	45	15	22	217	60	111
12	44	14	21	210	57	107
Based on Chain:	106mmORQ 858 tonnes	106 mm R3 907 tonnes	106 mm diameter	139mmORQ 1367 tonnes	139mm R3 1444 tonnes	139 mm diameter

Table 9. Summary Results for Case 4 System with Flowlines EPS increased 20%.

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	215	1200	580
2	215	1200	568
3	215	1200	593
4	110	1000	289
5	110	1000	300
6	110	1000	309
7	110	1000	276
8	110	1000	273
9	110	1000	267
10	215	1200	571
11	215	1200	551
12	215	1200	549



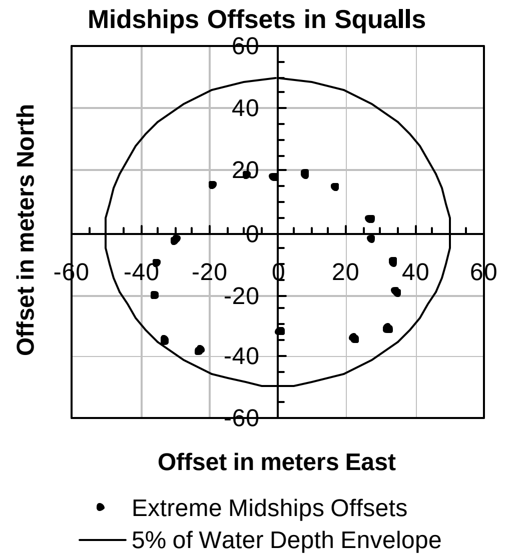
Estimated Size for Sheathed Spiral Strand Wire Rope:
1004 tonne MBL (SF 1.69), 95.5 mm plus jacket
Equivalent Chain Size for Strength: 108 mm studless R4 chain
1152 tonne BS new
1006 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
Fatigue calculations based on 104 mm chain (0.4 mm/yr for half the design life)
Chain Size Needed to meet Fatigue Requirements:
131 mm Studless ORQ or 131 mm Studless R3
Fatigue calculation based on 127 mm chain (0.4 mm/yr for half the design life)

Table 10. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	71	22	32	226	63	107
2	69	22	32	222	62	106
3	68	22	31	217	61	104
4	84284	13969	20400	269935	39499	67648
5	87779	14457	21113	281126	40879	70011
6	91162	14919	21787	291960	42184	72247
7	91625	14943	21823	293443	42254	72367
8	88463	14515	21198	283317	41044	70293
9	85296	14075	20555	273176	39799	68162
10	68	21	31	216	60	103
11	69	22	32	221	61	105
12	70	22	32	225	62	106
Based on Chain:	104mmORQ 830 tonnes	104mm R3 877 tonnes	104 mm diameter	127mmORQ 1174 tonnes	127mm R3 1241 tonnes	127 mm diameter

Table 11. Summary Results for Case 5 System with Flowlines EPS increased 30%.

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	198	1300	553
2	198	1300	532
3	198	1300	552
4	110	1000	302
5	110	1000	317
6	110	1000	325
7	110	1000	288
8	110	1000	286
9	110	1000	279
10	198	1300	539
11	198	1300	522
12	198	1300	523



Estimated Size for Sheathed Spiral Strand Wire Rope:
944 tonne MBL (SF 1.71), 92.5 mm plus jacket
Equivalent Chain Size for Strength: 104 mm studless R4 chain
1078 tonne BS new
935 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
Fatigue calculations based on 100 mm chain (0.4 mm/yr for half the design life)
Chain Size Needed to meet Fatigue Requirements:
117 mm Studless ORQ or 117 mm Studless R3
Fatigue calculation based on 113 mm chain (0.4 mm/yr for half the design life)

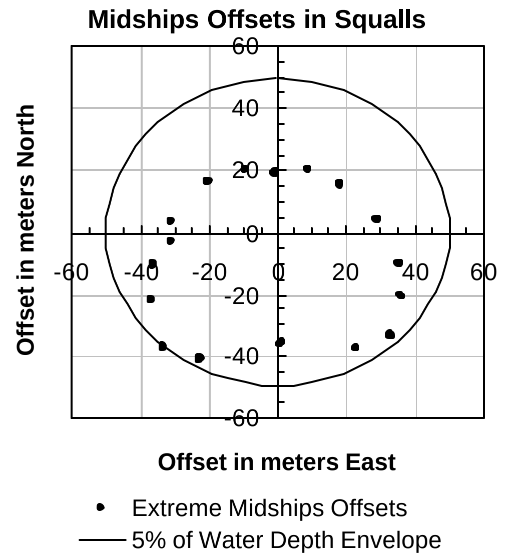
Table 12. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	103	31	44	212	60	93
2	104	32	45	215	61	94
3	105	32	46	217	62	96
4	69903	11810	16797	144059	22525	34971
5	72678	12186	17332	149778	23242	36085
6	75354	12563	17869	155291	23962	37202
7	75491	12578	17890	155575	23990	37245
8	72806	12198	17349	150040	23265	36120
9	70086	11818	16809	144435	22541	34995
10	106	32	46	218	61	95
11	104	32	45	215	60	94
12	102	31	44	211	59	92
Based on Chain:	100mmORQ 774 tonnes	100mm R3 818 tonnes	100 mm diameter	113mmORQ 960 tonnes	113mm R3 1015 tonnes	113 mm diameter

Case 5

Table 13. Summary Results for Case 6 System with Flowlines and EPS increased 40%.

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	198	1400	525
2	198	1400	508
3	198	1400	525
4	110	1000	313
5	110	1000	331
6	110	1000	344
7	110	1000	303
8	110	1000	299
9	110	1000	289
10	198	1400	507
11	198	1400	489
12	198	1400	496



Estimated Size for Sheathed Spiral Strand Wire Rope:
892 tonne MBL (SF 1.70), 90 mm plus jacket
Equivalent Chain Size for Strength: 101 mm studless R4 chain
1023 tonne BS new
883 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)
Fatigue calculations based on 97 mm chain (0.4 mm/yr for half the design life)
Chain Size Needed to meet Fatigue Requirements:
107 mm Studless ORQ or 107 mm Studless R3
Fatigue calculation based on 103 mm chain (0.4 mm/yr for half the design life)

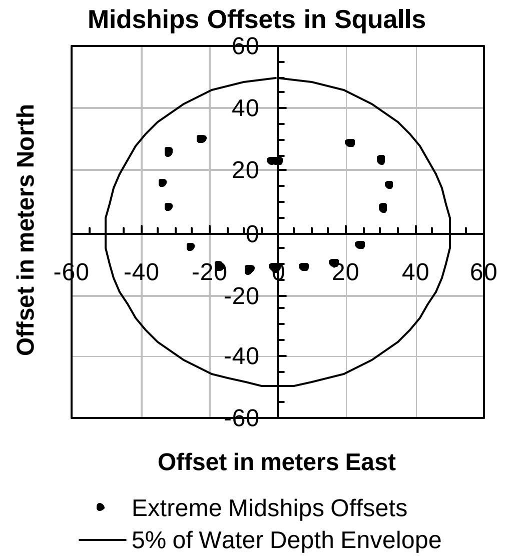
Table 14. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	142	42	46	204	58	84
2	143	43	46	205	59	85
3	144	43	47	206	59	86
4	57690	9946	10770	82595	13702	19877
5	60132	10286	11138	86091	14170	20557
6	62521	10625	11506	89512	14638	21235
7	62563	10626	11507	89572	14639	21236
8	60353	10316	11171	86408	14212	20617
9	57946	9966	10792	82961	13729	19917
10	144	43	46	207	59	86
11	144	42	46	206	58	85
12	142	42	45	203	58	84
Based on Chain:	97 mm ORQ 733 tonnes	97 mm R3 775 tonnes	97 mm diameter	103mmORQ 816 tonnes	103mm R3 862 tonnes	103 mm diameter

Case 6

Table 15. Summary Results for Case 7 System with Flowlines into Swell.

Mooring Leg Number	Pretension Tonnes	Fairlead to Anchor Distance meters	Maximum Line Load (Squalls) Tonnes
1	110	1000	286
2	110	1000	291
3	110	1000	291
4	221	1000	651
5	221	1000	648
6	221	1000	666
7	221	1000	644
8	221	1000	625
9	221	1000	619
10	110	1000	283
11	110	1000	274
12	110	1000	265



Estimated Size for Sheathed Spiral Strand Wire Rope:

1147 tonne MBL (SF 1.72), 102 mm plus jacket

Equivalent Chain Size for Strength: 114 mm studless R4 chain

1266 tonne BS new

1115 tonne BS after 20 years (based on 0.4 mm/yr wear and corrosion allowance)

Fatigue calculations based on 110 mm chain (0.4 mm/yr for half the design life)

Chain Size Needed to meet Fatigue Requirements:

136 mm Studless ORQ or 136 mm Studless R3

Fatigue calculation based on 132 mm chain (0.4 mm/yr for half the design life)

Table 16. Estimated Chain Fatigue Life (years) at Anchor for Three Sets of T-N or S-N Curves.

Mooring Leg #	For Chain Size Matched to Wire MBL			For Chain Size Needed for Fatigue		
	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001	API RP 2SK March '97	API RP 2SK Early 2005	POSMOOR June 2001
1	41620	7056	5494	119236	18053	16405
2	40550	6911	5382	116169	17684	16069
3	39491	6772	5273	113138	17329	15746
4	77	25	19	220	63	57
5	81	26	20	232	66	60
6	85	27	21	243	69	62
7	85	27	21	243	68	62
8	81	26	20	233	66	60
9	77	25	19	221	63	57
10	41148	6937	5402	117885	17750	16130
11	42215	7080	5513	120940	18115	16461
12	43273	7223	5624	123972	18481	16794
Based on Chain:	110mmORQ 916 tonnes	110mm R3 968 tonnes	110 mm diameter	132mmORQ 1253 tonnes	132mm R3 1324 tonnes	132 mm diameter

Case 7

Conclusions

The research presented in this paper was an ambitious study undertaken with the goal of educating the audience in how the field layout decisions can adversely affect the fatigue life of the mooring chain. A summary of the points discussed and deduced in the Results section is as follows:

- A mooring system analyzed without its flowlines cannot be considered to be an equivalent system as one with the flowlines included.
- Increasing the allowable anchor to fairlead distances (endpoint separations) is an effective means of increasing the fatigue life of the chain without resorting to massive chain sizes.
- Fatigue damage can occur in mooring legs away from the swell, not just in mooring legs into the swell.
- The pretension expressed as a percent of wire minimum break load (or even chain break strength) is an unreliable predictor of potential fatigue problems.

There are further lessons from this research that can be extrapolated to field layout design philosophies. As mooring designers, we would like to suggest that the following points be considered for their relative importance when a field layout is developed:

- Positioning the flowline connection point at the vessel with either a plan angle or bcation that causes a moment about the FPSO midships will also require increased mooring line tensions to counter this effect, causing potential fatigue problems in those mooring legs. (Significant moments induced on the vessel would result in changes to the vessel heading, which then would affect the angle of incidence between the swell and the vessel.)
- Geotechnical investigations of the seabed should include a variety of assumed mooring leg endpoint separation distances for legs expected to be countering high external load or moments. Investigation of a slight range of mooring leg plan angles would be beneficial to the mooring system design.
- FEED studies must include the effects of the flowlines and all risers on the mooring system. Although not covered in this study, West Africa projects tend to have a very large number of risers connected to the side (or sides) of the vessel, which in sum can exert tremendous horizontal loads on the FPSO that must also be balanced by the mooring system.
- Companies should be open-minded about the possibility of reducing the number of mooring legs in groups that have very low maximum line loads and high fatigue life estimates. For example, if it was important for Case 2 to have limited EPS distances, an option to evaluate could be 4 legs in each group away from the flowlines and 2 legs in each group on the side of the flowlines, thus still having a 12 leg system, but with more reasonably sized chain and wire that is efficiently used in all leg groups.
- Companies should take care when specifying a required fatigue life safety factor, especially as API RP 2SK guidelines change. Refer to the Case 1-7 fatigue tables to see how the fatigue life estimates vary by guideline applied, and note that each guideline has its own recommended factor of safety. A requirement of a fatigue life safety factor of 10 when the

new API guideline comes into effect will result in extremely large chain sizes or the addition of mooring legs just to accommodate this criteria.

It is also important to note that although other fatigue analysis methods are available, for example Rainflow Cycle Counting, or the use of a combined spectrum rather than simple summation, these conclusions would still remain valid. Rather than interpreting the results presented here to indicate a specific chain size is required, it should be interpreted as a comparison between sizes needed for different constraints on the system.

References

1. User Manual for Moorsim™ and SPMsim™, Comprehensive Catenary-Based Simulation Software, Seasoft Systems.

2. Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, API RP 2SK, March 1997.

3. Design and Analysis of Stationkeeping Systems for Floating Structures, API RP 2SK, Third Edition, Draft. Effective date sometime in 2005.

4. Offshore Standard DNV-OS-E301, Position Mooring, June 2001.