Final Report

Contract No.: M09PC00005

Evaluate New Materials for Deepwater Synthetic Mooring Systems

Response to Solicitation Number M08PS00074,

Issued by the Minerals Management Service

U. S. Department of Interior,

Posted date: May 19, 2008

White Paper Objective:

Item 1:

"Compare materials for use in construction of a synthetic mooring system (polyester, High modulus polyethylene-HMPE, Kevlar, etc)"

Submitted: April 15, 2010

Applicant:

Stress Engineering Services, Inc.

PN 118189

STRESS ENGINEERING SERVICES INC.

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Evaluate New Materials for Deepwater Synthetic Mooring Systems

Summary

This report is divided into two parts:

- Part A covers the mooring system sensitivity study we conducted to determine under what conditions advanced fiber ropes - having a higher rope axial stiffness than polyester - would be needed. We learned that for water depths from 5000 to 15000 feet, polyester ropes will continue to be practical, and they are cost effective. The key learning from this part is that the steel components in the mooring leg create a catenary effect between fiber rope segments, so the mooring system is really semi taut, rather than taut line. As a result the axial stiffnesses of the rope segments are less of a factor affecting mooring system response than we would otherwise believe.
- Part B covers the mechanical properties of the fibers that are brought together to form the ropes, as well as the mechanical properties of the fiber ropes. Key rope properties for a variety of advanced fibers are compared with that of polyester. In addition we show the tests and analyses that are needed in detailed design to confirm the structural integrity of the rope product. Overall, API RP 2SM (Ref. 1) was found to apply well to fiber ropes other than polyester, but there are four parts of this report which can complement the recommended practice for advanced fibers and ropes.

Introduction/Objectives

In this report we compare and contrast - with polyester - some advanced fiber materials for use in construction of a deepwater synthetic mooring system. The term “advanced fiber” generally refers to improved thermal, chemical and mechanical properties with higher-modulus “stiffer” fibers than polyester. Advanced materials evaluated include, for instance, aramids, HMPE and, PEN.

Specific objectives of this report are:

1. Compare and contrast the risks and benefits of using stiffer synthetic fibers vs. polyester fibers for mooring rope design, manufacturing, installation and long-term operations. Perform this study based on the last decade polyester mooring experience in the GOM (embodied in API RP 2SM (Ref 1) and revisions to it in progress), rather than the 1998 Engineers Design Guide (Ref 2). However bring forward parts of the EDG that are still valid and appropriate.
2. By theoretical analysis, compare dynamic responses of typical floaters moored with polyester segments and with stiffer fiber segments. This objective is essential because any mooring system design must satisfy the response and station-keeping requirements of the floater type.
3. Using the same format as API 2SM, provide updated information for advanced fibers providing specific design guidance on mooring systems incorporating rope segments from stiffer advanced fibers than polyester. This update would provide a quick reference guide for considering new fiber alternatives, and would be available to the API RP 2SM committee for their actions. Included would be a matrix of properties, attributes, strengths, weaknesses, etc., of each material as well as a short discussion of the most appropriate applications for each and any specific situation or use which should be avoided.
4. Determine which advanced materials will offer the greatest promise of fulfilling the MMS criteria of “meeting or exceeding” traditionally accepted practice (polyester). Identify the high risk issues that are peculiar to each fiber material type, rope design and splice design, and how those risks can be controlled.

Scope of Work

In part A, we have performed engineering analyses and evaluations to explore the opportunity to utilize newer stiffer synthetic fibers along with traditional polyester in rope segments comprising deepwater and ultra deep water mooring systems. We view synthetic fiber ropes as normal structural engineering components having a relatively complex viscoelastic behavior. The fiber manufacturers have provided technical data

on their products for us to compare and contrast, and rope manufacturers offer subrope/rope and splice designs using yarns from those fibers.

The purpose of this report is to show the application of advanced fibers such as PEN, aramid, LCP and HMPE to the mooring of deepwater floating production systems (FPS) and Mobile Offshore Drilling Units (MODU), where polyester fiber ropes have been almost exclusively used to date.

The reader is referred specifically to the 2004 Handbook of Fibre Rope Technology (Ref 3) for a wealth of up to date design information on fiber ropes, and to API RP 2SM (Ref 1) for recommended practices for manufacture, installation and maintenance of synthetic fiber ropes for offshore moorings.

Please be advised that the data and results contained in this report are NOT for purposes of performing project specific mooring systems: they are merely provided to demonstrate similarities and differences of various advanced fiber ropes with polyester ropes for use in FEED (front end engineering design) studies prior to detailed design.

Part A: Conclusions

Based on the sensitivity study results using the RAMS software for the DeepStar medium semi-submersible we studied, and considering three different water depths (5,000 ft, 10,000 ft and 15,000 ft), the following conclusions are offered:

1. Low modulus polyester ropes are viable for all water depths studied.
2. High-modulus (aramid, HMPE) fibers and medium modulus (PEN) ropes are viable as well.
3. A catenary effect is caused by the weight of steel components in the fiber rope mooring legs, and that catenary effect causes the mooring system to be semi-taut, rather than taut-line.

4. Due to the catenary effect, a high-modulus fiber rope with an in-line stiffness 3 times that of polyester will increase the effective lateral spring constant of the mooring leg only 80 % (approximately) over polyester in a 100-year hurricane for all water depths. Only HMPE, due to its nonlinear creep, might need to be considered as a special case for evaluation.

Part A: Recommendations

The sensitivity study analysis discussed in this part is based on a frequency domain analysis using RAMS software. If a detailed design analysis is required, it would be prudent to conduct selected time-domain analyses to supplement and validate the frequency domain study results.

Also, a 4-column medium semi-submersible hull was the subject of this particular study. It would be prudent to conduct a similar study for a typical spar shape and a FPSO vessel shape. Project funds did not permit evaluations of the spar and vessel shapes.

In Part B which follows, we have investigated the comparative properties of various advanced fibers of interest, and then we show how the mechanical properties of the fibers transfer into the fiber rope properties.

Part B: Conclusions

1. Descriptive data has been summarized for polyester, PEN, Aramid, HMPE, and LCAP.
2. Polyester is the lowest modulus fiber we considered for deepwater applications. On the stiffer end of advanced fibers are aramid, and LCAP at three times the stiffness of polyester, and PEN is a medium stiffness fiber at two times the stiffness of polyester. HMPE – because of non-linear creep – is a special consideration.
3. HMPE has an issue with non-linearly increasing creep (elongation over time with a constant load applied), while aramids have the issue of compressive cyclic loadings and fatigue to be dealt with.
4. Since yarn-on-yarn testing comparisons of various advanced fibers with polyester are not considered valid for determining abrasion effects during rope cycling, a strand-on strand (20-hurricane) test method is recommended instead.
5. Methods for confirming advanced fiber rope and rope splice designs have been recommended to ensure that safe rope designs are the result. Key engineering properties to address by test and analysis are full rope Minimum Breaking Load and elongation testing, rope splice slip factor of safety, mooring rope (or subrope) axial stiffness, effective horizontal system stiffness, rope abrasion and cyclic wear, rope fatigue, rope axial compression and rope creep elongation.
6. For purposes of FEED studies, a table of nominal rope stiffnesses are provided for analysis purposes.
7. General regulatory requirements are offered, and key enhancements to API RP 2SM are suggested.

FIBER AND ROPE PROPERTIES COMPARISON MATRIX

	Polyester PET	PEN	Aramid	HMPE	LCAP	Steel
Main Characteristics	Well established properties	Improved thermal, chemical and mechanical performance	Very low creep, poor axial compression fatigue performance, needs marine finish to improve abrasion resistance	High Creep resistance, very high strength to weight ratio, Excellent dynamic toughness	Low Creep	
Creep at 50% Load	Good	Good	Good	Increases nonlinearly with time.	Good	Good
Properties when wet	Same	Same	Same	Same	Same	Same
Strength to Weight Ratio	Good	Very good	Excellent	Excellent	Excellent	Low
Axial compression fatigue performance	Good	Good	Poor	Good	Good	Good
Cost	Low	High	High	High	High	
Melting Point °F	496	515	800***	300	625	
% Elongation at 100% MBL	13%	6%	2.40%	2.40%	~4%	1.4
Fiber Modulus Gpa	15	43.5	105	143.5	91	150
Fiber Density g/cc	1.39	1.36	1.42	0.97	1.47	8
Modulus N/tex	10.79	31.99	73.94	147.94	61.90	18.75
Friction Coefficient Relative to Polyester	1		1.82*	0.65	1.53	
Intermediate Stiffness**	15 * MBL	20 * MBL	35 * MBL	60 * MBL		
Storm Stiffness	30 * MBL	39 * MBL	70 * MBL	90 * MBL		
Approximate Diameter in mm for 400 Ton and 1000 Ton rope	107-193		80-125	80-125	80-125	80-125

* Marine finish can greatly affect results
** MBL = Minimum Breaking Load
*** Does Not Melt - Decomposes

Part B: Recommendations

1. Advanced fiber test results are needed from strand-on-strand testing, considering windward lines and leeward lines, to compare with existing results from polyester ropes.

PARTS A and B REPORT

Background

The White Paper request that formed the basis of this scope of work asked us to: **"Evaluate New Materials for DW Synthetic Mooring Systems (polyester, High modulus polyethylene-HMPE, Kevlar, etc).** Many new materials are being proposed for construction of synthetic moorings. Investigate the current construction materials as well as alternative materials and provide a comparison of each, including a quick reference guide for reference when considering new alternatives. The desired outcome should include a matrix of properties, attributes, strengths, weaknesses, etc., of each material as well as a short discussion of the most appropriate uses for each and any specific situation or use which should be avoided. The matrix of different synthetic materials and their properties also needs to include any updated information since the Engineer's Design Guide (Ref 2) was published as well as a summary of that data."

Approach

Our approach in responding to the White Paper request was to offer what we consider to be an improved approach to responding to this technology need than that requested.

Since the Engineer's Design Guide (EDG) (Ref 2) has been published back in 1998, a decade ago, a lot has happened with the installation and operation of deepwater mooring systems – now polyester fiber rope mooring systems (as opposed to steel wire rope and chain) have become the technology of choice for deepwater mooring systems. In the last decade in the Gulf of Mexico, polyester mooring systems have been designed based on API RP 2SM, specifically using polyester rope.

Over time these designs have advanced:

- from an art only known to <u>a few rope experts</u> and considered an art and not sound engineering to mooring system engineers

- to an accepted engineering practice understood by a community of mooring system engineers (and fiber rope experts).

We have endeavored to build on our current successful experience with polyester mooring engineering – that we can now call "preferred technology" for deepwater moorings in the GOM - and compare and contrast the result of expanding the choice of fiber from polyester to stiffer materials for ultra deep water applications where polyester could possibly become too flexible - axially - to maintain suitable station for oil and gas exploration and production operations using MODUs and floating production systems.

Polyester became the fiber of choice based on knowledge gained from the EDG because (1) it was significantly lighter than steel, (2) it had the correct stiffness (modulus) for station-keeping in 4,000 to 8,000 feed of sea water (fsw), and (3) it was relatively inexpensive – as a commodity product - when compared with advanced fiber materials, and (4), its mechanical properties were well established.

We initially expected mooring systems for water depths approaching 15,000 feet of seawater to naturally evolve to having mooring lines with a combination of polyester rope segments and stiffer advanced fiber rope segments in series, chosen to achieve the desired mooring stiffness for the moored structure in the required water depth. In this way we expected to continue to use polyester segments whose performance we understand and value, and then add non-traditional fiber rope segments (that we understand less) specifically for achieving lighter weight (than steel) for the required non-catenary segments that we want to be stiffer to work in combination with polyester. Part A of this report shows the analysis results that changed our minds.

Experience with Polyester in Brazil and GOM

The use of polyester fiber rope moorings for permanently moored oil and gas floating production systems was pioneered by Petrobras in offshore Brazil (Corvina and Moreia Fields) in 1995. The technology for this application was developed by Cesar del Vecchio, of Petrobras, in his doctoral thesis published in 1992 (Ref 4). By 2001 there

were 19 polyester rope moored floating production systems in operation in offshore Brazil. So polyester mooring systems have become the system of choice for drilling and production in offshore Brazil over much heavier chain and wire rope systems in deeper waters. This was a pioneering effort of which Petrobras should be proud. Now industry in the U. S. Gulf of Mexico has become “fast followers” to the Brazilian pioneers.

Based on the Petrobras favorable experience with polyester fiber moorings and with joint industry funded technology developments in the U.K. and the U.S. polyester moorings became the mooring system of choice for permanent floating production systems and for moored drilling applications in the GOM.

Breakthrough Technology for Deep Waters

Based on additional technology development as part of the U.S. DeepStar Project (Refs 5-8) , in 1999, an American Petroleum Institute recommended practice, API RP 2SM, based on DeepStar Ref 8 became available to guide rope design in the Gulf of Mexico in 2001.

A major milestone in 2004 was the installation by BP of the Mad Dog Spar (Ref 9), in 4400 foot waters, which became the first permanently moored fiber rope production system in the GOM.

Presently, essentially all floating production systems and moored drilling systems for deep water in the GOM utilize polyester fiber rope because it is lightweight, durable and inexpensive.

Advanced Fibers over Polyester?

As the technology for the application of polyester mooring systems for the deepwater GOM becomes more mature, the question has become: “Is it time to transition from polyester fiber ropes to more advanced fiber ropes like PEN and Aramid and HMPE?

Without a clear understanding of the mooring stiffnesses required to avoid steel catenary riser SCR and top-tensioned steel riser failure, we expected mooring systems for water depths approaching 15,000 fsw to naturally evolve into having mooring lines with perhaps a combination of “regular-stiffness” polyester rope segments and then stiffer advanced fiber rope segments in series, chosen to achieve the desired mooring stiffness for the moored structure in the required water depth.

So the first question that we needed answered is the question about mooring stiffness requirements as a function of both water depth and advanced fiber rope stiffness.

PART A: Parametric Study of Advanced Fiber Ropes VS. Polyester Fiber Ropes for Various Water Depths

Input Information

To perform the required parametric analyses, we have chosen to use a fully coupled system analysis – including floater, risers (top tensioned and steel catenary) and mooring lines (including synthetic fiber and steel components).

To accomplish this analysis in the most cost effective way, we adopted the model previously developed for DeepStar CTR 7404. The numerical model using RAMS software is based on a 4-column medium semi-submersible, published in OTC 18467 (Ref 10). Appendix A contains a description of the RAMS software, and Appendix B contains PowerPoint Handouts showing the entire results of the analysis, from which Figures 1 – 18 were extracted.

The hull has a displacement of 60,000 short tons, and a length and width of 242 feet. Its height is 170 feet, and the deck area is 85,000 square feet. The topsides payload is 12,000 short tons.

We considered:

- Three water depths:
  - 5,000 ft.
  - 10,000 ft.
  - 15,000 ft.

- Three mooring rope AE stiffnesses:
  - 17.2 x MBL (Low stiffness like polyester)
  - 34.4 x MBL (Medium stiffness like PEN)
  - 51.6 x MBL (High stiffness like aramid or HMPE)

- Four design environments:
  - Fatigue event (Hs = 6.6 ft)
  - 10-year hurricane (Hs = 32.8)
  - 100-year hurricane (Hs = 51.8 ft)
  - 1000-year hurricane (Hs = 65.0 ft)

Output from the analysis came in 4 different areas:

- Vessel response:
  - Offset
  - Heave
  - Heel

- Mooring response:
  - Tension
  - Fatigue

- Steel catenary riser (SCR) response:
  - Stress and fatigue in sag bend

  - Top angle

- Top-tensioned riser response:
  - Stress and fatigue in the seafloor stress joint
  - Tensioner stroke

In the mooring model we used a nominal horizontal force of about 295 kips, and we assumed a mooring line break strength of 3970 kips. The nominal pre-tension is 15% and the aspect ratio horizontal to vertical is about 1. The 15% of MBL pretension we used in the MMS study is pretty typical for permanent installations. This is our understanding of pretensions used for the following polyester rope projects:

- Mad Dog = 14% MBL
- Red Hawk = 11% MBL
- Blind Faith = 10% MBL
- Mirage/Titan = 17% MBL
- Octabuoy = 13% MBL
- Perdido = 20 - 22% MBL

The pretension cannot be set too high because the increase in tension due to the static offset and dynamic motions in the 100-yr or 1000-yr hurricane events will exceed allowable limits. Also, the higher the tension in the line, the worse the dynamic effect will be, i.e., plucking a guitar string. Higher initial pretensions may be useful for temporary mooring installations (MODOS) that are not expected to experience 100-yr to 1000-yr events.

We should explain that the choices for fiber rope stiffnesses used in the analysis were based on convenient multiples of the reference polyester rope stiffness being 17.2 times MBL. If the rope stiffness the readers are concerned about does not fall on one of these multiples of the reference rope stiffness, they may want to interpolate between the results shown.

Figure 1 shows the details of the mooring lines used for this study:

Details of Each Mooring Leg

Component Description	Component Weight		Component Length		
	In Seawater	In Air	5000-ft Water Depth	10,000-ft Water Depth	15,000-ft Water Depth
	(lb/ft)	(lb/ft)	(ft)	(ft)	(ft)
Ground Chain	218	251	656	656	656
Connector	232	266	6	6	6
Rope	7	26	1,577	3,531	5,492
Connector	232	266	6	6	6
Rope	7	26	1,577	3,531	5,492
Connector	232	266	6	6	6
Rope	7	26	1,577	3,531	5,492
Connector	232	266	6	6	6
Rope	7	26	1,151	2,577	4,008
Connector	232	266	6	6	6
Platform Chain	218	251	656	656	656

Figure 1. Length/weight details of mooring leg segments for three water depths.

For simplicity and cost reasons, in this parametric study, the assumption here is that all rope weights are polyester. The weights of the steel components will be much more critical than the rope weight in affecting the lateral stiffness of the floater, so this assumption should be sound.

Since we are determining how the stiffness of the mooring system affects the structural limits of the SCR and the TTR, Figures 2 and 3 and 4 show the summarized designs of the representative risers. Of course, in detailed design, each individual riser design can be optimized for the specific application.

Steel Catenary Model

- Wet Insulated flowline
- 10.750-in OD x 1.375-in WT
- Shape parameter F_H/WD ~ 2900
- Fully straked

Water Depth	Horizontal Force	Top Tension	Top Angle	F_H/WD
(ft)	(kips)	(kips)	(kips)	(-)
5,000	270	778	20.3	2,902
10,000	270	1,297	12.0	2,902
15,000	270	1,815	8.5	2,902

Figure 2. SCR Design Conditions

Top-Tensioned Riser Model

- Dual-casing riser
  - Outer casing - 10.750-in x 0.650-in
  - Inner casing – 7.625-in x 0.500-in
  - Tubing – 3.500-in x 0.254-in
- Steel stress joint
  - Length = 29.2-ft
  - Wall thickness at base of taper = 1.500-in

Figure 3. TTR (Top Tensioned Riser) design conditions.

Top-Tensioned Riser Model, cont.

- Overpull at stress joint = 200 kips
- Tensioner stiffness = 1.5% of nominal tension

Water Depth (ft)	Nominal Tension (kips)	Tensioner Stiffness (kips)	Overpull (kips)
5,000	767	11.5	200
10,000	1,289	19.3	200
15,000	1,811	27.2	200

Figure 4. TTR tensions

Analysis Results

The first important result from this study is shown in Figure 5. In this figure the relative system lateral stiffness against the fiber rope AE assumed stiffness are plotted. Data is plotted for the equilibrium (static) offset condition as well as for the 100 year hurricane offset condition.

Evaluating the plot, we see that polyester plots at the coordinates of (1, 1), so for the equilibrium offset condition for PEN (x= 2.0), the lateral system stiffness is only 20% higher, and for the 100-year hurricane offset the lateral system stiffness is 50% higher. This condition is approximately true for all water depths studied.
For the Aramid or HMPE fiber rope, x = 3.0, and the lateral system stiffnesses are 30% and 80 % higher, respectively for approximately all water depths studied.

The significant point to be made from these results is that increasing the rope AE stiffness by a factor of 3 does not result in as great a change in the system lateral stiffness. The reason for this is that the mooring legs are in fact semi- taut (with a catenary steel weight effect) rather than taut line.

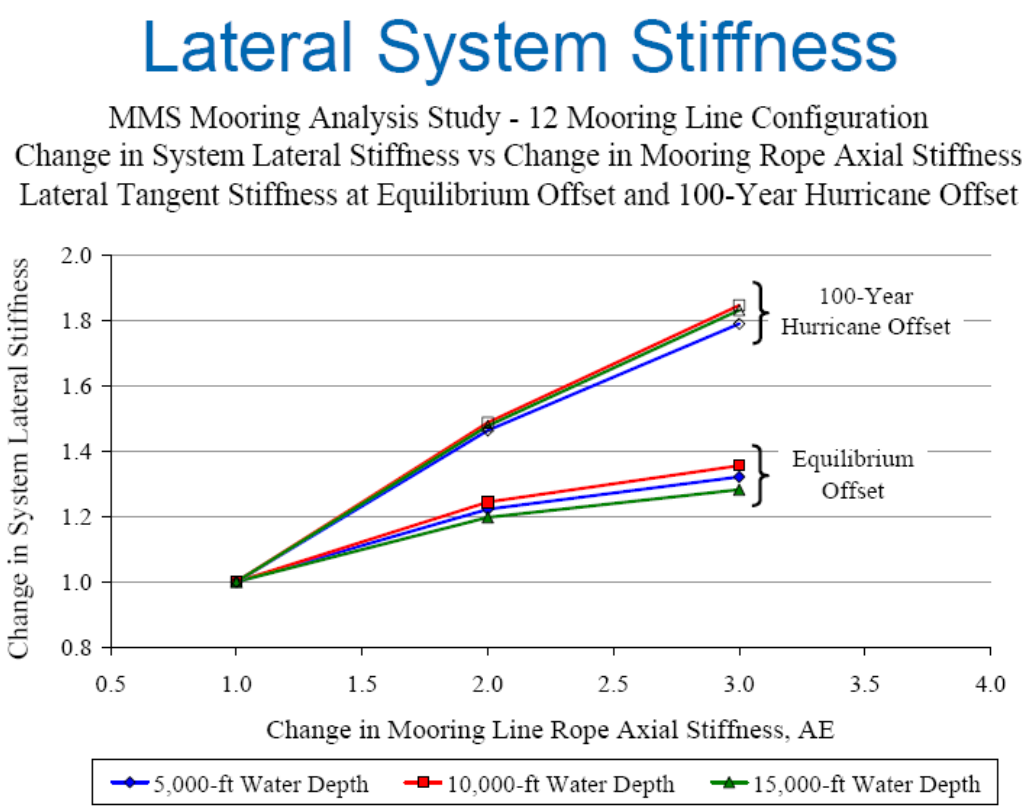
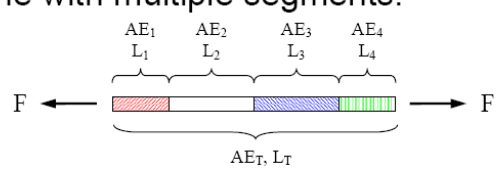


Figure 5. Change in lateral stiffness with change in rope axial stiffness.

To better understand Figure 5, please see our stiffness calculation formulas in Figures 6 and 7 that were used in constructing Figure 5.

Axial Stiffness of a Mooring Line

- For a line with multiple segments:



- The axial stiffness, AE_T, is given by:

$$AE_T = \frac{L_T}{\frac{L_1}{AE_1} + \frac{L_2}{AE_2} + \frac{L_3}{AE_3} + \frac{L_4}{AE_4}}$$

- The spring stiffness, K_T, is given by:

$$K_T = \frac{AE_T}{L_T}$$

Figure 6. Axial stiffness formulas.

Theoretical Spring Stiffness

- A spring connected at an angle imparts an effective horizontal and vertical stiffness, K_{HH} and K_{VV}
- Effective horizontal stiffness,

$$K_{HH} \approx K_{LINE} \sin^2 \theta$$

- Effective vertical stiffness,

$$K_{VV} \approx K_{LINE} \cos^2 \theta$$

- Combined stiffness,

$$K_{LINE} \approx K_{HH} + K_{VV}$$

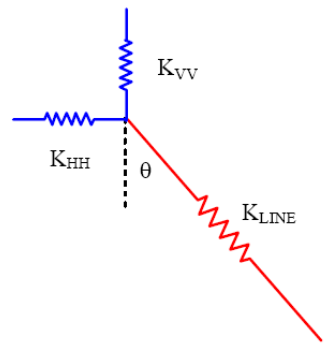


Figure 7. Effective horizontal spring stiffness formulas.

Mooring Line Tensions

The following two figures, Figure 8 and Figure 9, show the fully coupled analysis results for the windward and leeward lines respectively during a 100-year hurricane.

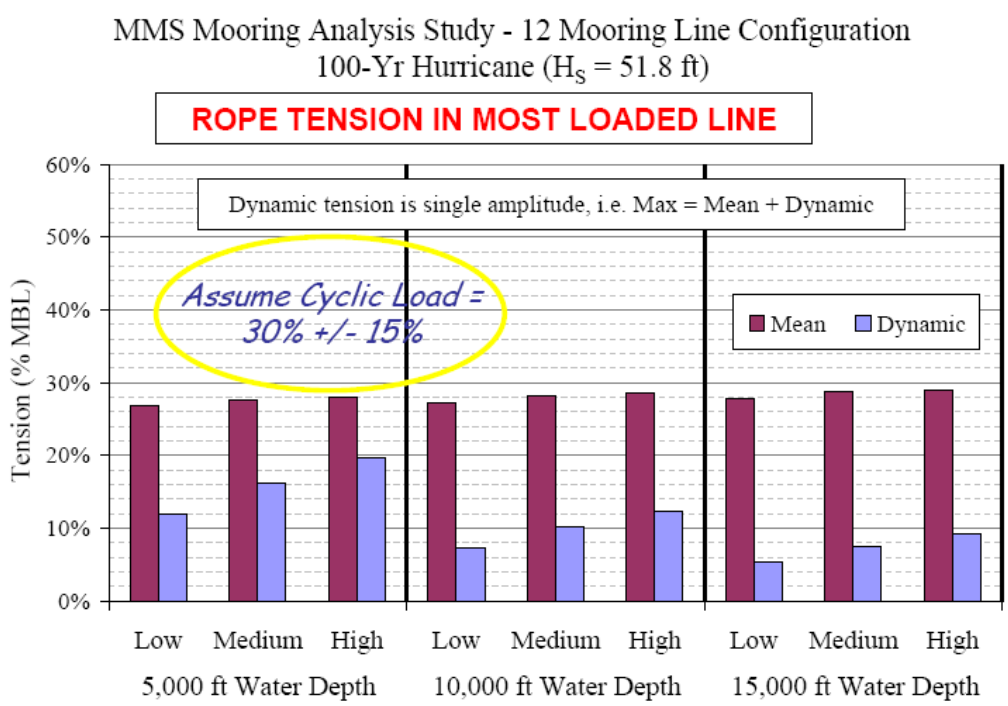


Figure 8. Rope dynamic tensions on the most loaded line for Low, Medium and High stiffnesses. H_s is the significant wave height.

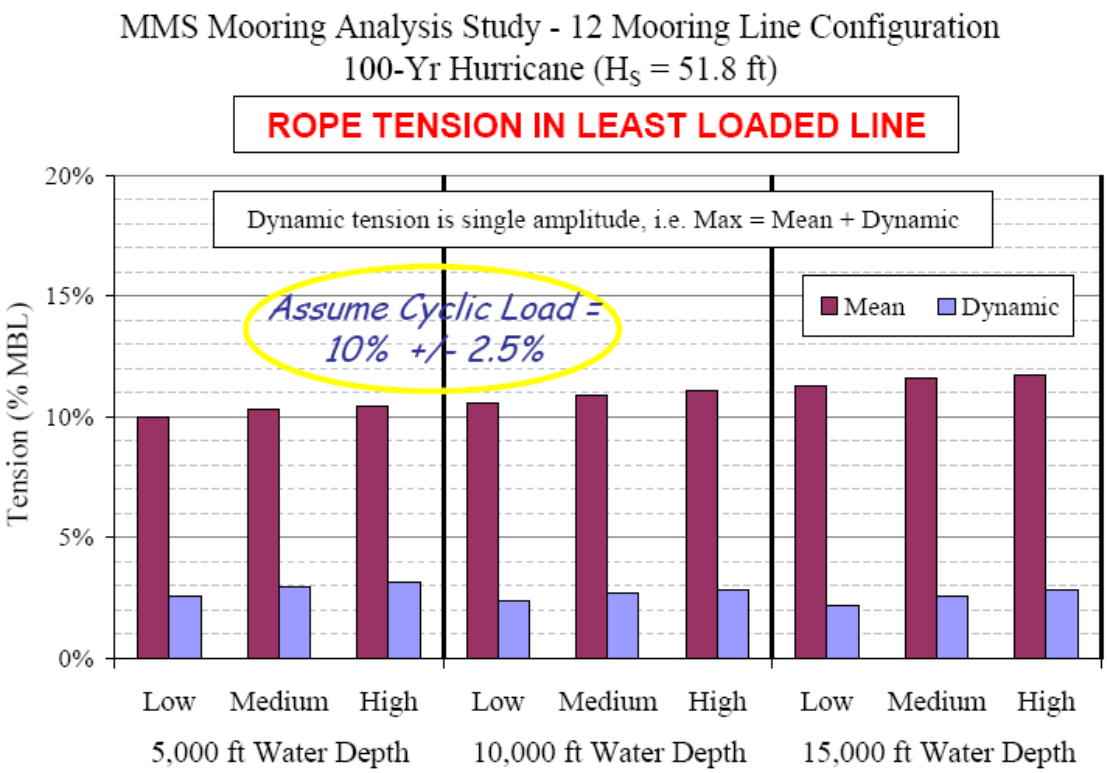


Figure 9. Rope dynamic tensions on the least loaded line for Low, Medium and High stiffnesses.

These two figures confirm the wisdom of the recommended cyclic fatigue loadings for the most loaded line to be approximately 30% mean plus or minus 15% amplitude as shown in the original API RP 2SM. Please note that this cyclic loading condition applies to both low (polyester) and high-modulus (aramid, HMPE) ropes.

Figure 9 shows that on the most leeward line a more appropriate cyclic fatigue loading for both low and high modulus ropes would be only 10% mean plus or minus 2.5%. Based on Reference 11, we find that cyclic wear for polyester (low modulus) rope is greater for lower mean loads than for higher ones, provided that the amplitude stays the same. Cyclic wear has been found to reduce the breaking load after cycling. It would be wise, then to test the least loaded line condition as well as the most loaded line condition to ensure the wear integrity of the rope of any modulus. Since the amplitude for the least loaded line is only 2.5% as compared with the amplitude of 15% for the most loaded line, future testing could show that the leeward line cyclic wear condition is not very damaging.

Fatigue of Mooring Chain and Risers

Numerous fiber manufacturer funded studies, as well as the NEL/TTI Durability Study (Ref 12) have shown that fiber rope materials – including advanced fibers – have a fatigue life that is much greater than that of the mooring hardware. So in this report we concentrate on the mooring chain to which the fiber rope segments are connected.

The primary objective of this sensitivity study, then, is to determine if using either low (polyester) or high (HMPE, aramid) modulus ropes would the cause the steel mooring hardware or the SCR or top-tensioned risers to experience a maximum stress or a fatigue failure.

The maximum stress results are shown in Appendix B, and not here, because there is no significant problem with maximum stress of the mooring chain and risers. Of more interest are steel component fatigue results. Figures 10 through 12, show the fatigue results for those components in terms of number of fatigue events to failure.

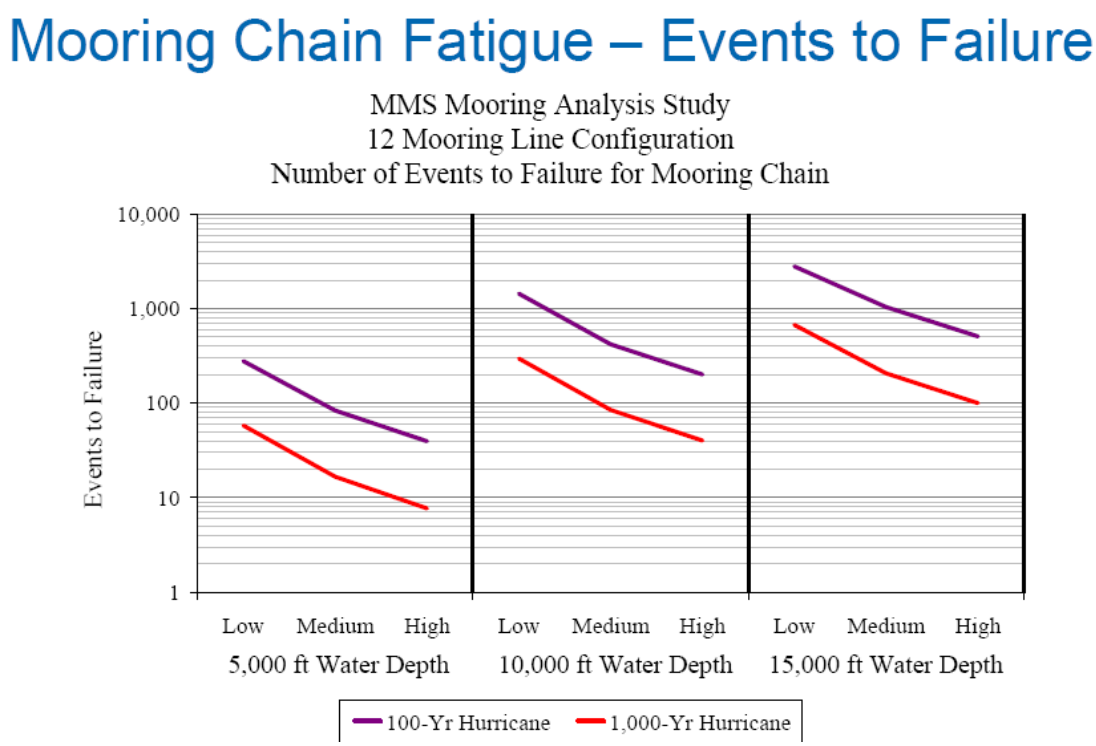


Figure 10. Mooring chain fatigue – number of events to failure for Low, Medium and High stiffnesses.

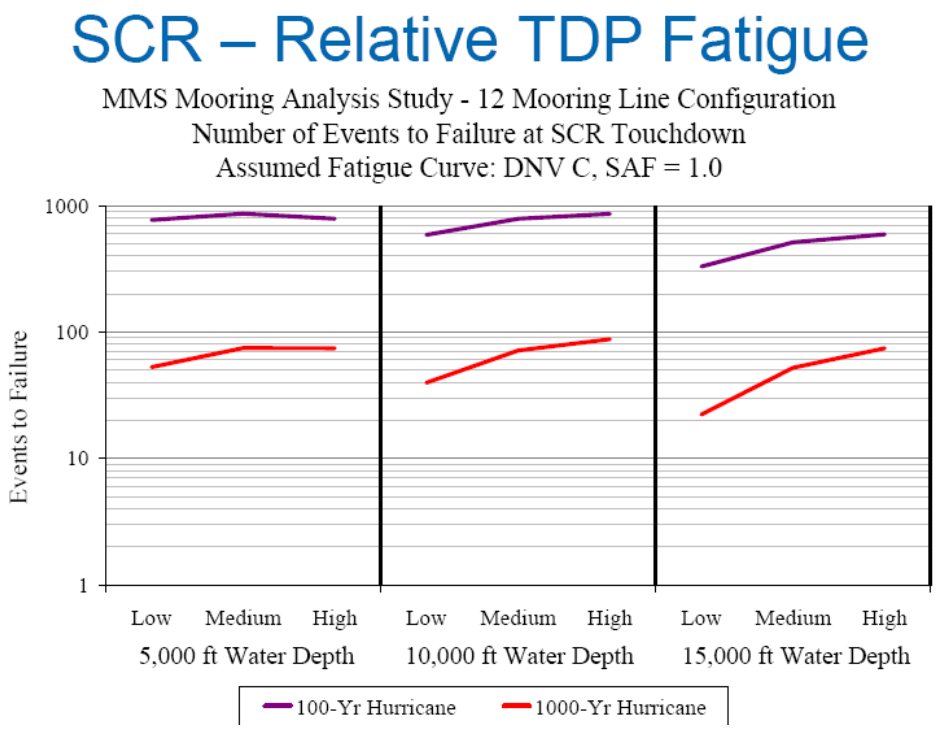


Figure 11. SCR touchdown fatigue – number of events to failure for Low, Medium and High stiffnesses.

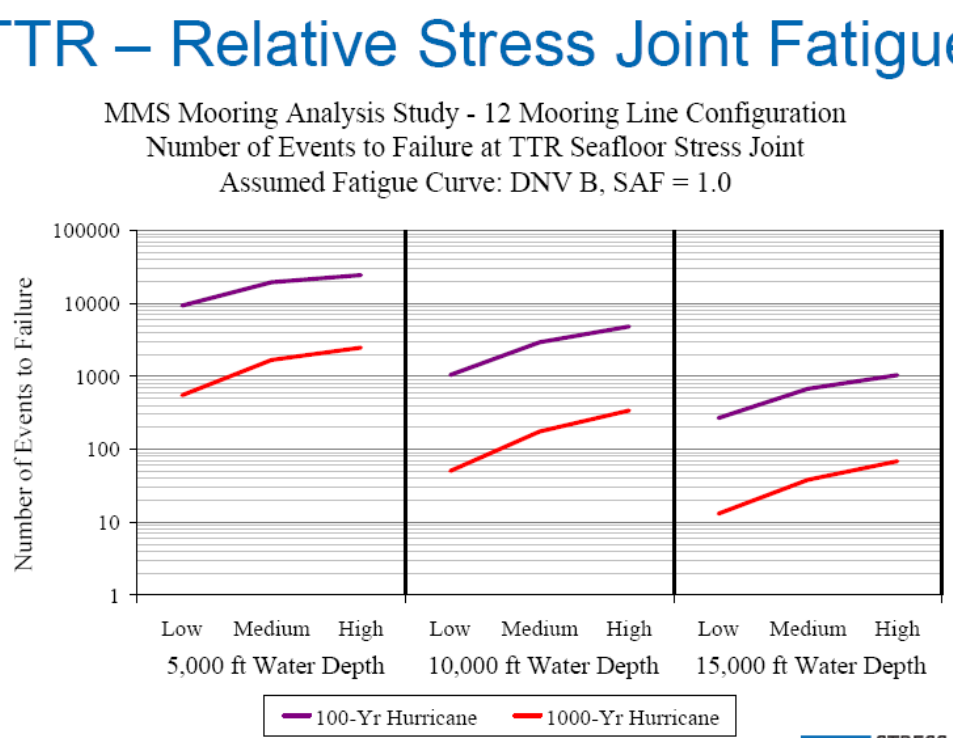


Figure 12. TTR stress joint fatigue – number of events to failure for Low, Medium and High stiffnesses.

These three figures show that a factor of safety of 10 or more is possible for every mooring and riser condition except for the high modulus, shallow water case of mooring fatigue, where the number of events is slightly less than 10.

We have looked in more detail at the cases showing events to failure of less than ten, and we have determined that by individually optimizing the design (chain, SCR, TTR) for the specific design conditions, an improved design can be achieved that raises the number of events to be over 10. Remember, this is a sensitivity study to show potential problems. These analysis results would not be used for final design.

Relationship of Offset (% water depth) with Offset Force

Figure 13 shows a plot of offset in % water depth with offset force in kips for three rope stiffnesses in 10,000 ft of water.

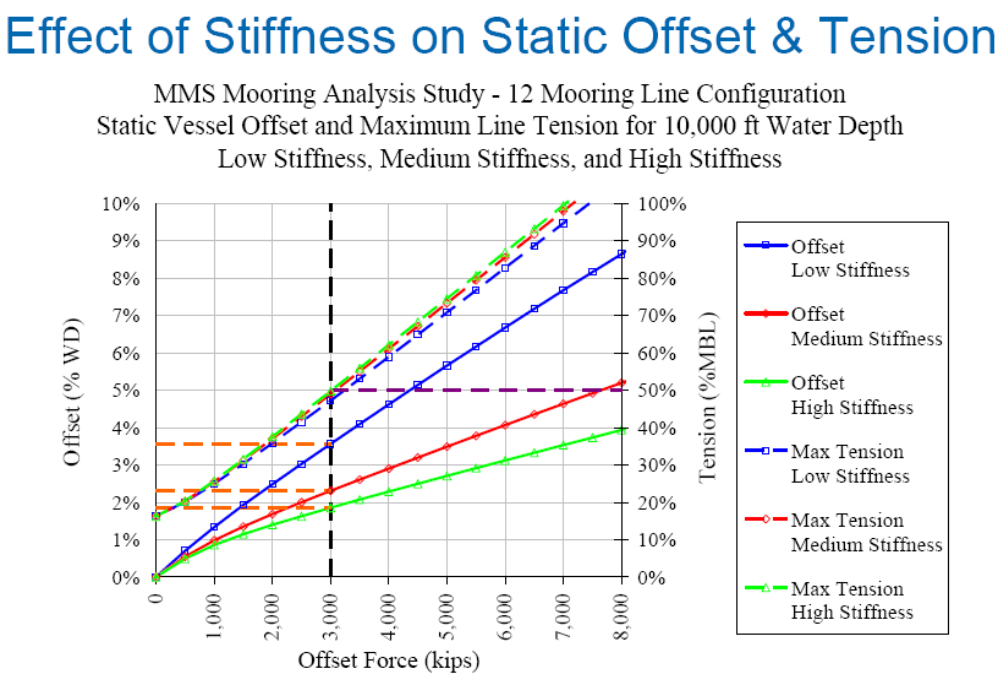


Figure 13. Hull offsets for various offset forces. Applicable to all hulls.

The mooring line stiffness will affect the static and dynamic response of the system. The plot on Figure 13 shows the vessel offset and mooring line tension as a function of

a static force applied to the vessel, and thus shows the effect of mooring line stiffness on the dynamic response.

Here is an example of using Figure 13 for a total hull offset force of 3,000 kips: The dashed purple horizontal line indicates that the maximum mooring line tensions (for all 3 stiffnesses) are approximately 50% of MBL. The dashed orange horizontal line indicates that the vessel offset is approximately 3.5% of water depth for the low stiffness system, and approximately 2.3% of water depth for the medium, and around 2% for the high stiffness system.

The plot shows that for a static event, increasing the mooring stiffness will decrease the vessel offset, while having a negligible effect on the maximum mooring tension.

Although this plot was prepared for the DeepStar semisubmersible hull, it is equally applicable to spars and FPSOs.

Part B: Advanced Fiber Rope Technology

Introduction

The basic building block of the synthetic fiber rope as used in deepwater floating production systems and moored offshore drilling units is the individual fiber. But fiber makers generally twist a number of individual fibers into a yarn, and it is this yarn that is delivered to the rope makers. The rope makers build up yarns into strands, and from strands are made subropes. Finally a number of subropes are laid in parallel to form a mooring rope.

To date the large majority of fiber rope mooring systems are made from polyester fiber. Polyester fiber ropes are lightweight, strong, and durable, and are relatively inexpensive when compared with advanced fibers. In addition, polyester has a stiffness value which is viable for mooring applications. However, with the deeper water requirements, it is needed to see if polyester is still applicable or if advanced fibers would be a better fit.

Kevlar was the first high performance fiber, developed in the 1960's. Following that, polyester was processed into HMPE based on gel spinning technology in 1980's. Other innovations of high strength "advanced" fibers followed due to demand in high performance applications such as firefighter clothing, bulletproof vests, sports and leisure goods.

Except possibly for PEN, which is melt spun, it should be noted that due to manufacturing processes, different manufacturer's fibers will have different properties even though they may be in the same category such as aramids or HMPE. Advanced synthetic fibers typically are processed from solutions that have 5 to 20 weight percent (wt%) of polymer and the rest of the mass is the solvent. The final strength of the fiber depends on the combination of the manufacturing processes along with solvent removal process. During these processes, different imperfections occur such as: entanglement, chain ends, voids and foreign particles. These imperfections cause stress concentrations and thus reduce the strength (See Figure 14.)

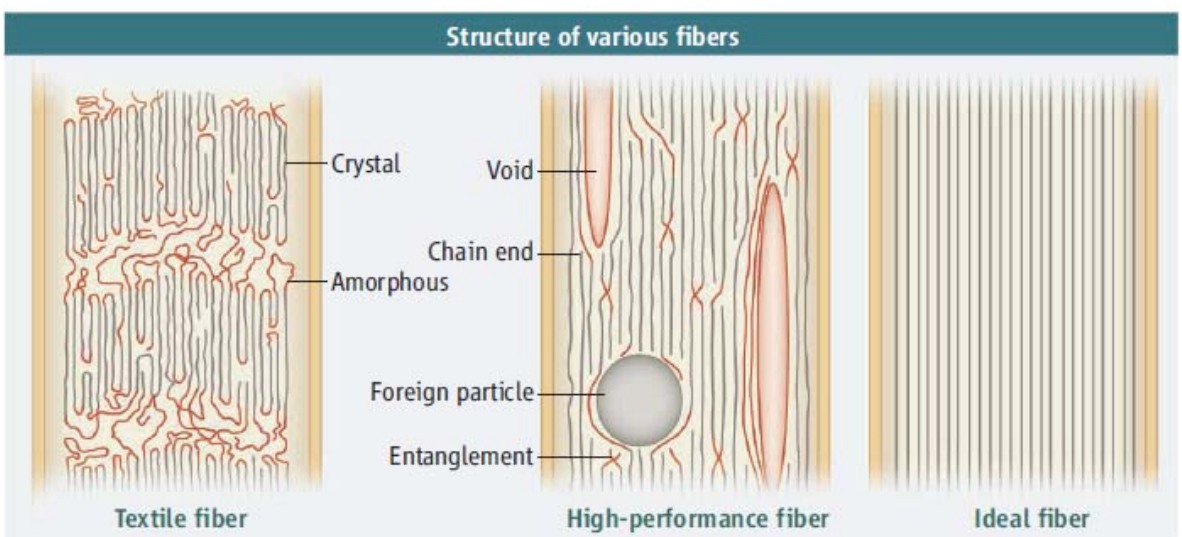


Figure 14. Representation of the structure of various fibers (Ref 13).

In general, molecules of advanced fibers are highly oriented and have small strain to failure. Sometimes crystallinity is used to explain this phenomena but it should be clarified that molecular orientation and crystallinity are different concepts: high

crystallinity means molecules are parallel to each other but they do not need to be parallel to the longitudinal fiber axis whereas highly oriented refers to molecular crystallinity in the fiber axis. And it should also be noted that molecules might be arranged in some crystalline and amorphous areas in the same fiber.

Following is a comparison of more well known polyester (and Nylon fibers) with other more advanced fibers.

Fiber Comparisons

A relatively complete comparison of advanced fibers was found on the fibermax.com website. We supplemented this information by searching the Internet for other fiber suppliers. Also refer to the 2004 Handbook of Fibre Rope Technology (Ref 3.).

Polyester

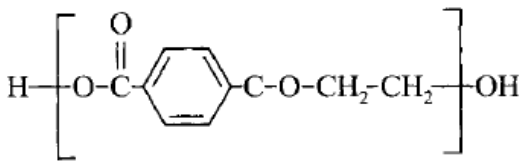
Polyester is a category of polymers which contain the ester functional group in their main chain. Although there are many polyesters, the term "polyester" as a specific material most commonly refers to polyethylene terephthalate (PET). The Federal Trade Commission's definition for Polyester fiber: a manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of at least 85% by weight of an ester of dihydric alcohol and terephthalic acid.

Main characteristics:

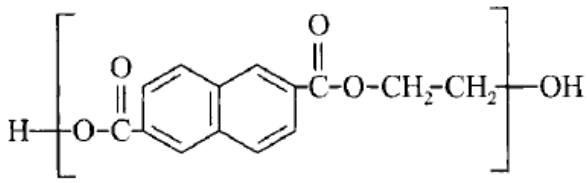
- Good strength-to-weight ratio.
- Moderate elongation (12% - 15%).
- Highest UV resistance of any fiber.
- Good abrasion resistance.
- Keeps strength when wet.

PEN

The double (naphthenic) ring of the PEN compared to the single (benzene) ring of the PET is the structural difference between PEN and PET.



PET



PEN

Presence of double naphthalate ring improves thermal, chemical, mechanical, and barrier performance versus polymers based on single aromatic rings.

Commercial producers of PEN are Teijin Ltd. (Japan), M&G (USA), 3M (USA), KoSa (Europe), Toyobo (Japan), Kolon (Korea), MCC (Japan), Kimex (Mexico), and Shinkong (Taiwan), Honeywell (formally AlliedSignal) in the United States and Europe, Kosa in Europe, and Hyosung in Korea.

Main characteristics:

- Improved mechanical performance compared to PET.
- Very good strength-to-weight ratio.
- May be up to twice as stiff as PET.
- Very good UV resistance.
- Keeps strength when wet.

Polyamide (Nylon)

Nylon was the first synthetic fiber to go into full-scale production. Although many different nylon structures can be formed, the ones that are of major commercial importance are nylon 6.6 and nylon 6. The numerical nomenclature for nylon is derived from the number of carbon atoms in the demine and dibasic acid monomers used to manufacture nylon. The ratio of carbon atoms is what gives each nylon type its unique property characteristics.

Manufacturing processes along with the physical parameters such as polymer molecular weight, fiber spinning speed, quenching rate, and draw ratio dictate the mechanical properties of nylon 6.6 and nylon 6.

The worldwide nylon fibers market is shared by DuPont, BASF, Rhodia, Solutia (formerly Monsanto fibers), AlliedSignal and the remaining by many smaller manufacturers.

- Good strength-to-weight ratio.
- High elongation - 18 to 25%.
- Absorbs a considerable amount of water which leads to significant change in properties – low tensile strength, lower modulus and poor resistance to abrasion.

Aramid

Aramid fibers are a class of heat-resistant and strong synthetic fibers. The name is a shortened form of "aromatic polyamid". They are fibers in which the chain molecules are highly oriented along the fiber axis, so the strength of the chemical can be exploited. The Federal Trade Commission's definition for aramid fibers a manufactured high-modulus fiber in which the fiber-forming substance is a long-chain synthetic aromatic polyamide in which at least 85% of the amide linkages are attached directly to aromatic rings. Aramid is also known by its trade names Kevlar® or Twaron®.

Main characteristics:

- Mainly known as Kevlar® or Twaron®.
- Excellent strength-to-weight ratio.
- Crystallinity > 90%
- Highest resistance to heat of any fiber.
- Very low creep.
- Very low elongation (2 to 4%).
- Poor abrasion resistance.
- Susceptible to axial compression fatigue.

- Non conductive.
- Poor UV resistance.

HMPE

HMPE (High Modulus Polyethylene) is a subset of the thermoplastic polyethylene. It has extremely long chains, with molecular weight numbering in the millions, usually between 2 and 6 million. The longer chain serves to transfer load more effectively to the polymer backbone by strengthening intermolecular interactions. The result is a very tough material, with the highest impact strength of any thermoplastic presently made.

Main characteristics:

- Mainly known as Dyneema®, Spectra® or Plasma®.
- Highly resistant to corrosive chemicals, with exception of oxidizing acids.
- Extremely low moisture absorption.
- Very low coefficient of friction, is self lubricating and highest abrasion resistance of any fiber.
- When formed to fibers, the polymer chains can attain a parallel orientation greater than 95% and a level of crystallinity of up to 85%. In contrast aramid derives its strength from relatively short molecules.
- Highest strength-to-weight ratio of any fiber.
- Excellent dynamic toughness.
- Very low elongation (3% - 5%).
- Excellent flex fatigue resistance.
- Low resistance to heat.
- Very high creep.

LCAP

LCAP (Liquid Crystal Aromatic Polyester) are a unique class of wholly aromatic polyester polymers that provide previously unavailable high performance properties.

LCAP fibers are produced by melt-spinning from thermotropic liquid crystalline aromatic polyester.

Main characteristics:

- Mainly known as Vectran®.
- High strength-to-weight ratio.
- Low creep.
- Excellent dynamic toughness.
- Excellent flex fatigue resistance.
- Good abrasion resistance.
- High resistance to heat (melting point of 625°F).

Fiber Engineering Properties

Following is a summary of the engineering properties of the various advanced fibers as compared with polyester.

When stress-strain curves are shown for rope fibers, it is customary to use the units of grams per denier, where the gram is well known and a denier is the number of grams per 9000 meters of the single fiber. Percent elongation is the change in length per unit of length, unitless.

Figure 15 shows that aramid, LCP and HMPE are the stiffest fibers, where PEN falls between the high modulus fibers and PET (polyester). When these fibers are made into yarn and the yarn into strands and the strands into subropes and the subropes into ropes, the differences in fiber stiffnesses (observe slope of the curves) will be similar in relative magnitude. Of course variations in subrope designs will result in variations in stiffnesses.

Since the high modulus fibers will generally have a higher strength at failure, ropes made from these fibers will require a lesser number of fibers to achieve the same breaking strength as lower modulus fibers like polyester. Hence high modulus fiber

ropes of the same breaking strength will be smaller in diameter than low modulus ropes. An exception to this is that PEN will have the same approximate diameter as PET, because the fiber break strengths are about the same, even though the PEN is stiffer.

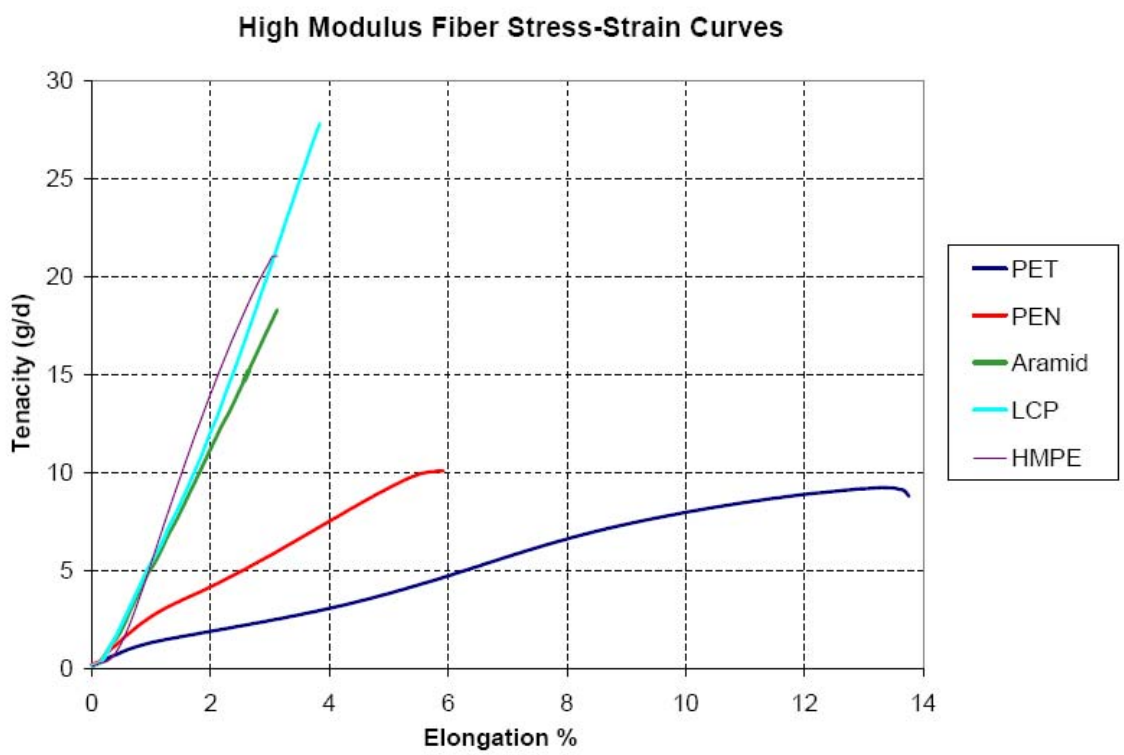


Figure 15. High-modulus fiber stress-strain curves (Ref 14).

During the fiber rope workshop conducted as a part of this study, various advanced fiber manufacturers took issue with the appropriateness of certain results for their choice of fiber, and they offered to supply improved results for their specific fiber. We chose this particular set of data because it is performed at the same test lab using the very same test method. We have resisted changing the data for one particular fiber in a multiple fiber set. The fibers tested here have experienced no prior cycling.

Figure 16 is another way of plotting the same data - % load vs. % elongation. Note that PET (polyester) fails at a much larger % elongation than the other fibers. This provides a built in confidence in structural integrity, since the mooring leg will be 12% longer before failure can occur. Thus peak dynamic loads will be moderated.

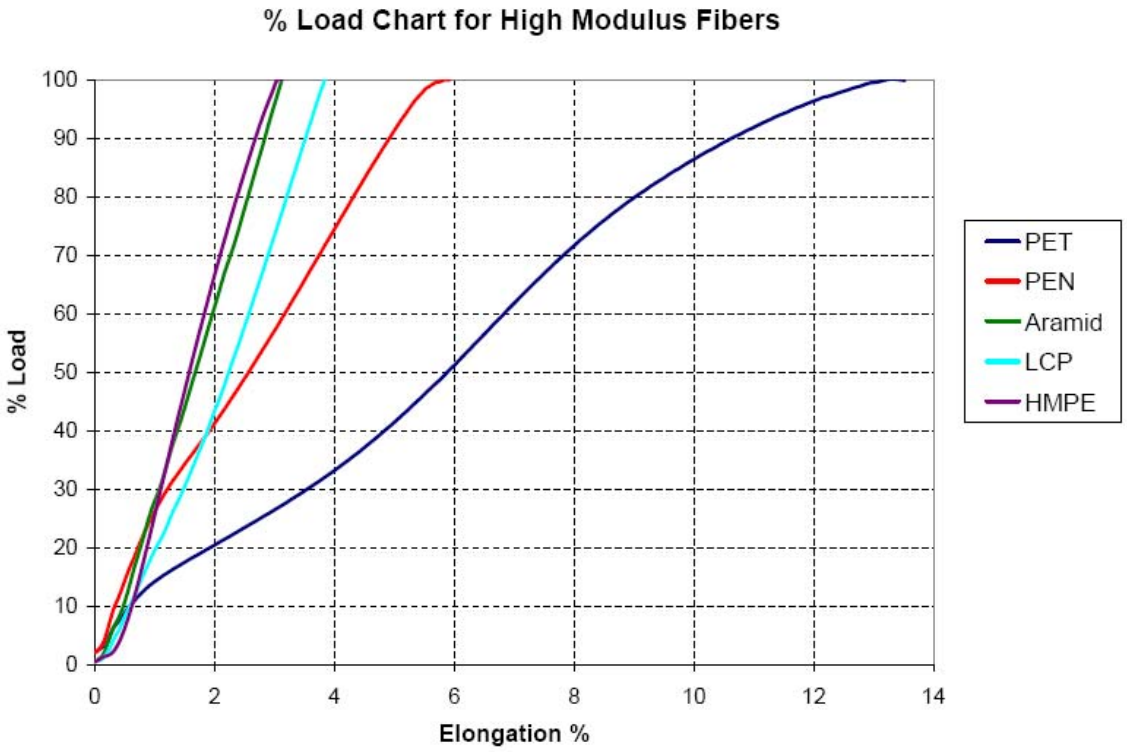


Figure 16. Percent load chart for high-modulus fibers (Ref 14).

Synthetic fibers, because they have viscoelastic properties, will tend to creep over time under load. Figure 17 shows that all of the fibers except HMPE tend to display a linear creep elongation with log time. This unique property of HMPE makes it important to determine the actual creep elongation properties of an HMPE fiber rope for the project life of the mooring system. For instance mooring systems for MODUs might be a better application of HMPE fiber rope than for a permanently moored FPS.

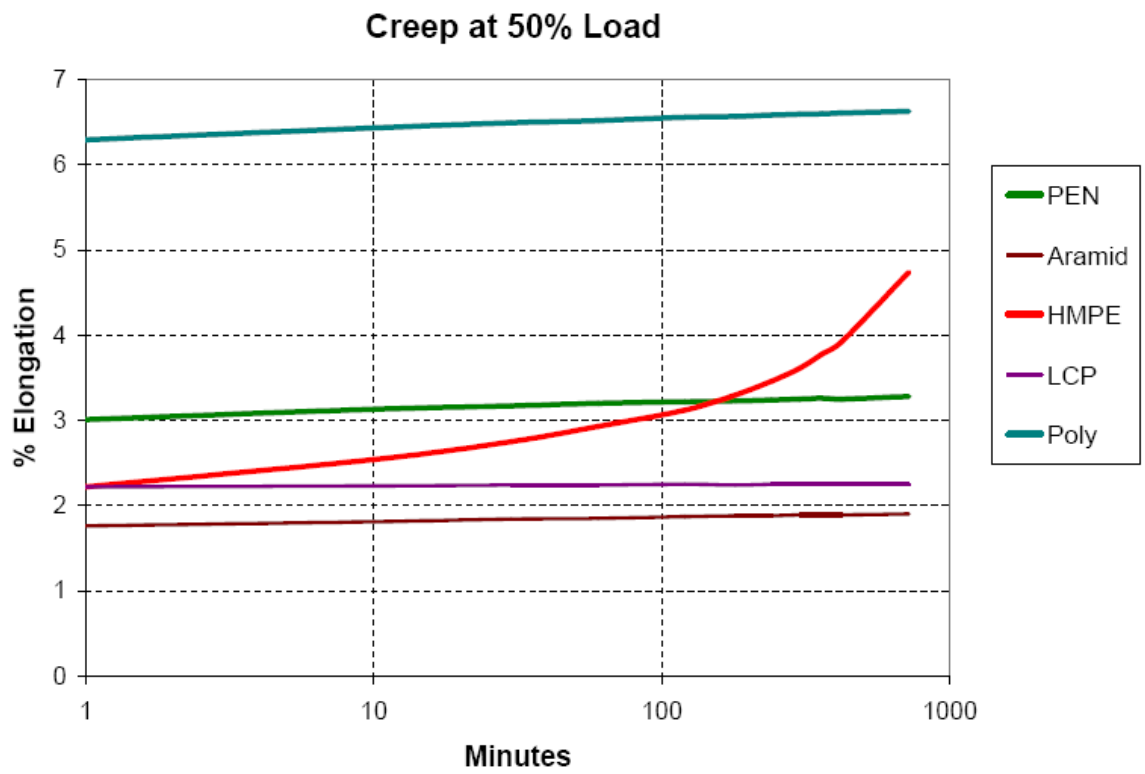


Figure 17. High-modulus fiber creep at 50% load (Ref 14).

Another way of displaying the various advanced fiber properties is provided in Table 1 from a NASA report, Reference 15.

TYPICAL FIBER MODULUS VALUES				
	Strength, Gpa	Modulus, Gpa	Modulus EA	Density , g/cc
HMPE	3	171	57	97
	3.25	116	36	97
LCP	3.2	91	28	147
ARAMID	2.9	135	47	145
	3	110	37	
	3.3	70	21	139
POLY	1.13	15	13	
NYLON- Dry	0.96	8	8	
STEEL	7.6	150	20	8

Table 1. Typical fiber modulus values from NASA report (Ref 15).

Advanced Fiber Yarn Properties

An important structural aspect of fiber yarns is that of yarn-on-yarn abrasion, which is the result of the frictional forces of one yarn rubbing against another. For Polyester yarns the Cordage Institute has developed a yarn on yarn abrasion test specification, CI-1503 (Ref 16).

The test fixture is shown in Figure 18 below.

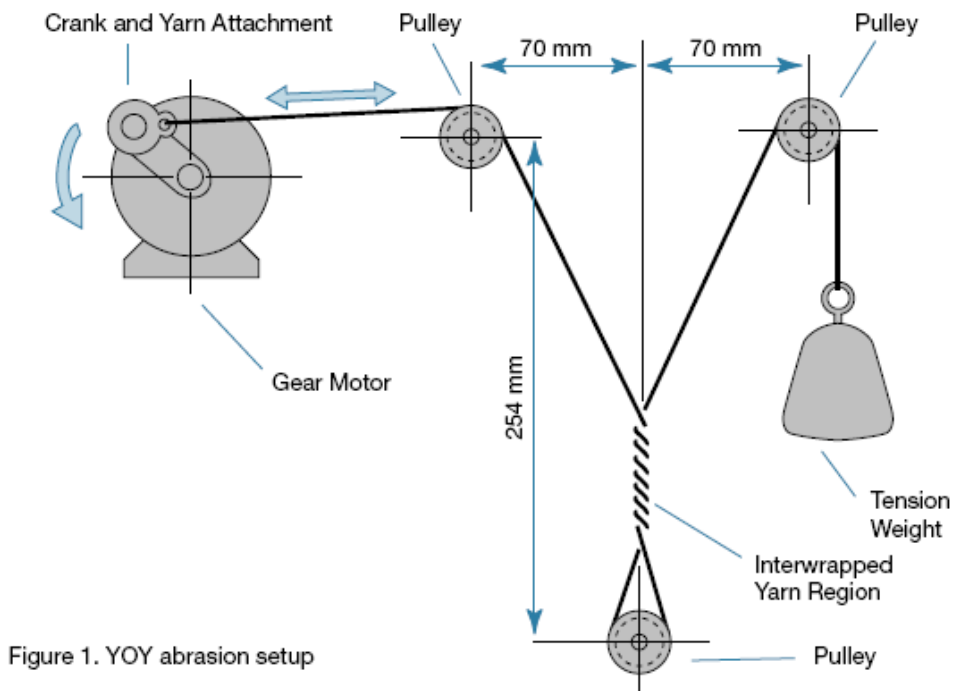


Figure 18. Yarn-on-yarn abrasion set-up based on CI-1503 (Ref 16).

From the figure, one can see that the length of the crank determines the length of abrasion, and thus the results. For very flexible polyester yarns a predetermined crankshaft length is stipulated. This test can be used to compare various grades of polyester fiber and to compare various kinds of marine finishes for friction reduction.

The same setup can be used for other fibers, but any relative comparisons of fiber materials should not be made. Engineering intuition would say that a stiffer yarn should

be tested using a shorter crankshaft. Consequently the yarn-on-yarn abrasion test should NOT be used to compare the abrasion properties of various advanced fiber materials. A method for testing abrasion – this time strand-on-strand – is discussed later in the report.

Another way to use the yarn-on-yarn assembly shown in the figure is to determine friction coefficients for various advanced fiber yarns without abrading the yarns. The following Table 2 shows friction coefficients for the various fiber yarns.

Fiber	Mean	Max.	Relative to Polyester
Aramid*	0.131	0.180	1.82
LCP	0.144	0.151	1.53
HMPE		0.064	0.65
PET	0.060	0.099	1.00
** Marine finish can greatly affect results*			

Table 2. Typical yarn-on-yarn friction coefficients (Ref 3).

Note that the frictional characteristics of aramid and polyester can vary from that shown, depending on the kind of marine finish applied.

Parallel Subrope Rope Design

Figure 19 shows the types of fiber mooring ropes we are studying. Generally the rope makers use similar rope design assemblies for various advanced fibers. Part (a) shows a typical jacketed full rope with multiple parallel subropes inside. In this figure, the subrope is seen to be a three-strand twisted design which is not torque-balanced. To make the full rope torque-balanced, equal numbers of left-hand lay subropes and right-hand lay ropes are used to comprise the full rope. Part (b) is a photo of a three-strand unjacketed subrope. Part (c) shows an eight-strand braided subrope which is naturally torque-balanced in its design. Such subropes can be used (rather than three-strand designs) as subropes in the full rope as shown in Part (a). Finally, Part (d) shows a

single jacketed strand that can be used to form a three-strand subrope as shown in Part (a). Such a subrope would need to be added to the full rope in equal parts to make the final rope torque-balanced. Depending on the deepwater floating system application, a typical full rope has a breaking strength of 2000 to 4500 kips, and the corresponding multiple subropes might have strengths between 75 and 350 kips.

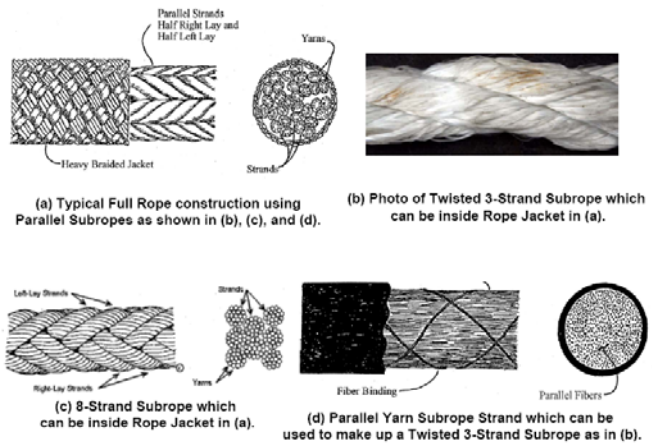


Figure 19. Polyester rope design details (Ref 11).

The full rope design, consisting of a number of parallel subropes enclosed in an outer jacket, will be like the polyester fiber rope being installed for a MODU application. See Figure 20 below.

Figure 20. Typical polyester rope installation operations.

Comparison of Rope Engineering Properties

Overview

Care should be exercised in introducing a new advanced fiber, rather than using polyester fibers which have some level of maturity of use for deepwater moorings.

Table 3 below contains a summarized list of recommended testing and analysis that should be performed in order to ensure the structural integrity of the installed mooring system over the life of the installed FPS.

If we assume ropes containing multiple parallel subropes are being evaluated, it is often possible to test individual subropes in place of the full rope.

Rope and Rope Splice Design Checks			
Item	Key Engineering Property	Test or Analysis Method	Critical Fiber
1	Minimum Breaking Load (MBL), and Maximum % Elongation	Test Full Rope Using RP of API 2SM	All
2	Rope Splice Slip Factor Of Safety	Test Subropes* Using Test Method Described Here	All
3	Mooring Rope Axial Stiffness	Test Subrope Using RP of API 2SM	All
4	Effective Horizontal Mooring System Stiffness	Calculate this Using Test Results for Mooring Rope Stiffness	All
5	Rope Abrasion and Cyclic Wear	Use 20 Hurricane Subrope* Testing (with Described Here	All
6	Rope Fatigue	Test Subrope* Using API RP 2SM	All
7	Rope Axial Compression Effects	Use 20 Hurricane Subrope* Testing Described Here	Polyester & Aramid
8	Rope Creep Elongation	Use Yarn or Subrope Testing per API 2SM	HMPE
	** Use Identical Splice As Used In Full Rope Subrope Splices*		

Table 3. Advanced fiber rope and rope splice design checks.

Here are details for each item above:

Item 1 - MBL and Elongation: Looking at the table, the first item is testing for the MBL and the % elongation at failure. This needs to be done with a full rope sample according to API RP 2SM, so that the full rope splice is validated for strength.

Item 2 – Rope Splice Slip FOS: Not included as part of API RP 2SM is a requirement to confirm that the subrope splice has a positive factor of safety against slipping. One can use the 20-hurricane testing in items 5/7, and then add one (or more) additional tuck(s) in the splice production design, in case the splice design (number of tucks) was very close to slipping in the 20 hurricane test, but did not. Item 2 is important when rope makers are using fibers other than polyester where they might have less experience.

Item 3 - Rope Axial Stiffness: Standard API 2SM testing of a subrope will suffice.

Item 4 – Effective Horizontal Stiffness: The designer needs to understand how rope axial stiffness will convert to mooring system effective horizontal stiffness as described as part of previous Figure 5. Depending upon how close the mooring system design is to that evaluated in Part A of this report, a new fully-coupled analysis of the entire hull, riser and mooring system may be required. (Also see the recommendations of Part A.) A key consideration is how the mooring hardware differs from that assumed for Part A.

Item 5 – Rope Abrasion and Cyclic Wear: This design check addresses the issue of cyclic wear and how that affects the loss in strength of the rope segments over the project life. This issue is addressed more fully in the section on strand-on-strand testing discussed later in this report.

For Item 6 – Rope Fatigue: If the rope or fiber manufacturer has prior fatigue results on the advanced fiber and rope design, further fatigue testing might not be needed. Generally speaking, fatigue data for full ropes made from advanced fibers is scarce.

Item 7 – Rope Axial Compression Effects and Item 5 above: There are in fact two critical cyclic conditions that should be checked. Current 20-hurricane testing has primarily been conducted using the windward line conditions – 30% mean load and 15% amplitude. Item 5 uses this cyclic condition and Item 7 should use both a lower mean load and amplitude as described in the following.

When testing polyester, we have found that the lower the mean load with the same amplitude (15%), the greater the loss in breaking strength.

Results of Part 1 show us that a more realistic cyclic load condition for the leeward line low mean load condition is better represented by 10% mean and 2.5% amplitude. We do not have any test results for this low of a mean load low-amplitude case, so until we understand the effect of this condition (for all fibers), we are recommending that the test be run. The good news is that when applying 2.5% MBL amplitudes, one can use a much shorter cyclic period, and thus the testing will be perhaps 5 to 10 times shorter than for the 30% mean, 15% amplitude case. We believe that the critical fibers for this test are polyester and aramid, which have similar wear characteristics. To be thorough, it would be wise to perform this test on all fiber subrope designs.

Item 8 addresses creep elongation. There is a reasonable amount of creep data that shows that all fibers considered except HMPE show a linear creep elongation with log time. Figure 17 shows this case for HMPE fibers in contrast to other fibers. Consequently creep testing of mooring systems constructed from HMPE must be carefully tested according to API RP 2SM.

Comparison of Stiffnesses (Modulii) for Advanced Fiber Ropes

Previously in this report the relative stiffnesses of various advanced fibers were compared. In this section we are concerned with rope rather than fiber stiffness or modulii.

Table 4 has been constructed based on accumulating modulus data from a variety of published and unpublished sources. When a rope is being designed for a particular project, the designer must conduct more specific tests on that particular design – and use the table only for guidance.

Shown are rule-of-thumb stiffness values shown as a multiple of MBL. Actual stiffnesses – particularly for the stiffer fibers - can vary widely from that shown in the table according the exact fiber designation.

Typical Stiffness Times MBL For Ropes			
			Relative to Polyester
	Intermediate Stiffness	Storm Stiffness	Storm Stiffness
	(+/- 5)	(+/- 5)	
Polyester	15	30	1.00
PEN	20	39	1.30
Aramid	35	70	2.33
HMPE	60	90	3.00

Table 4. Typical stiffness (modulus) values for advanced fiber ropes.

The intermediate stiffness is defined in API RP 2SM to be the secant stiffness over the load or strain range of interest in quasi-static loading immediately after installation. This is the minimum stiffness. The storm stiffness represents the maximum secant stiffness in cycling from the mean load during the maximum design storm to the cyclic strain limits predicted in the maximum design storm. For further details see the RP.

The authors have been advised informally by Dr. Cesar del Vecchio of Petrobras that when considering specifically the creep of HMPE, there appears to be a need for new definition of post installation (or quasi-static) modulus (usually the modulus used for offset calculations).

The modulus relevant to verifying vessel offsets under extreme conditions such as storms and loop current must take into account the persistence of the environmental loads. This puts HMPE in a class of its own. Thus, it is necessary to determine an

equivalent secant stiffness that incorporates creep (in the load and temperature corresponding to the loading and position of the HMPE rope in the mooring line).

The impact of HMPE creep in offset during a storm or a loop current event is much more important than the likelihood of creep rupture or the constant need for re-tensioning of mooring lines.

From 2SM we see that the intermediate stiffness is the secant modulus determined using load cycling of 20% MBL +/- 5% and resulting elongations using load cycling of 40% MBL +/- 15%. Inspection of Figure 21 shows the range of periods of oscillation of the moored system in 10,000 ft of water. It can be seen that there are combinations of first and second order oscillations. So what stiffness (or modulus) should we use? That is difficult to answer because we are not aware of test results to guide us.

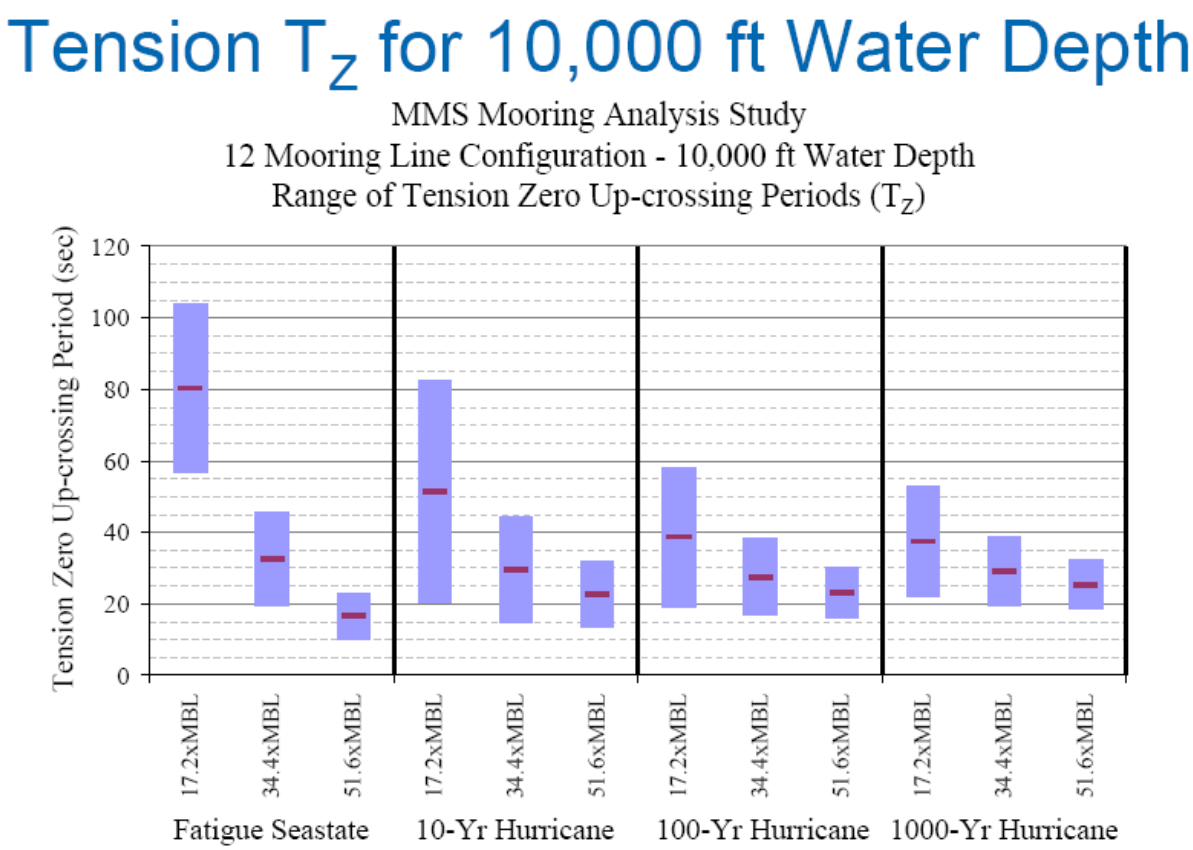


Figure 21. Plot of natural response periods in simulated wave conditions.

Finally, as explanation, the zero up-crossing period is the average interval between successive crossings of the mean in an upward direction. This provides us with a simple numerical method to determine the representative period for a time history, especially when the frequency content of the signal contains a range of frequencies. The "zero" part of the term indicates that the time history has been adjusted for the mean value.

A Comparison of Rope Diameters for Various Advanced Fibers

An important aspect of high-modulus advanced fiber ropes is that for the same breaking load, MBL, the high-modulus rope will have a smaller diameter than that for polyester, as shown in Figure 22. This feature is very important for MODUs where re-mooring the drilling floater is a frequent event. Smaller diameters mean less reel storage volume for the same MBL.

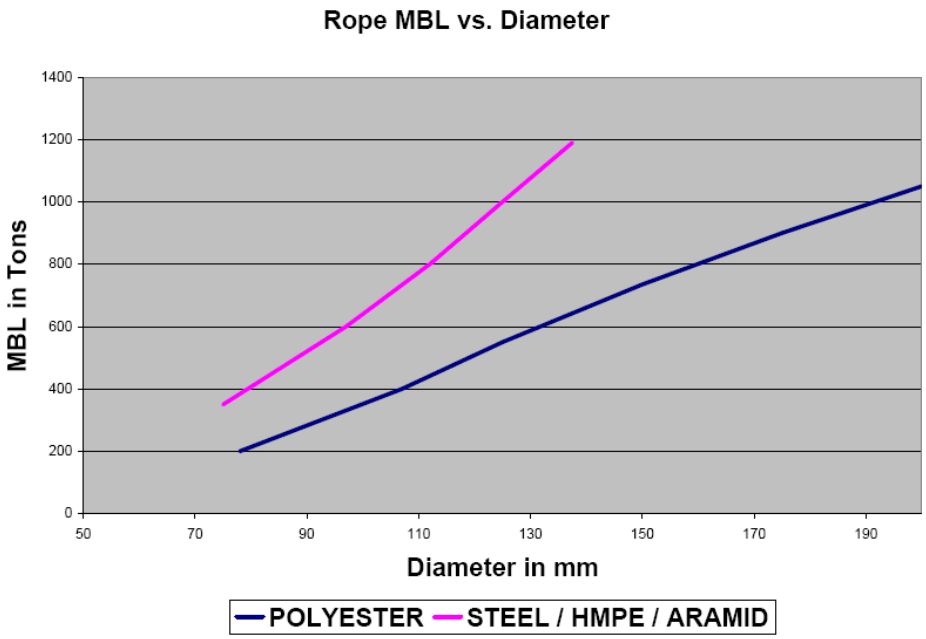


Figure 22. Typical rope MBL vs. rope diameter (Ref 17).

Fatigue Testing to Determine Strand-on-Strand Wear

For polyester ropes, the traditional means of assessing rope wear – other than at the yarn level with the yarn-on-yarn test-has been to use the API RP 2SM fatigue test (See Table 6.3.6 in Ref 1). A 300,000 cycle fatigue test can be used to show how an advanced fiber rope life compares with a polyester rope. This is a direct comparison, but it is an expensive test – running for 300,000 cycles. Comparisons of any fiber rope with the fatigue of spiral strand wire rope (80,000 cycle test) , or with six-strand wire rope (30,000 cycles) could be made, but if the fiber rope does not fail, no direct one-on-one comparison of an advanced fiber rope with polyester is possible other than by using the 300,000 cycle test. We have documented fatigue results for polyester ropes as contained in Appendix C. Published rope fatigue results advanced fibers are difficult to find. We have seen unpublished results for one vendor's HMPE product which indicates that HMPE is even better than polyester in cyclic tension-tension fatigue. Based on our knowledge of aramids, depending on product and marine finish used, the tension-tension fatigue life for aramid might be less than polyester under some conditions, <u>but still better than the steel components</u>. More quantitative data – rather than speculation - is needed for advanced fiber ropes. Fatigue tests generally provide a pass/fail result unless the cyclic rope is subjected to a break test after cycling.

Strand-on-Strand Abrasion Testing – The 20-Hurricane Test

The 20 hurricane test (Ref 11), under development for polyester fiber ropes, is considered by its developers to be viable for comparing advanced fiber ropes with polyester ropes. Unlike the fatigue test, the 20-hurricane test provides quantitative residual strength results, as opposed to pass/fail results. Some form of strand-on-strand test is needed because we have previously shown that the yarn-on-yarn test is not viable for comparing different advanced fibers with polyester.

The 20-hurricane test method has been under continuous development since GOM Hurricanes Katrina and Rita.

Even though years have passed, the destructive power of Katrina and Rita are still vivid in the industry. Strong hurricanes do not happen every year but it would be good practice to consider such hurricanes in the design process of polyester mooring lines of offshore structures. The author proposed that a useful and meaningful measure of the ability of a polyester mooring system to perform under the worst storm cycles would be to determine how a rope in a mooring leg would resist 20 hurricanes with the strength of Katrina, with a direct hit from one hurricane per year for a period of 20 years. Of course this is an extreme condition, but we have found that in general, all kinds of fiber ropes have a fatigue life that is much greater than the steel hardware that is part of the mooring system. So we need to use an intensive wear condition in order to discern the difference in rope and fiber designs.

The 20-hurricane test method consists of the following: steps shown in Figure 23.

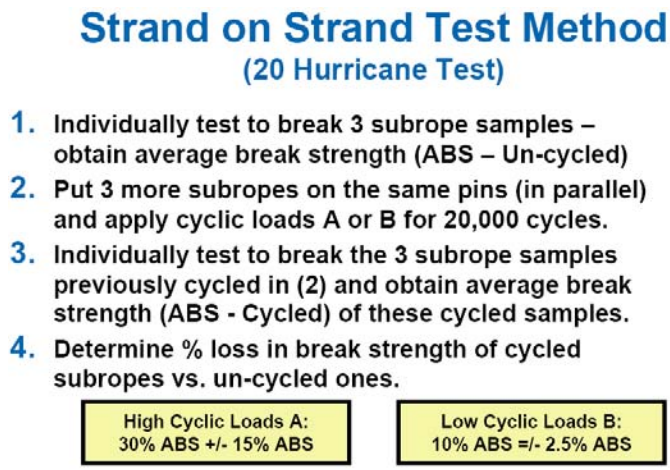


Figure 23. Strand-on-strand (20-hurricane) test method.

Two cyclic load conditions are shown, one for the windward line and the other for the leeward line.

The results to date – primarily for the windward line condition are shown in Figure 24.

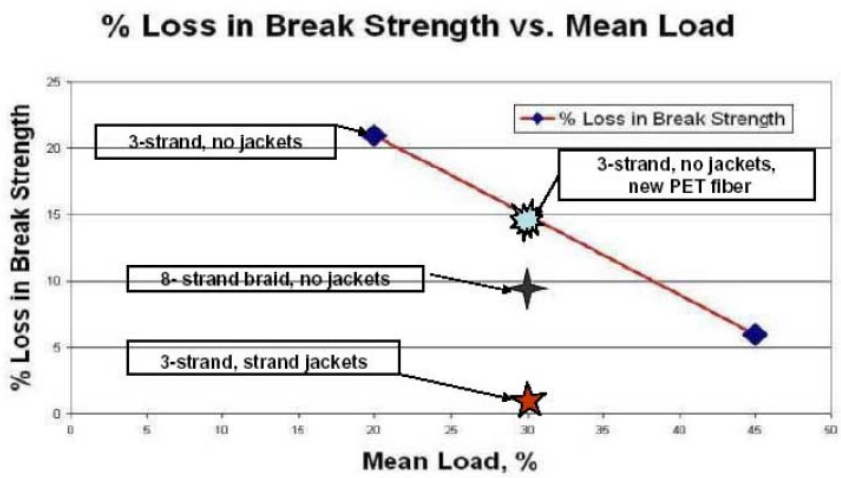


Figure 24. Strand-on-Strand Abrasion Testing of Eye-Spliced Polyester Subropes using the 20-Hurricane Method (Ref 11).

For polyester ropes, the data points associated with the red line, for eye-spliced 3-strand ropes with no strand jackets, demonstrate that for the same amplitude condition, +/- 15%, using a lower mean load (20%) results in a larger reduction in rope strength than by using a higher (45%) mean load.

For the 30% mean load, the 8 strand braid has a smaller reduction in breaking strength than for the 3-strand un-jacketed. Finally the 3 strand jacketed subrope shows almost no reduction in break strength, presumably because the strand jackets protect the toe-of splice region from strand-on-strand wear.

It should be pointed out that <u>all of the test results</u> shown in Figure 24 are satisfactory. It is difficult to believe that one mooring system will ever experience 20 large hurricanes in 20 years: We think that a more realistic number of large hurricanes over 20 years would be more like one or two, and the amount of cyclic damage would be less than 5%.

<u>This strand-on-strand test was purposely developed to be very severe</u> in order to quantitatively determine the difference in cyclic wear properties for various rope materials/finishes, rope core designs and splice designs. The fact that this test is called the 20-Hurricane Test does not mean that it has no applicability for deepwater locations that do not have hurricanes.

At present we have no 20-hurricane data for fibers other than polyester. However we would recommend that the best comparison of cyclic wear of advanced fiber subrope designs would be to compare 20-hurricane test results for the advanced fiber design with the equivalent polyester design.

Since (a) cyclic wear is the key condition that reduces the rope breaking strength over project life, (b) yarn-on-yarn testing is not valid, and (c) the key wear condition (for rope and subrope) is strand-on-strand abrasion of the subrope, we recommend this test method for evaluating advanced fiber subropes.

Other Failure Modes for Advanced Fiber Ropes

All of the advanced fiber manufacturers provide an abundance of chemical resistance, thermal resistance, and other properties. For all advanced fibers, nothing has been found to cause concern about a failure mode from these conditions as compared with polyester.

The key failure modes potentially affecting the structural integrity of advanced fiber ropes are:

1. Creep elongation for HMPE.
2. Compressive cyclic loadings for aramids.

Even when considering these potential failure modes, there are numerous potential applications for HMPE and aramids in mooring deepwater systems. For example, HMPE can work well with MODU applications calling for shorter fully-loaded times of operation than that for a permanently moored FPS production system. Further, an HMPE rope has a much smaller diameter for the same MBL than polyester, to make it easier to reuse and store for drilling operations over time, and HMPE is quite durable, causing reduced handling damage over time.

For aramids, specific rope designs can be made and tested to minimize compressive cycling effects. Further, improved marine finishes can be used for aramids to minimize this potential failure mode. Aramid ropes also have smaller diameters for the same MBL when compared with polyester ropes, just like that for HMPE.

Regulatory Requirements for Mooring Systems Using Synthetic Fiber Ropes

Following is the authors understanding of the very general regulatory requirements applicable to the technology we are evaluating. Please be advised that we cannot speak for the regulators.

It is our understanding that the regulators generally require permit applicants for synthetic rope mooring systems to prove that any new technology (advanced synthetic fiber mooring systems) have key capabilities that at least equal or exceed the performance of polyester mooring systems.

Therefore the authors believe that proof of the structural integrity of rope mooring systems utilizing advanced fibers should be accomplished by making comparisons of advanced fiber ropes with both polyester ropes and traditional steel mooring systems as appropriate.

API RP 2SM Relevance for Advanced Fiber Ropes

API RP 2SM (2SM) was issued in March of 2001 and an Addendum was added in May of 2007. A major re-write is in progress this year in 2010. 2SM was written to cover all synthetic fiber ropes, and it still contains useful information on advanced fibers available at that time.

The finding of this study on advanced fiber ropes is that 2SM is still generally appropriate for use with advanced fiber ropes as compared with polyester fiber ropes.

Following are some sections of API RP 2SM where this study provides additional information:

1. Section 4:

   4.2 - Rope Material (2001/2007) - Part B of this study includes additional fiber/rope design data on advanced fibers to that available in 2SM.

2. Section 6:

   6.3 - Rope Testing (2001/2007) – Part B of this study describes a subrope strand-on-strand abrasion test to evaluate cyclic wear, and its affect on reducing the residual break strength over a project life.

3. Section 10:

   Part A of this study provides a valuable sensitivity study in the form of a fully-coupled floating system analysis of three fiber stiffnesses (polyester, PEN and Aramid/HMPE) in water depths of 5,000, 10,000 and 15,000 ft.

4. Appendix B:

   Changes are needed in the section on creep measurement are needed to account specifically for the creep of HMPE

Advanced Fiber Workshop Expert Advice

Included as part of this project was a one day Advanced Fiber Workshop, held in Houston on September 29, 2009. Objectives of the workshop were to present preliminary results on the analysis of Part A, and the advanced fiber materials of Part B. The summarized agenda included:

1. Workshop Design and Objectives
2. Presentation and Feedback on:
   a. RAMS Analysis
   b. Presentation and Feedback on Advanced Fiber Technology
   c. Presentation and feedback on potential failure modes

3. Discussion of the Relevance of API RP 2SM for Advanced Fiber Ropes
4. Discussion of Making a Case for Advanced Fiber Ropes vs. Polyester

Appendix D contains the workshop agenda, the participants and a summary of feedback provided on the preliminary final report materials presented.

Acknowledgments

The authors wish to thank Mr. Mik Else of the MMS for his efforts and encouragement in helping us deal with contractual and procedures issues. Mr. Christopher Phillips, formerly with Performance Fibers, and currently with Whitehill Manufacturing, provided critical data on fibers used in this report, and we are grateful to him. To Dr. David Garrett of Stress we give thanks for helping us to formulate the sensitivity analysis and interpret results. Finally, we give our appreciation to the attendees of the Advanced Fibers Workshop for the technical insights and data provided to us.

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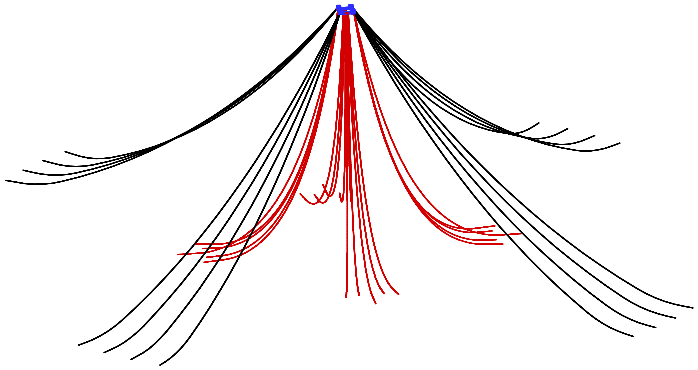
APPENDIX A

COUPLED ANALYSIS OF FLOATING PRODUCTION SYSTEMS

Coupled Analysis of Floating Production Systems

D.L. Garrett
Stress Engineering Services, Inc.



Outline

- Coupled Analysis
- Numerical Models
  - Rigid Bodies
  - Risers and Moorings
  - Connecting Links
- Example – Large Semi
  - 16 Mooring Lines
  - 20 Steel Catenary Risers

Coupled Analysis

- Details in a Single Model
  - Floater(s)
  - Risers
  - Mooring
- Why Coupled Analysis?
  - Accuracy
  - Efficiency
  - Damping from Drag on Mooring and Risers

Numerical Models

- Floater
  - Modeled as a Rigid Body
- Mooring Lines and Risers
  - Slender Elastic Lines
- Connecting Links
  - Springs, etc.

Rigid Body Models

- Large Motion Rigid Bodies
  - (X, Y, Z) of Reference Point
  - Euler Angles
    - Roll, Pitch, Yaw for small angles
- Large volume, small angle
  - Consistent linearization
  - Forces Depend on Hull Geometry

External Forces

Force **F** acting at point **P**

Generalized Forces $\mathbf{Q} = \mathbf{F} \cdot \frac{\partial \mathbf{P}}{\partial \mathbf{x}}$

Stiffness $\mathbf{K} = -\frac{\partial \mathbf{Q}}{\partial \mathbf{x}} = -\frac{\partial \mathbf{F}}{\partial \mathbf{x}} \cdot \frac{\partial \mathbf{P}}{\partial \mathbf{x}} - \mathbf{F} \cdot \frac{\partial^2 \mathbf{P}}{\partial \mathbf{x}^2}$

DOFs $\{\mathbf{x}\} = \{X, Y, Z, \phi, \theta, \psi\}^T$

Slender Elastic Lines

Equation of Motion $-(B\mathbf{r}'')'' + (\lambda \mathbf{r}')' + \mathbf{q} = \rho \ddot{\mathbf{r}}$

Constraint $\frac{1}{2}(\mathbf{r}' \cdot \mathbf{r}' - 1) = \dfrac{T - T_0}{AE}$

Galerkin's Method

$$\int_0^L \left[-B\mathbf{r}'' \cdot \delta\mathbf{r}'' - \lambda \mathbf{r}' \cdot \delta\mathbf{r}' + (\mathbf{q} - \rho\ddot{\mathbf{r}}) \cdot \delta\mathbf{r} \right] ds = (\mathbf{r}' \times \mathbf{M}) \cdot \delta\mathbf{r}' \Big|_0^L - \mathbf{F} \cdot \delta\mathbf{r} \Big|_0^L$$

$$\int_0^L \tfrac{1}{2}(\mathbf{r}' \cdot \mathbf{r}' - 1)\delta\lambda ds = \int_0^L \frac{T - T_0}{AE} \delta\lambda ds$$

Hydrodynamic Load

Morison Equation $\mathbf{q} = C_d \mathbf{V}_n \left| \mathbf{V}_n \right| + C_m \mathbf{a}_n - C_a \ddot{\mathbf{r}}_n$

Drag Force Linearized in Frequency Domain

Linearization Matches Energy Dissipated

Connecting Links

Extensional Spring $V = \frac{1}{2} K \left(\mathbf{P}_1 - \mathbf{P}_2\right) \cdot \left(\mathbf{P}_1 - \mathbf{P}_2\right)$

Rotational Spring $V = \frac{1}{2} K_r \left(\frac{\mathbf{E}_1}{|\mathbf{E}_1|} - \frac{\mathbf{E}_2}{|\mathbf{E}_2|} \right) \cdot \left(\frac{\mathbf{E}_1}{|\mathbf{E}_1|} - \frac{\mathbf{E}_2}{|\mathbf{E}_2|} \right)$

Generalized Force and Stiffness $\mathbf{Q} = -\frac{\partial V}{\partial \mathbf{x}}; \ \mathbf{K} = -\frac{\partial \mathbf{Q}}{\partial \mathbf{x}}$

Time Domain Procedures

Reduce to 2 First Order Equations

$$\mathbf{M}\ddot{\mathbf{y}} = \mathbf{Q} \text{ or}$$

$$\mathbf{M}\dot{\mathbf{z}} = \mathbf{Q}$$

$$\dot{\mathbf{y}} = \mathbf{z}$$

Trapezoidal Rule Integration

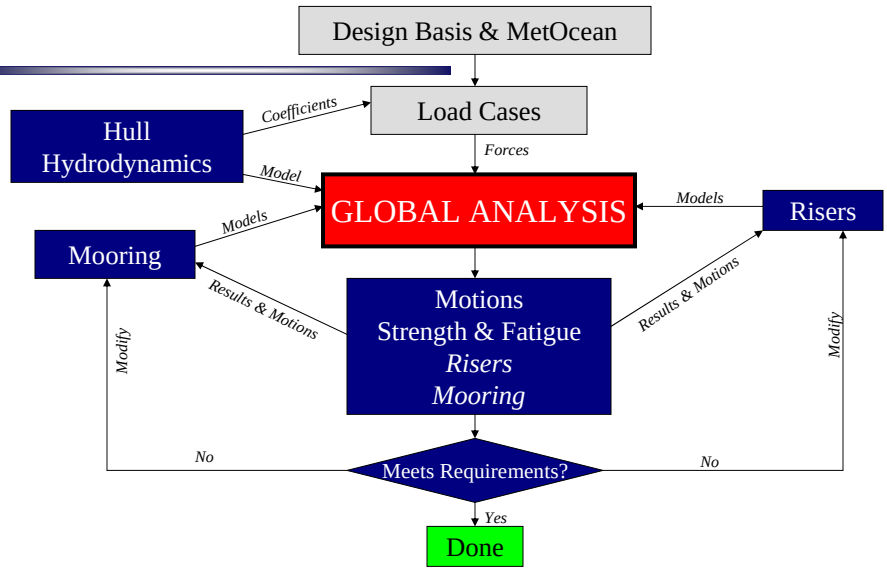
$$\mathbf{M}\left(\frac{\mathbf{z}_{\mathbf{n+1}} - \mathbf{z}_{\mathbf{n}}}{h}\right) = \frac{1}{2}\left(2\mathbf{F}_{\mathbf{n}} - \mathbf{K}\left(\mathbf{y}_{n+1} - \mathbf{y}_{n}\right)\right) + \frac{1}{2}\left(3\mathbf{H}_{\mathbf{n}} - \mathbf{H}_{\mathbf{n-1}}\right)$$

$$\frac{\mathbf{y}_{\mathbf{n+1}} - \mathbf{y}_{\mathbf{n}}}{h} = \frac{1}{2}\left(\mathbf{z}_{\mathbf{n}} + \mathbf{z}_{\mathbf{n+1}}\right)$$

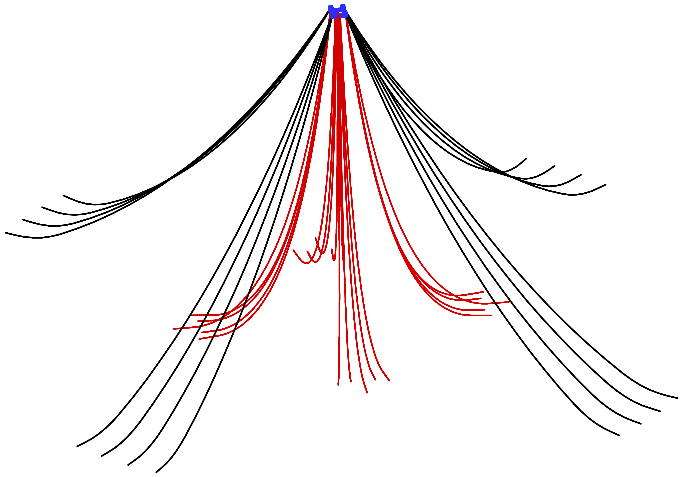
Frequency Domain Procedures

- Nonlinear Statics
- Linearize at Mean Position
- Statistical Linearization
  - Coefficients Depend on Solution
  - Iterative

Rational Approach To Marine Systems



Example - Semi
16 Mooring Lines and 20 SCRs



Size of Model

- Riser Elements 3,170
- Mooring Elements 384
- Total Line Elements 3,554
- Degrees of Freedom 21,546

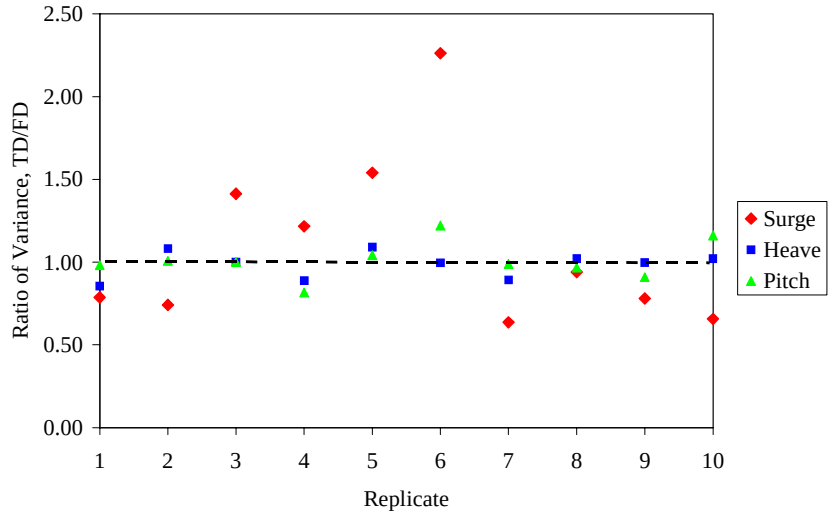
Time Domain vs. Frequency Domain

- Fatigue Sea State (H_s=3m)
  - Time Domain – 10 one hour simulations
  - Comparison of key results
    - Motions
    - SCR and Mooring Line
- Extreme Sea State (H_s=12.2m)
  - Use FD Result to force component in TD
    - SCR
    - Mooring Line

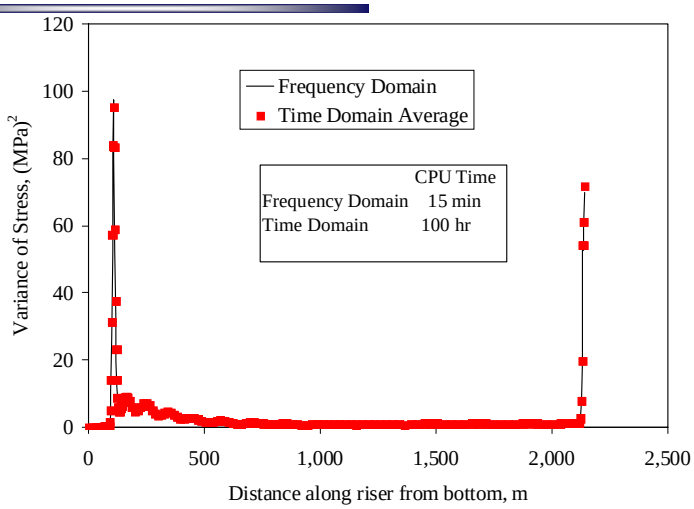
Fatigue Sea State

- Time Steps
  - Time Step 0.1s
  - Transient 2000s
  - Single Replicate 3600s
  - 10 Replicates 560,000 time steps
- Frequencies
  - Wave Frequencies 899
  - Wind Frequencies 470
  - Slow Drift Frequencies 470
  - Total Frequencies 1,839 frequencies

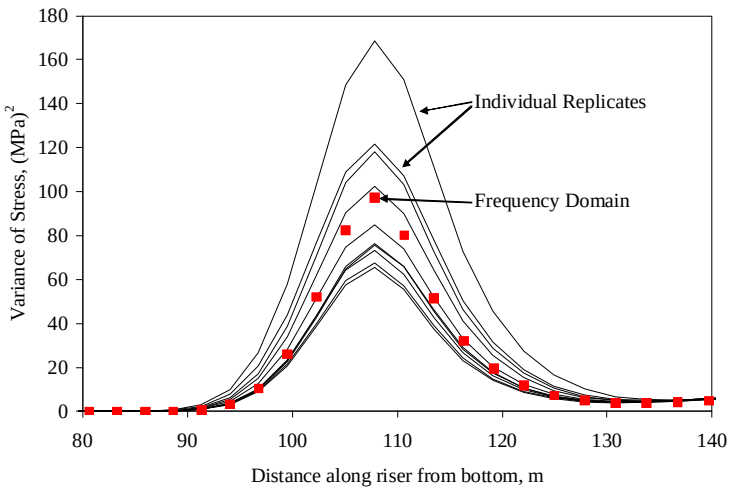
Rigid Body Motions



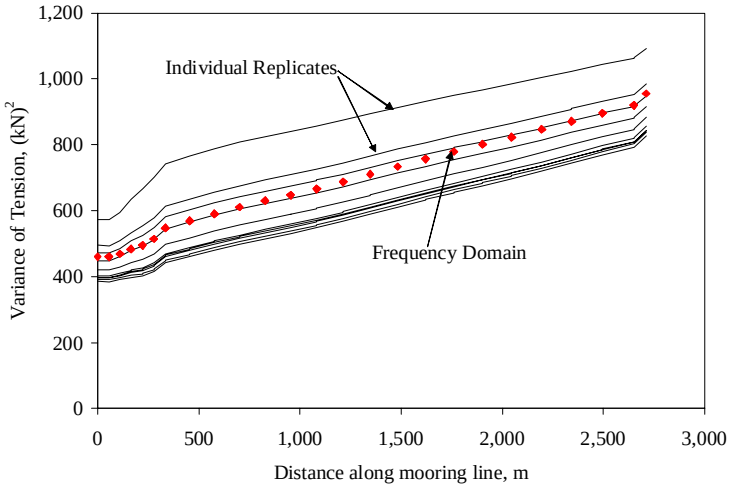
SCR Stress



SCR Stress at Seafloor



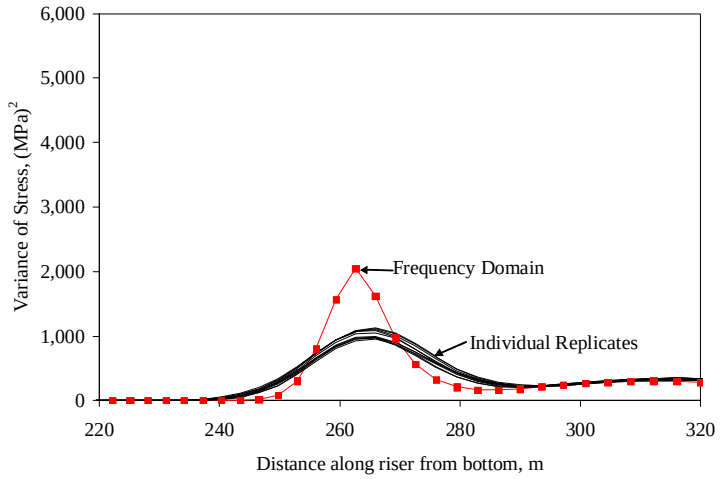
Mooring Line Tension



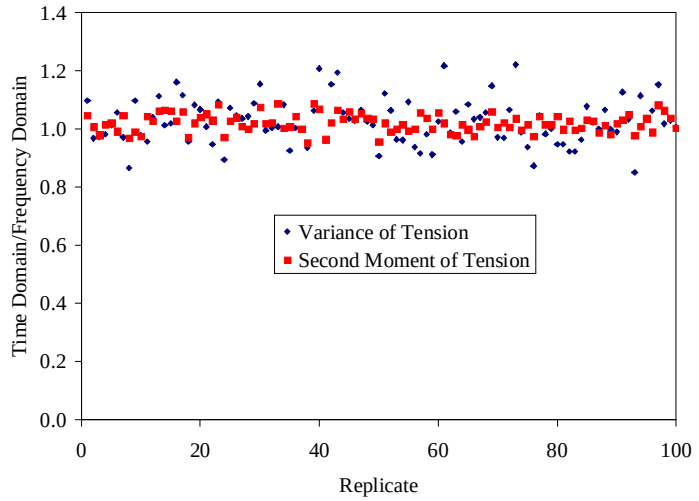
Extreme Sea State

- Coupled Frequency Domain Analysis
- Motions from Frequency Domain
  - 10 one hour simulations for SCR
  - 100 one hour simulations for Mooring Line
- Comparisons
  - SCR Stress at Seafloor
  - Mooring Line Tension Statistics

SCR Stress at Seafloor



Mooring Line Statistics



Conclusion

- Coupled Modeling Described
  - Accurate and Efficient
  - Both Time Domain and Frequency Domain
- Frequency Domain
  - Accuracy and Efficiency for Routine Design
- Time Domain
  - For Transients
  - Some Extreme Load Cases

APPENDIX B

MMS MOORING ANALYSIS SUMMARY

MMS Mooring Stiffness Comparison

Summary of Analysis Results
31 March 2009

Taking on your toughest technical problems

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Overview

- Evaluate effect of mooring stiffness on system performance
- Vessel response
  - Offset
  - Heave
  - Heel
- Mooring response
  - Tension
- SCR response
  - Stress & fatigue in sagbend (TDP)
  - Top angle
- TTR response
  - Stress & fatigue in seafloor stress joint
  - Tensioner stroke

2

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Overview, cont.

- 3 Water Depths
  - 5,000 ft
  - 10,000 ft
  - 15,000 ft
- 3 Mooring Rope Stiffnesses
  - 17.2 x MBL
  - 34.4 x MBL
  - 51.6 x MBL
- 4 Environments
  - Fatigue Event (H_S = 6.6 ft)
  - 10-Yr Hurricane (H_S = 32.8 ft)
  - 100-Yr Hurricane (H_S = 51.8 ft)
  - 1000-Yr Hurricane (H_S = 65.0 ft)

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Mooring Model

- Nominal horizontal force = 295-kips
- Nominal pretension ~ 15% of MBL
- Aspect ratio is approximately constant

Water Depth	Horizontal Force	Pretension		Aspect Ratio
(ft)	(kips)	(kips)	(% MBL)	(-)
5,000	295	534	13.5%	1.07
10,000	295	557	14.0%	1.06
15,000	295	580	14.6%	1.06

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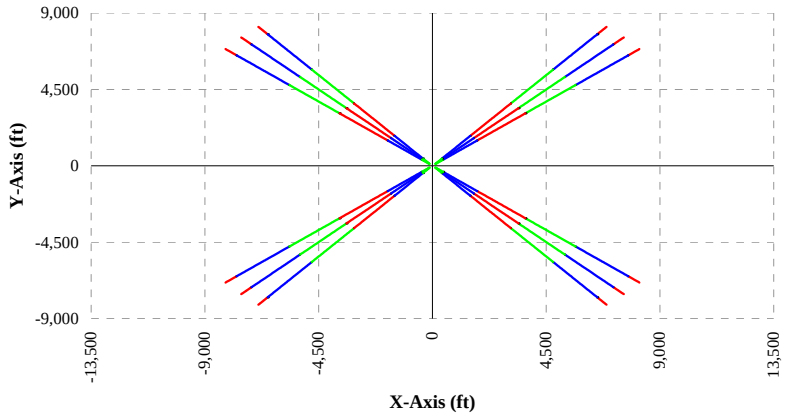
Mooring Model – Plan View

MMS Mooring Stiffness Study
Configuration 2 - 10,000 ft Water Depth
Base Mooring Model Plan View



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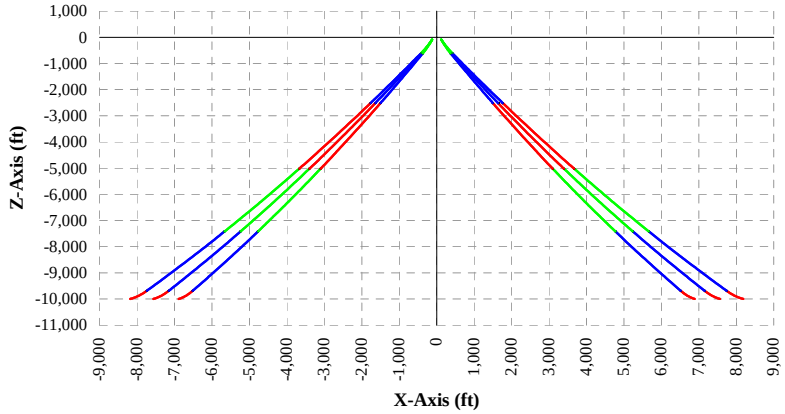
Mooring Model – Elevation View

MMS Mooring Stiffness Study
Configuration 2 - 10,000 ft Water Depth
Base Mooring Model XZ Elevation View



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SCR Model

- Insulated flowline, 10.750-in x 1.375-in
- Shape parameter F_H/WD ~ 2900
- Fully straked

Water Depth	Horizontal Force	Top Tension	Top Angle	F_H/WD
(ft)	(kips)	(kips)	(kips)	(-)
5,000	270	778	20.3	2,902
10,000	270	1,297	12.0	2,902
15,000	270	1,815	8.5	2,902

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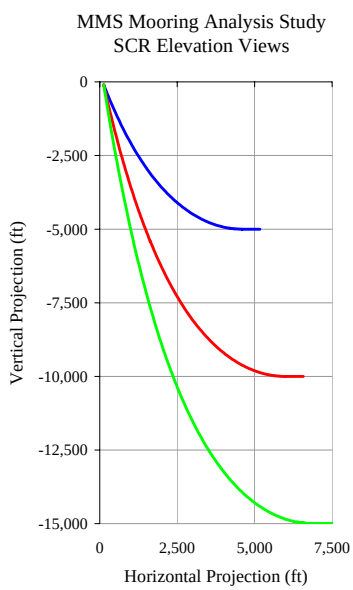
SCR Model, cont.



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TTR Model

- Dual casing riser
  - Outer casing - 10.750-in x 0.650-in
  - Inner casing – 7.625-in x 0.500-in
  - Tubing – 3.500-in x 0.254-in
- Steel stress joint
  - Length = 29.2-ft
  - Wall thickness at base of taper = 1.500-in

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TTR Model, cont.

- Overpull at stress joint = 200-kips
- Tensioner stiffness = 1.5% of nominal tension

Water Depth (ft)	Nominal Tension (kips)	Tensioner Stiffness (kips)	Overpull (kips)
5,000	767	11.5	200
10,000	1,289	19.3	200
15,000	1,811	27.2	200

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Load Case Matrix

Configuration	Water Depth	Mooring Configuration	SCR Configuration	TTR Configuration	Synthetic Rope Stiffness	FATIGUE	STRENGTH		
						Small Seastate (3 Heading)	H10 (3 Headings)	H100 (3 Headings)	H1000 (3 Headings)
Configuration 1 (C1)	5,000 feet	F_H = 295 kips	10.75-inch OD Insulated Flowline (T/WD=2,900)	10.75-inch OD Dual Casing (Overpull = 200-kips)	Low	X	X	X	X
					Medium	X	X	X	X
					High	X	X	X	X
Configuration 2 (C2)	10,000 feet	F_H = 295 kips	10.75-inch OD Insulated Flowline (T/WD=2,900)	10.75-inch OD Dual Casing (Overpull = 200-kips)	Low	X	X	X	X
					Medium	X	X	X	X
					High	X	X	X	X
Configuration 3 (C3)	15,000 feet	F_H = 295 kips	10.75-inch OD Insulated Flowline (T/WD=2,900)	10.75-inch OD Dual Casing (Overpull = 200-kips)	Low	X	X	X	X
					Medium	X	X	X	X
					High	X	X	X	X

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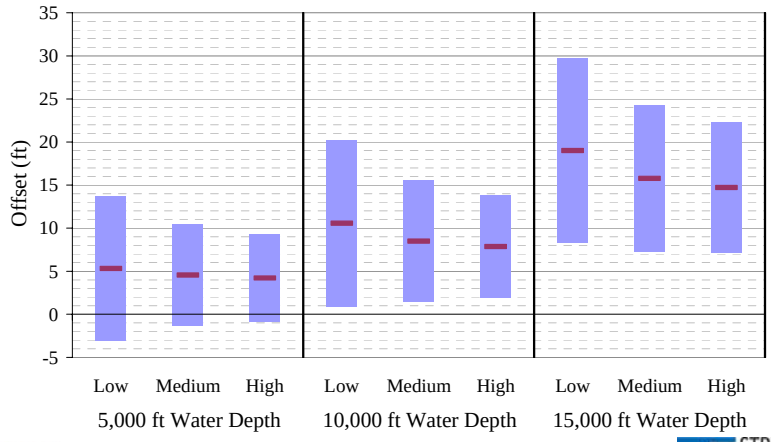
Vessel Offset – Fatigue Event

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Offset in Fatigue Seastate (H_S = 6.56 ft)



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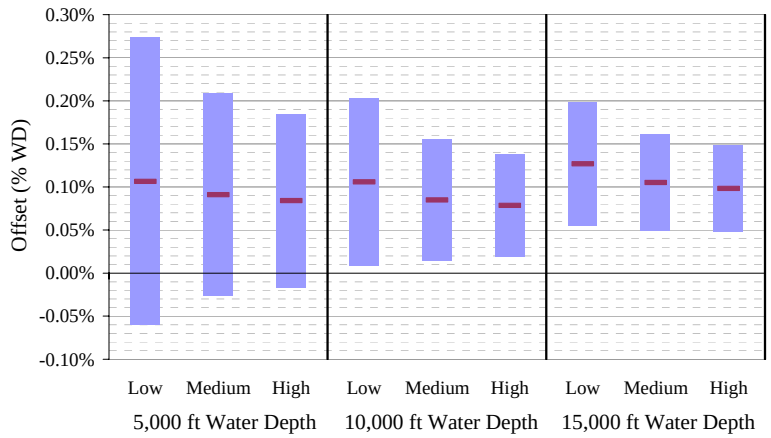
Vessel Offset – Fatigue Event

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Offset in Fatigue Seastate (H_S = 6.56 ft)



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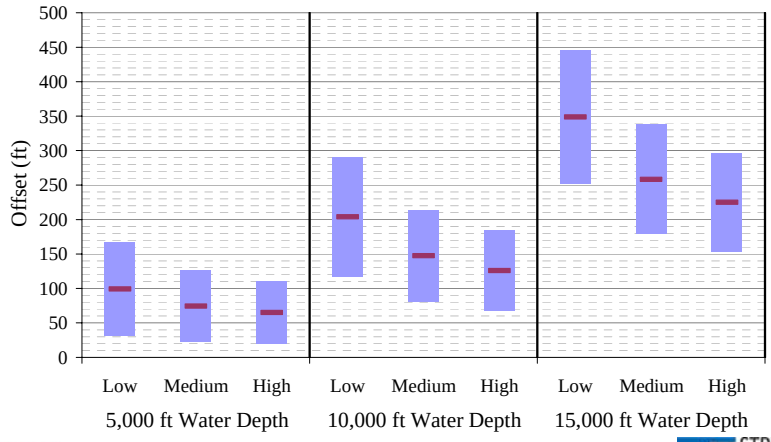
Vessel Offset – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Offset in 100-Year Hurricane (H_S = 51.8 ft)



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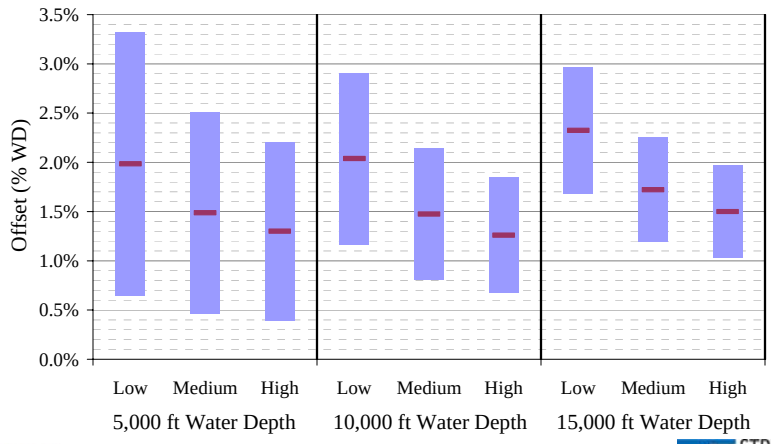
Vessel Offset – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Offset in 100-Year Hurricane (H_S = 51.8 ft)



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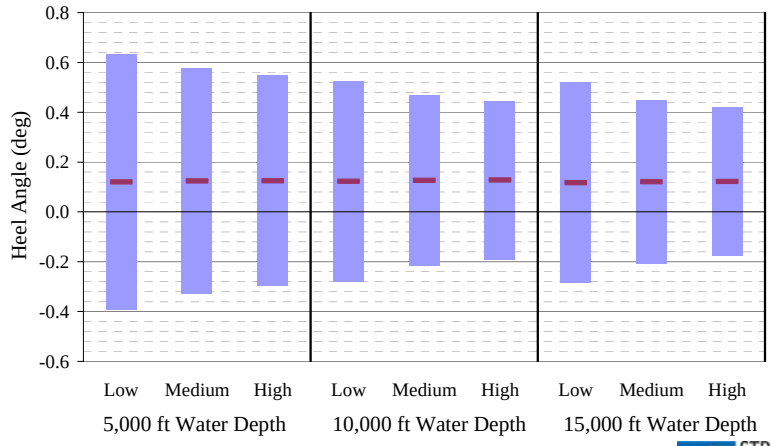
Vessel Heel – Fatigue Event

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Heel in Fatigue Seastate (H_S = 6.56 ft)



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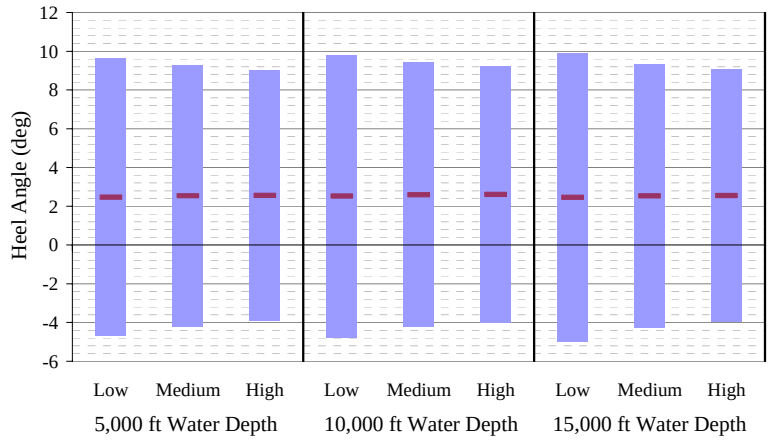
Vessel Heel – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Heel in 100-Year Hurricane (H_S = 51.8 ft)



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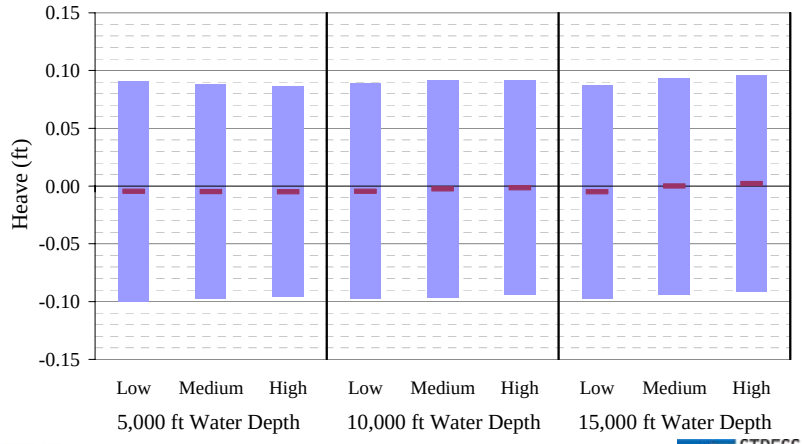
Vessel Heave – Fatigue Event

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Heave in Fatigue Seastate (H_S = 6.56 ft)



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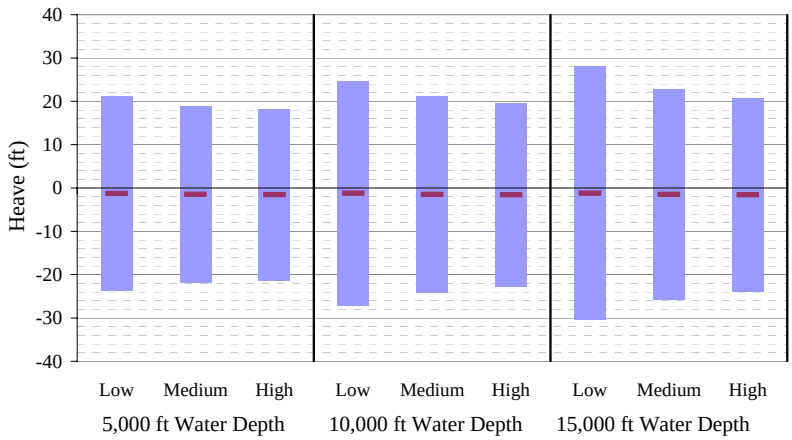
Vessel Heave – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Vessel Heave in 100-Year Hurricane (H_S = 51.8 ft)



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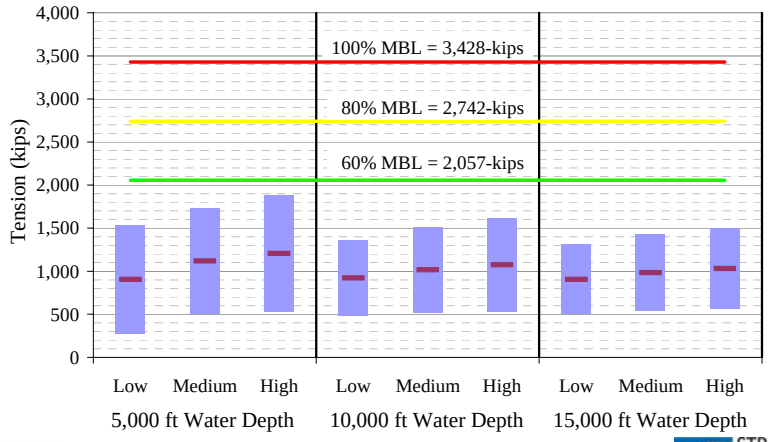
Mooring Tension – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Tension in 100-Yr Hurricane (H_S = 51.8 ft)



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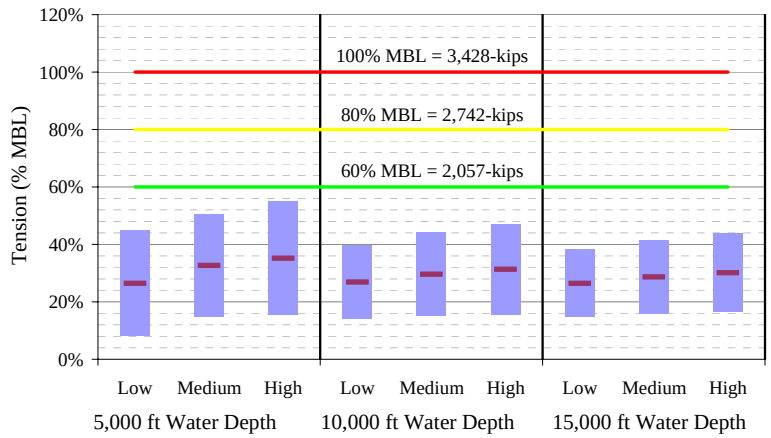
Mooring Tension – 100-Yr Hurricane

MMS Mooring Analysis Study
12 Mooring Line Configuration
Tension in 100-Yr Hurricane (H_S = 51.8 ft)



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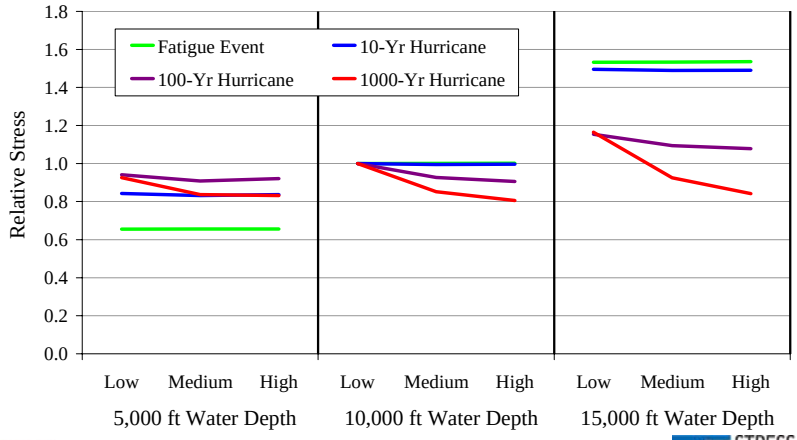
SCR – Relative TDP Stress

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative Stress at SCR Touchdown
Baseline = 10,000 ft Water Depth, Low Stiffness



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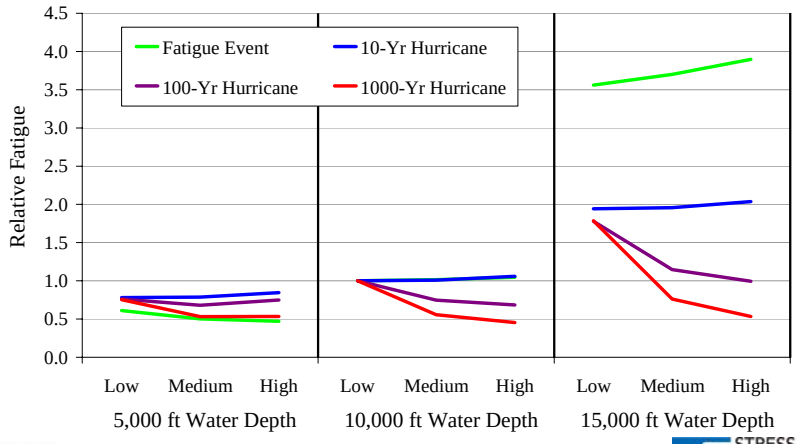
SCR – Relative TDP Fatigue

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative Fatigue at SCR Touchdown
Baseline = 10,000 ft Water Depth, Low Stiffness



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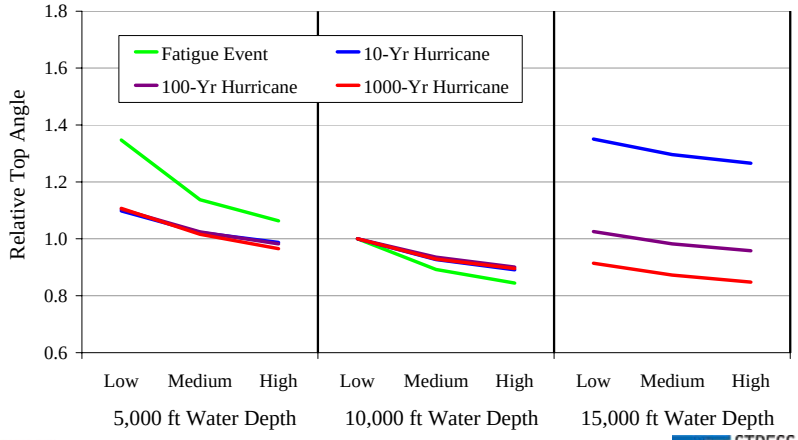
SCR – Relative Top Angle

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative SCR Top Angle
Baseline = 10,000 ft Water Depth, Low Stiffness



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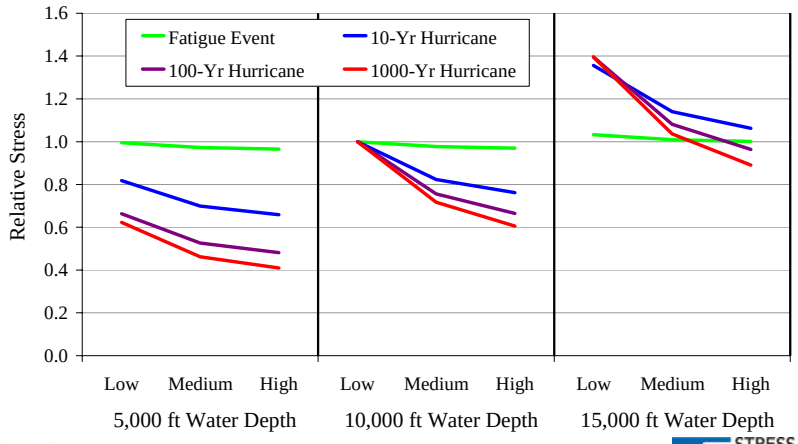
TTR – Relative Stress Joint Stress

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative Stress at Seafloor Stress Joint
Baseline = 10,000 ft Water Depth, Low Stiffness



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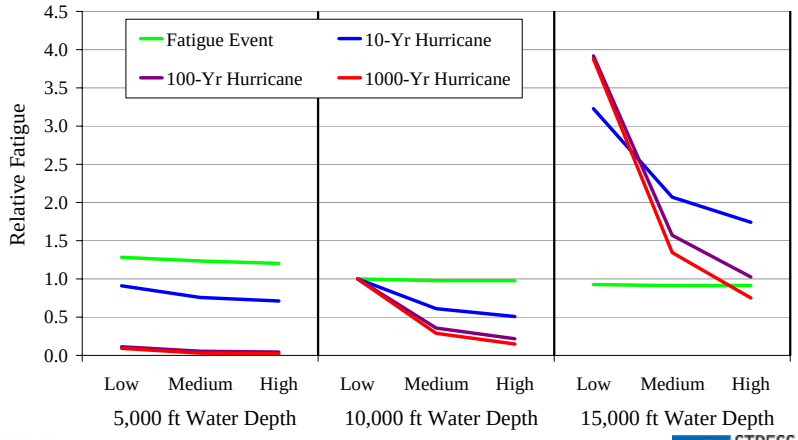
TTR – Relative Stress Joint Fatigue

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative Fatigue at Seafloor Stress Joint
Baseline = 10,000 ft Water Depth, Low Stiffness



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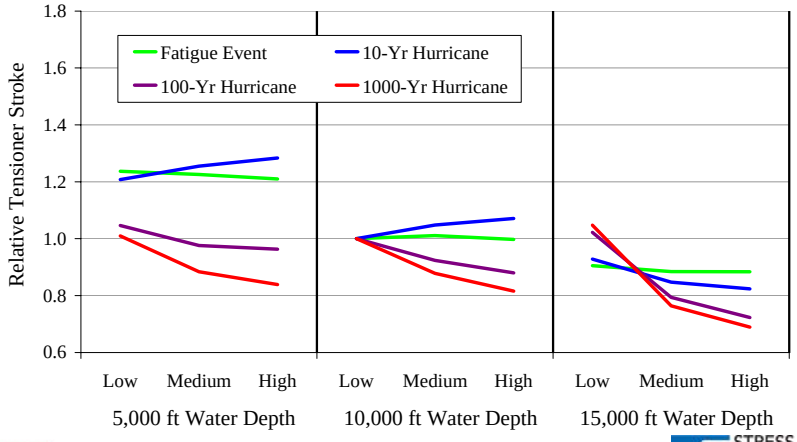
TTR – Relative Tensioner Stroke

MMS Mooring Analysis Study - 12 Mooring Line Configuration
Comparison of Relative Tensioner Stroke
Baseline = 10,000 ft Water Depth, Low Stiffness



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Work Progress

- Budgeted hours – 80 hrs
- DFR ~ 38 hrs as of 12:00 PM, 31 March 2009

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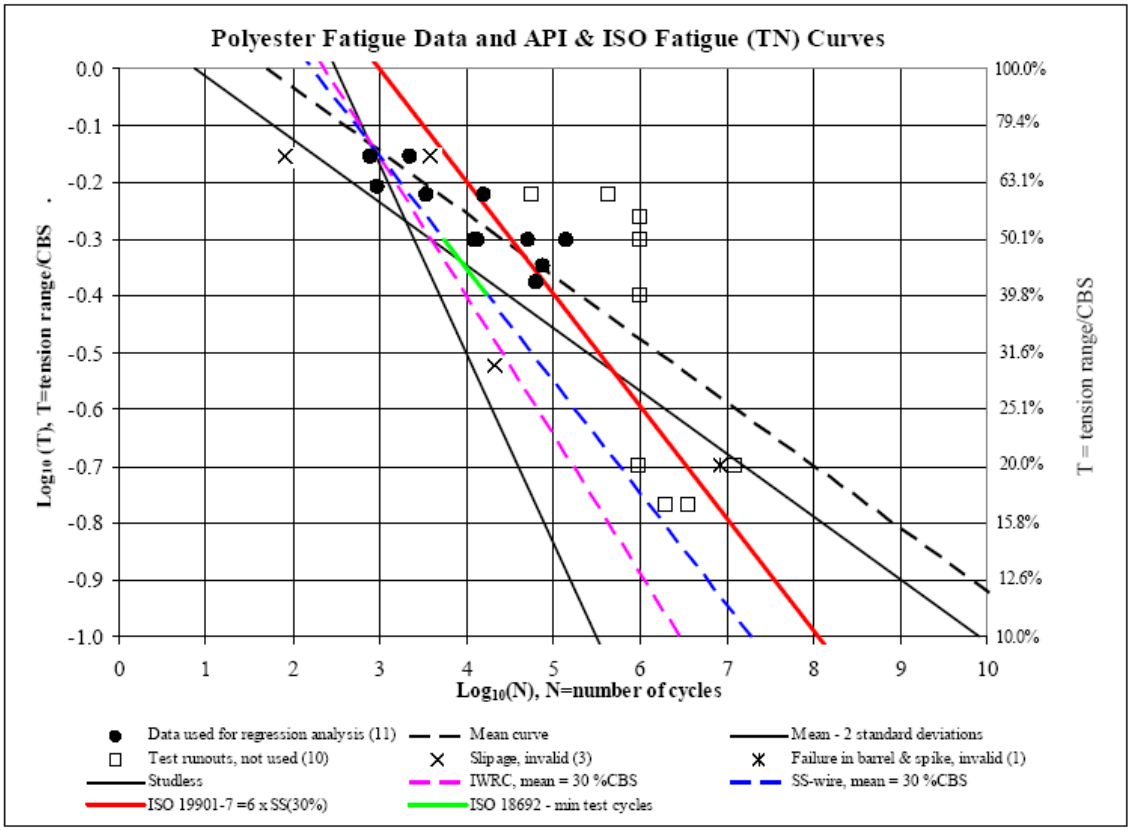
APPENDIX C
POLYESTER ROPE FATIGUE RESULTS

POLYESTER ROPE FATIGUE RESULTS

Plot of polyester fatigue data based on the TTI/NEL Durability Study (OTC 17510) provided by David Smith of ExxonMobil for the API RP 2SM re-write task group.

API 2SM TG – Polyester Fatigue

API 2SM Polyester Fatigue Data (Fig. 4.6.7.2) –with– API & ISO Fatigue (TN) Curves



URC/dws 6 12 May 2009

APPENDIX D
WORKSHOP RESULTS

REPORT ON
MMS-SPONSORED WORKSHOP ON:
USE OF ADVANCED FIBERS
FOR DEEPWATER MOORING SYSTEMS
Held September 28, 2009

WORKSHOP AGENDA

8:00 am	Light Breakfast Items for Gathering
8:30	Welcome, Workshop Objective and Introductions - Ray
9:00	MMS-Funded Project Tasks Outline - Ray
9:15	Developing the Case for High-Modulus Fiber Ropes for DW Moorings: Presentation of Results of a Fully-Coupled Dynamic Analysis of Floater, Risers and Moorings using RAMS Software – David Renzi
	Break when Appropriate
	Continue Case for High-Modulus Fiber Ropes
10:00	Constructive Feedback from Group on Results – Group
10:30	Develop Group Conclusions on Results
11:00	Comparison of Advanced Fiber/Yarn Engineering Properties - with Group Feedback.
11:30	Lunch Provided (45 minutes)
12:15pm	Comparison of Advanced Fiber Rope Engineering Properties – with Group Feedback
12:45	Presentation of Advanced Fiber Cost Estimates – with Group Feedback
1:00	Group Discussion of Failure Modes Different From Polyester – Ray and Group
1:45	Relevance of API RP 2SM for Advanced Fiber Ropes
2:15	Making the Case for Advanced Fiber Ropes for DW Moorings
2:45	Thanks To All
3:00	Adjourn

WORKSHOP PARTICIPANTS

	First Name	Last Name	Company	E-mail
1	Saltuk	Aksu	Mohr Engineering Division	Saltuk.Aksu@mohreng.com
2	Alfred	Allchorn	Meta Partners, Inc.	Awameta@cs.com
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7	Paul	Devlin	Chevron	PaulDevlin@chevron.com
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9	Arun	Duggal	SOFEC, Inc.	Arun.Duggal@sofec.com
10	Sid	Falk	US Department of Interior	Sid.Falk@mms.gov
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12	Tom	Fulton	InterMoor Inc.	tfulton@intermoor.com
13	Dave	Garrett	Stress Engineering Services, Inc.	dave.garrett@stress.com
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16	Mark	Huntley	Whitehill Manufacturing Corporation	mbh@whitehillmfg.com
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22	Jean-Paul	Michaud	Performance Fibers	
23	Ronaldo	Rosa Rossi	Petrobras	ronaldorr@petrobras.com.br
24	Neil	Schulz	Parker	Neil.Schulz@Parker.com
25	Arvind	Shah	Minerals Management Service	arvind.shah@mms.gov
26	Partha	Sharma	DNV-Houston	Partha.Sharma@dnv.com
27	Keith	Shepherd	Cortland Puget Sound Rope	Keith.shepherd@psrope.com
28	Hongbo	Shu	Shell International Exploration and Production Inc.	Hongbo.Shu@shell.com
29	Forrest	Sloan	Kuraray America, Inc.	Forrest.Sloan@kurarayamerica.com
30	Amy	Solomon	Teijin Aramid USA, Inc	amy.solomon@teijinaramid.com
31	Jenifer	Tule	Anadarko Petroleum	Jenifer.Tule@anadarko.com
32	Todd	Veselis	InterMoor Inc.	tveselis@intermoor.com

WORKSHOP PRESENTATIONS

Presentations made in the workshop consisted of the PowerPoint slides found in Appendix B, as well as slides generally consisting of the figures used in Part B of the Final Report.

WORKSHOP FEEDBACK NOTES

Project Team Response is Provided in Italics

PART A: ANALYSIS PRESENTATION FEEDBACK

Advanced fiber definition:

Which stiffness of the rope is selected and why? *Explained in Final Report*

Are Loop current events included in the dynamic analysis? *Yes – on offset plot.*

Need to show the response in time domain to verify the results – *We save this for detailed design – this is FEED (Front End Engineering Design)*

Also need to show the offsets. *Done*

On slide 28 add (y axis) Relative fatigue LIFE – *Yes, you are correct.*

Agreed on the conclusion that polyester works for all water depths however the volume will be large. *Yes, covered in Final Report*

Need to specify the conclusions more in detail ie. Cases that are studied… *Explained in Final Report*

3x change in the stiffness causes a change of 80% in lateral spring constant - Sometimes considered to have significant affect. *Yes*

PART B: MATERIALS PRESENTATION FEEDBACK

Fiber ropes are different from single fibers; single fiber results are purely academic. *We do not agree – fibers are the building blocks of ropes.*

The charts shown from Bunsell – no consistent mean load… So, recommendation: Re-run the tests with appropriate mean loads. *We agree, but have no funding to do so.*

Slide #2 HMPE 35-40 g/den. On Slide to we have a set of different fiber data performed under the same test method and equipment. *To change one result would not be appropriate. If you have a better complete set of fiber data, we will consider using it instead.*

Single fiber failure in fatigue does not affect the performance of the rope as much. *Yes, fiber results are only indicators. The truth is in less expensive 20-hurricane testing or more expensive full fatigue testing.*

Strand on strand? Or tension-tension fatigue testing? *Explained in Final Report*

Have you studied HMPE in DeepStar 6403? *This March 2004 DeepStar Report is proprietary to DeepStar. The report covers polyester, aramid and HMPE materials in some detail. The sensitivity study study of the spar hull mooring system does not appear to cover the semi-taut behavior of the mooring legs (no apparent catenary effect due to chain and connectors).*

Compare fibers with respect to abrasion wear. *The Final Report shows that strand-on-strand abrasion testing across different advanced fibers is not valid. A better test is strand-on-strand, 20 hurricane abrasion (cyclic wear) testing*

Permanent lines need more in-depth look*. Agreed – See Final Report*

MMS Comments: Polyester is being used comfortably based on specific cases (water depth, platform type, etc.) One question: What kind of info do I need to compare polyester vs other fibers? *See Final Report*

New product discussion:

- Need to cover the design life. *Yes, we consider 20 years.*
- Demonstrate Applicability *See Final Report*
- Justification of the new product is needed (ie use in somewhere else with success) *All of the advanced fibers have applicability for rope applications outside of deepwater permanent mooring systems. But other applications are outside of our scope.*
- Try to find the best way to prove the product is safe to use. *See our Final Report.*

Peter Davies – ask for tension-tension fatigue data. *Yes, but this is not an issue for advanced fiber ropes in general. More critical is steel mooring component fatigue.*

Fiber failure modes are known, focus on the rope data to understand how the rope will perform. *Thank you for your advice. We believe that it is important to know both how fibers perform, and how that translates into rope performance.*

Aramid fiber stress-strain data will be provided (could not catch the name). *To change one result would not be appropriate. If you have a better complete set of fiber data, we will consider using it instead.*

<u>YOY Testing Discussion</u>:

Applicability of YOY on High modulus fibers is questioned. *Yes, we believe that yarn-on yarn testing across different advanced fibers is not valid. We recommend strand on strand testing instead.*

It is hard to quantify the material due to dependence on the finish. *Yes, different marine finishes for polyester and aramids impact rope performance, and we have indicated this in the Final Report.*

Change in the yarn-on-yarn crankshaft stroke – *Will it change anything? (Duration of life, etc?). We won't know this unless we test it.*

What is the data source? (Should the fiber have marine finish? How long the marine finishes stay on the fiber?). *Marine finishes are a proprietary part of the fiber or rope manufacturers confidential design. We can only test what we get, and explain that results might differ with different marine finishes. This discussion is appropriate for polyesters and aramids primarily.*

Agreed to conclusion using YOY results to compare 2 different fibers is not relevant. *Thanks*

MMS:

- Need a quick reference for mooring design.
- Need to be updated on the new technology and need to stay up with the industry.
- Need to know the specific limitations of materials.
- Discussion on YOY and an alternative

To the best of our ability we have tried to provide a useful and concise guide to currently available fiber rope technology. Aside from this report, the new revised API RP 2SM, and the 2004 Handbook of Fibre Rope Technology are the best sources of advanced fiber rope technology.

Strand On Strand

Need to clarify: 3 Ropes for each data point. *This is clarified in the Final Report.*

Temperature, Sample Length, Couple of photos of the sample, Failure point etc… *This will be covered in the upcoming DeepStar CTR 9402 Report*

Are there any scaling effects? *Scaling of subropes to full ropes is well understood. Scaling from fibers, to yarns, to strands to subropes is more complex. Rope makers keep their scaling techniques from yarn to subrope confidential, but the rope purchaser will have access to test results of the purchased rope.*

Mean load reduces the relative motion. *We have lost the context of this question.*

Need a standard test procedure. *See Final Report.*

COST:

Need to contact rope manufacturers for more accurate data.

$/EA Need to use static stiffness value.

We could not get consensus on cost at the workshop. The vendor community is very competitive. Advanced fiber materials will cost say two to four times that for commodity polyester fibers. The Final Report says no more. The advanced fiber rope purchaser will need to ask rope makers for the total cost (fiber cost plus rope manufacturing cost) of the desired rope.