



GUIDANCE NOTES ON

THE APPLICATION OF FIBER ROPE FOR OFFSHORE MOORING

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Updates

February 2014 consolidation includes:

- March 2012 version plus Corrigenda/Editorials

March 2012 consolidation includes:

- August 2011 version plus Corrigenda/Editorials

Foreword

These Guidance Notes have been prepared to assist the industry with standardized criteria for applications of fiber ropes in offshore mooring systems. These Guidance Notes describe criteria for design, materials, testing, manufacturing, installation and subsequent survey of fiber ropes to be used in offshore mooring systems to be classed or certified by ABS. These Guidance Notes should be used in conjunction with other Rules and Guides published by the American Bureau of Shipping as specified herein. During the preparation of these Guidance Notes, ABS recognizes that industry participation is a vital factor due to rapidly progressing nature of this technology, and for the success of developing an appropriate standard which satisfies practical classification requirements. ABS appreciates the industry's input in the development of these Guidance Notes.

These Guidance Notes supersede the ABS *Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring, 1999*. The main purpose of these new Guidance Notes is to reflect the latest technology developments and industry practice for applications of fiber ropes in offshore mooring systems.

These Guidance Notes provide detailed guidance for three fiber materials: polyester, HMPE (high modulus polyethylene), and aramid (aromatic polyamide). This does not exclude the use of other fibers in the design of mooring systems, provided that good engineering practice is followed, all relevant fiber properties are considered and justification for the use is adequately documented. Designers of mooring system are encouraged to consult fiber rope experts and manufactures when other rope materials are considered.

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

GUIDANCE NOTES ON THE APPLICATION OF FIBER ROPE FOR OFFSHORE MOORING

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SECTION 1 General

1 Scope

The main purpose of these Guidance Notes is to describe criteria for design, material, testing, manufacturing, installation and subsequent survey of fiber ropes to be used as mooring components in offshore mooring systems. The secondary purpose of these Guidance Notes is to highlight differences between fiber rope mooring systems and typical steel mooring systems, and to provide guidance on how to handle these differences during system design and installation.

In view of the influence of rope properties on mooring system performance, these Guidance Notes include details of how rope testing, mooring analysis and installation can be integrated to provide a consistent mooring system design methodology. In this matter, these Guidance Notes cover the following aspects:

- Design and Analysis Considerations of Mooring System
- Design Criteria for Mooring Components
- Design of Fiber Rope
- Testing and Production of Yarn and Rope
- Inspection and Certification during and after Rope Production
- Survey and Witness by ABS Surveyor

Where the mooring design, construction and installation details are similar or equivalent to steel wire/chain mooring systems, no further guidance is included in these Guidance Notes. These Guidance Notes are not intended to provide a comprehensive manual on all aspects of mooring design, construction and installation since these details are adequately covered by other recognized standards, such as API RP 2SK.

The publication of these Guidance Notes reflects the growth in offshore mooring applications for fiber ropes and the need for a consolidated written guidance. These Guidance Notes summarize industry experience and common practices in application of fiber ropes for offshore mooring and provides a general guidance to check the integrity of fiber ropes application.

These Guidance Notes applies to fiber ropes used in the mooring system of both permanent and temporary offshore installations such as:

- Monohull Based FPSOs
- Semi-Submersible Based FPU's
- Mobile Offshore Drilling Units (MODUs)
- Drill-Ships
- Spar Platforms
- CALM Buoys

Therefore, these Guidance Notes should be used in conjunction with the latest ABS publications as follows:

- i) *ABS Rules for Building and Classing Mobile Offshore Drilling Units (MODU Rules)*
- ii) *ABS Rules for Building and Classing Single Point Moorings (SPM Rules)*
- iii) *ABS **Rules** for Building and Classing Floating Production Installations (FPI **Rules**)*
- iv) *ABS Guide for Certification of Offshore Mooring Chain (Chain Guide)*

These Guidance Notes are not intended to cover general marine applications of fiber ropes, such as berthing and mooring lines at piers and harbors, towing hawsers on tugs, mooring hawsers on Single Point Moorings (SPMs) and Tension Leg Platform (TLP) tendons.

2 Definitions

Aged Rope: The rope that has been subjected to preloading and subsequent environmental loads to reach a fully bedded in condition.

Amplitude to Diameter Ratio (A/D): The ratio of VIM amplitude to the diameter of a Spar or column of a deep draft semisubmersible.

Aramid Rope: Rope made of aromatic polyamide fiber, which has higher strength and stiffness than polyester rope. The issue of axial compression fatigue needs to be addressed.

Average Breaking Strength: The average of the results of several rope break tests.

Axial Compression Fatigue: A failure mode for fiber rope such as aramid under low tension or compression.

Bedding-In: The loading process of compaction of internal rope components to reduce construction stretch.

Creep Model: A model that generates creep and creep rupture design curves for ropes based on yarn test data, particularly applicable to HMPE ropes.

Creep: The increase in rope length under sustained tension or cyclic loading.

Creep Rate: The creep strain over unit increment of time.

Creep Regime: The time regime that can be clearly distinguished by a different behavior of the creep rate for an HMPE rope.

Creep Rupture: Failure of fiber rope, such as HMPE, due to continuous creep over time under a specific load and temperature.

Design Service Life: The intended life for the mooring system of a specific project. The design service life for the mooring system can be the same as or different from that for the floating unit.

Dynamic Stiffness: The ratio of change in load to change in strain in a rope under cyclic loading, typically normalized by MBS.

Elongation: The change in length between two gage marks, separated by a known distance (gage length) as tension is applied to the rope or as tension is maintained over time.

Fiber Finish: A designation of the process and finish used on a fiber for a particular purpose (e.g. “marine finish”).

Fiber Grade: A designation of the quality of a particular fiber, indicating adherence to tolerances for properties.

Fiber Type: A designation given by the fiber producer which indicates the manner in which a particular fiber has been drawn or spun, processed, and treated with various finishes and/or oils.

FPI: Floating Production Installations as defined in the ABS **FPI Rules** [1].

FPSO: Floating Production Storage and Offloading Unit as defined in the ABS **FPI Rules** [1].

Frequency Domain (FD) Analysis: An analysis method that considers system responses in terms of frequency rather than time. The analysis will produce responses such as dynamic tension or motion responses in a form of statistical values (standard deviation, significant, and maximum, etc.).

FSO: Floating Storage and Offloading Unit as defined in the ABS *FPI Rules* [1].

Group Approval: Approval for a group of different sizes of rope of the same design based on one or two rope tests.

HMPE Rope: Rope made of high modulus polyethylene fiber, which has higher strength and stiffness than polyester rope. The issue of creep needs to be addressed.

Jacket: A braided or plastic covering which is placed over the rope, subrope, or individual strand for protection and to hold the rope structure together.

Lay Length: The length along the axis of a rope in which a strand makes one complete spiral around the rope axis.

Low Frequency (LF) Response: The tension or motion dynamic response that has a period close to the natural period of the moored system, typically in the range of 100 to 400 seconds.

Manufacturing Specification: A document which completely describes the process of making the rope, including instructions for each step of the manufacturing process.

Material Certificate: A document prepared by the manufacturer and the fiber producer to certify that the type and grade of fiber material, the properties of the yarn, and the material used in rope production are those specified in the Rope Design Specification.

Material Chemical Composition: The generic designation of a specific chemical composition and process of material used in the fiber (i.e., nylon, polypropylene, Aramid, high-modulus polyethylene).

Material Specification: A document, which completely describes the fiber material used in the rope, including the material chemical composition, the fiber producer, the fiber type and grade, and the yarn test properties.

Minimum Bend Radius (MBR): Minimum radius to which the fiber rope can be bent without damage to the rope construction (including, as applicable, the jacket).

Minimum Break Strength (MBS): The wet breaking strength guaranteed by the rope manufacturer for a specific rope.

MODU: Mobile Offshore Drilling Unit, a floating drilling vessel that engages in exploratory drilling.

Mooring Line: A mooring component which consists of chain, wire rope, fiber rope or a combination of them to connect the floating unit with the anchor for stationkeeping.

Non-Dimensional Stiffness (K_p): Stiffness normalized by MBS.

Non-Torque Component: Mooring component for which twist is not generated or negligible due to tension variation, such as chain and spiral strand. Polyester rope is generally non-torque but can be a torque component by design.

Non-Torque-Matched Approach: The approach in which a non-torque fiber rope is connected to a torque component such as 6-strand wire rope.

Parallel Construction: The most commonly used type of fiber rope construction for offshore moorings consisting of parallel subropes held together by a braided jacket.

Particle Ingress: Penetration of soil particles into the load bearing fiber core.

Permanent Mooring: The mooring system for a floating platform that has a long design service life, typically 20 years or more.

Polyester Rope: Rope made of polyester fiber, which is the most widely used fiber rope for offshore mooring.

Post-Installation Rope: The rope that has been subjected to a specific preload during installation.

Pre-Installation Rope: The rope that has not been subjected to a specific preload.

Preloading: A procedure applying a specific load to induce bedding in, thus reducing construction stretch and increasing rope stiffness during mooring installation.

Pretension: The tension initially set in the mooring lines for normal operation.

Production Rope Sample: A rope sample removed from production or selected after production for the purpose of testing.

Prototype Rope Sample: A rope sample fully complying with the rope design specification made for the purpose of testing either before an order is placed or before regular rope production begins for an order.

Quality Assurance Manual: A document which completely describes the Manufacturer's quality control and assurance program.

Quality Control Data Sheet: A document which lists the important parameters in setting up and accomplishing a designated step of the rope making and assembly process, including normal values and tolerances.

Quality Control Report: A document prepared at the completion of rope making and assembly which includes the completed quality control data sheets, material certificates, and inspection reports.

Quasi-Static Stiffness: The static stiffness, which is reduced to account for the rope creep under an environmental event.

Rope Assembly Interface: Any physical connection which is a permanent part of the rope assembly (e.g., thimble) which is used to interconnect rope assemblies or to connect a rope assembly to another tension member (e.g., a wire rope or chain) or hardware (e.g., an anchor, a buoy, or a platform). [Note: this excludes shackles and other detachable links.]

Rope Assembly Length: The distance between the assembly interface points as measured at a defined tension and by a method agreed to by the Purchaser and the Manufacturer.

Rope Assembly: The rope, its terminations, and any other accessory gear such as thimble.

Rope Construction: The manner in which the fibers, yarns, strands and subropes are assembled together in making the rope.

Rope Design Specification: A document which describes the design of the rope, including the numbers and arrangements of strands, the strand pitch, the material chemical composition, and the manufacturing method.

Rope Fiber Area: The total cross-section area of load-bearing fiber in the rope, which is determined by dividing the weight of fiber per unit length by the fiber density.

Rope Production Report: A document which describes the rope product, including rope design, termination design, and assembly length, and which includes the material certificates, material test results, and the various data sheets.

Rope Termination: The method (e.g. splice, potted socket, wedged socket) by which the rope is attached to the assembly interface.

Rope Yarn: The largest yarn-like component of a strand generally formed by twisting intermediate yarns together.

Rotation Property: The relative rotation between one end and the other end of a rope of unit length caused by application of tension.

Rotation: The tendency of the unrestrained end of a rope to rotate about its axis when tension is applied.

ROV: Remotely Operated Vehicle.

SD: Standard deviation.

Segment: A length of chain, steel or fiber rope with terminations that can be connected to provide the required length of a mooring line.

Soil Filter: A barrier incorporated in fiber rope for blocking ingress of soil particles.

Spar: A type of FPI as defined in the ABS *FPI Rules* [1].

Splice: A termination type which is normally formed by passing the rope around a spool or similar attachment, and then separating the rope into strands or sub-ropes and tucking these strands or sub-ropes back into the rope structure.

Static Stiffness: The ratio of change in load to change in strain in a rope under slowly varying tension for a period of time, typically normalized to MBS.

Static-Dynamic Model: A stiffness model where the elongation under mean and cyclic load are represented by different slopes in a load versus elongation curve.

Stiffness Model: A simplified representation of the complex fiber rope load versus elongation behavior.

Stiffness: The ratio of change in load to change in strain in a rope in units of force such as kN or kips. Stiffness is typically normalized by the MBS in this document.

Strain: The ratio of elongation to the gage length over which the elongation takes place.

Strand: The largest component, which is twisted, braided, or otherwise assembled together to form the finished sub-rope.

Subrope: The largest component, which is assembled together to form the finished rope.

Termination Specification: A document which completely describes the design of the termination and the process of making that termination, including materials and steps for making or assembling the termination.

Test Insert: A short segment typically 10 m to 15 m long, placed at the top of the fiber mooring line, which can be taken out for testing and inspection.

Three-Slope Model: A stiffness model defined by 3 different slopes for mean load, LF, and WF dynamic load in a load versus elongation curve.

Time Domain (TD) Analysis: A dynamic analysis method that considers system responses as a function of time. The analysis produces dynamic tension or motion responses in a form of time history.

T-N Curve: A fatigue design curve that defines the relation between the mooring line tension range and number of cycles to failure.

Torque Component: Mooring component for which twist is generated due to tension variation, such as 6-strand or 8-strand wire rope.

Torque-Matched Approach: The approach in which a fiber rope is designed to match the torsion characteristics of a torque component such as 6-strand wire rope.

Two-Slope Model: A stiffness model defined by 2 different slopes for mean load and dynamic load (combined LF and WF) in a load versus elongation curve.

Upper-Lower Bound Model: A simplified stiffness model where the rope stiffness is defined by the maximum and minimum value for a specific rope.

Vortex Induced Motion (VIM): The vessel motions of a Spar or a deep draft semisubmersible induced by vortex shedding under current.

Wave Frequency (WF) Response: The tension or motion dynamic responses that have periods of waves, typically in the range of 4 - 30 sec.

Wire Rope Construction: Rope construction resembling steel wire rope either as subrope or as full rope.

Yarn Break Strength: The average breaking load from yarn break tests.

Yarn Creep: The characteristic of the yarn to undergo a time related non-recoverable increase in length when subjected to sustained load.

Yarn Elongation: The average elongation at break from several yarn break tests.

Yarn: A general term for a bundle of untwisted or twisted fibers.

Yarn-on-Yarn Abrasion Property: The average number of cycles of tested yarns to failure at designated loads in yarn-on-yarn abrasion tests.

SECTION 2 Scope and Procedure for Design and Analysis

1 General

This Section provides general guidance for the design and analysis of mooring systems incorporating fiber ropes. Requirements as specified in the *ABS Rules for Building and Classing Floating Production Installations (FPI Rules)* [1] and API RP 2SK (2005) [2] are generally applicable unless otherwise provided in these Guidance Notes. The purpose of design verification is to confirm that the proposed mooring system satisfies the specified design conditions, Rules, Guides and other related standards.

2 Submission of Design, Testing, Manufacturing, and Survey Documentation

In addition to the applicable documentation listed in the *FPI Rules* [1] and the *ABS Rules for Building and Classing Mobile Offshore Drilling Units (MODU Rules)* [3], design, testing, manufacturing, and survey documentation for fiber rope mooring system should include the following when applicable:

TABLE 1
Documentation for Design, Testing, Manufacturing, and Survey

No.	Document	Responsibility
1	Mooring Design and Analysis	Mooring Designer
2	Minimum Breaking Strength Test	Rope Manufacturer
3	Elongation and Stiffness Test	Rope Manufacturer
4	Splice Qualification Test	Rope Manufacturer
5	Particle Ingress Resistance Test	Rope Manufacturer
6	Torque Match with Steel Wire Rope Test	Rope Manufacturer or Mooring Designer
7	HMPE Creep Rate Verification Test	Rope Manufacturer
8	HMPE Creep and Creep Rupture Models and Basis	Fiber Producer
9	Aramid Axial Compression Fatigue Test	Rope Manufacturer
10	Yarn Dry Breaking Strength and Elongation Test	Rope Manufacturer
11	Yarn on Yarn Abrasion Test	Rope Manufacturer
12	Rope Design Specification	Rope Manufacturer
13	Yarn Specification	Rope Manufacturer or Fiber Producer
14	Manufacturing Specification	Rope Manufacturer
15	Termination Specification	Rope Manufacturer
16	Quality Control Report	Rope Manufacturer
17	Rope Production Report	Rope Manufacturer
18	Material Certificate	Rope Manufacturer or Fiber Producer
19	Survey during Installation	Mooring Installer or Operator
20	Annual Survey	Operator
21	Special Periodical Survey	Operator
22	Special Event Survey	Operator
23	Survey after MODU Mooring Failure due to Tropical Cyclone	Drilling Contractor

3 Mooring Configuration

A mooring system with fiber ropes can be configured as either a taut-leg or a catenary system. The choice depends on many considerations that are beyond the scope of these Guidance Notes. A taut-leg mooring (TLM) has a smaller mooring footprint than the conventional catenary mooring system. This can be particularly important for the field layout of production installations and in congested development areas. The taut leg mooring systems also differ from conventional catenary mooring systems in which the anchor must resist substantial vertical load.

4 Fiber Rope Types Covered by these Guidance Notes

These Guidance Notes provide detailed guidance for three fiber materials: polyester, HMPE (high modulus polyethylene), and aramid (aromatic polyamide). This does not exclude the use of other fibers in the design of mooring systems, provided that good engineering practice is followed, all relevant fiber properties are considered and justification for the use is adequately documented. Designers of mooring system are encouraged to consult fiber rope experts and manufactures when other rope materials are considered.

Fiber ropes offer several advantages over their steel counterparts in the design of mooring systems. However, unlike steel wire ropes, fiber ropes should be treated with due consideration of particular fiber specific characteristics. Some general discussion of material properties with regard to mooring design considerations is included in various sections.

The choice of fiber material depends on the nature of the application and on the level of confidence in the material. Currently, polyester is widely used for offshore mooring applications due to its low stiffness which induces less tension during design storm, good resistance to axial compression, good strength to weight ratio and good creep resistance. HMPE and aramid have better strength to weight ratios and are stiffer than polyester. However, HMPE can be subject to creep, potentially leading to a creep rupture problem, and aramid can be subject to axial compression fatigue failure under low tension or compression. These issues should be properly addressed in the design.

For taut-leg mooring systems, the fiber rope axial stretch provides load elongation characteristics which the catenary geometry traditionally provides in the conventional steel system. The lower elasticity of polyester makes it suitable for certain deep water TLMs. Other fibers such as HMPE and aramid may be more suitable for applications where frequent handling is required or for ultra-deep water TLM applications. Comparison of alternative fiber ropes in terms of their mechanical properties alone is not sufficient for design; the relative merit of each fiber rope can only be assessed through comparison of mooring system performance obtained from a detailed mooring analysis.

SECTION 3 Polyester Mooring Design and Analysis

1 Mooring System Arrangement

The fiber ropes should generally be fully submerged and freestanding, and the mooring line typically consists of:

- A top steel section, which can be chain or wire rope
- A fiber rope section, which can be made of several segments for manufacturing and handling
- A bottom steel section, which can be chain or wire rope

Guidance for the top and bottom steel section for permanent moorings is provided below. The same guidance can be considered for MODU moorings, but some of the guidance may not be directly applicable to them because of the temporary nature of the MODU operation.

1.1 Top Steel Section

For permanent moorings, the top steel section should have a suitable length to allow fiber rope stretching during preloading and further stretching and creep over platform life. The top of the fiber rope should be kept well below the water surface and clear of the fairleads throughout the design service life. In areas where marine growth can develop inside the rope, the top of the fiber rope should be kept at a sufficient depth based on marine growth profile to avoid such growth. In the absence of marine growth profile, currently a general industry practice is to keep the top of the fiber rope at least 100 m below the water surface. To determine an appropriate depth, however, a number of other factors should also be considered, such as:

- *The type of marine growth.* Some marine growths are more harmful than other marine growths
- *The type of soil filter.* Some soil filters are more efficient in blocking marine growth than others
- *Protective coating.* Penetration of marine growth into the load bearing fiber can be blocked by effective protective coating

In addition to above considerations, there are other factors to be considered for the length of the top steel section, such as installation tolerances on anchor locations, fabrication length tolerance, ground chain length tolerance and ground chain below mudline tolerance, removal of inserts, planned platform movements for drilling or spreading out catenary riser fatigue damage by shifting the touchdown point where fatigue damage is most severe.

1.2 Bottom Steel Section

For permanent moorings, the bottom section should have a suitable length to keep the fiber rope clear of seafloor in leeward lines under the severe storm environment (typically 100-year return period). For ropes fitted with soil filter, this condition applies only to the intact condition, provided the seafloor does not include hard soil and is free from other obstructions. Otherwise this condition applies to both intact and damaged condition.

2 Stiffness Characteristics

Polyester ropes as well as other fiber ropes are made of materials with visco-elastic properties, so their stiffness characteristics are not constant and vary with the load duration and magnitude, the number and frequency of load cycles, and the loading history. In general, polyester mooring lines become stiffer after a long time in service. Historical loading above a certain level may lead to a permanent increase of the rope length and results in a softer mooring system if no re-tensioning is performed. Because of this complex rope behavior, it is not possible to develop models that represent the precise stiffness characteristics of the rope. Currently the industry relies on some simplified models that capture the most important characteristics and at the same time yield conservative prediction of line tensions and vessel offsets.

3 Stiffness Model

The static-dynamic model [4] is recommended as the primary model for the following reasons:

- It is based on rigorous research
- It reflects the basic elongation behavior of polymer material
- It yields good approximation of line tension and vessel offset if the model parameters are properly determined
- Most commercial software can handle this model and therefore specialized software is not required.
- It allows efficient mooring analysis

An alternative to the static-dynamic model is the upper-lower bound model [6], which has been used by the industry for a long time because of its simplicity and unavailability of a better model. The accuracy of this model depends on selection of the upper and lower bound values, and improper selection of these values often leads to too conservative or non-conservative predictions. These Guidance Notes provide some guidance on establishing the upper and lower bound values for this model.

Other models have been used by the industry. They can be acceptable if they reflect the basic elongation behavior of polymer material and produce realistic predictions. However, these Guidance Notes provide no guidance for these models, and it is up to the designer to provide evidence for the validity of the model.

3.1 Static-Dynamic Model

3.1.1 Fundamental Elongation Behavior of Fiber Material

The behavior of fiber material, especially the elongation behavior, is very much dependent on the macro-molecular structure of the material (also called ‘morphology’). The morphology of polymer materials typically shows crystalline parts and non-crystalline (amorphous) parts. Static stiffness is the stiffness of a tension member when it is loaded slowly, leaving time for both the amorphous and crystalline part to react the load. The resulting fiber stiffness is an average of the stiffness of both parts. Dynamic stiffness is the stiffness response of a tension member when it is under cyclic loading. As the amorphous part does not react fast enough to the quickly changing loading regime, it is the stiffer crystalline part that takes on the load, resulting in a more ridged response of the whole fiber [7]. For polyester rope, this behavior results in dynamic stiffness being 2 to 3 times the static stiffness. Failure to account for this behavior will inevitably yield inaccurate line tension and vessel offset predictions, and the inaccuracy for vessel offset can be particularly large.

The static-dynamic model was developed to account for this fiber rope elongation behavior. In this model, the static stiffness is utilized for the initial region of the loading curve up to the mean load. Afterwards, the dynamic stiffness is used to predict the cyclic part of the loading (Section 3, Figure 1). This model more accurately simulates the actual conditions faced by a fiber rope mooring out at sea. A mooring line under a severe environment typically experiences a steady mean load and dynamic loads oscillating around the mean load. Section 3, Figure 1 represents a 2-slope model where LF and WF dynamics are combined. Separating the LF and WF dynamics will result in a 3-slope model. An industry study [5] indicates that the difference between predictions from the 2-slope and 3-slope model is small, and therefore the simpler 2-slope model is recommended.

3.1.2 Definition of Static and Dynamic Stiffness

The stiffness of a fiber rope is expressed as:

$$EA = \frac{\Delta F}{\Delta \varepsilon} \dots\dots\dots (3.1)$$

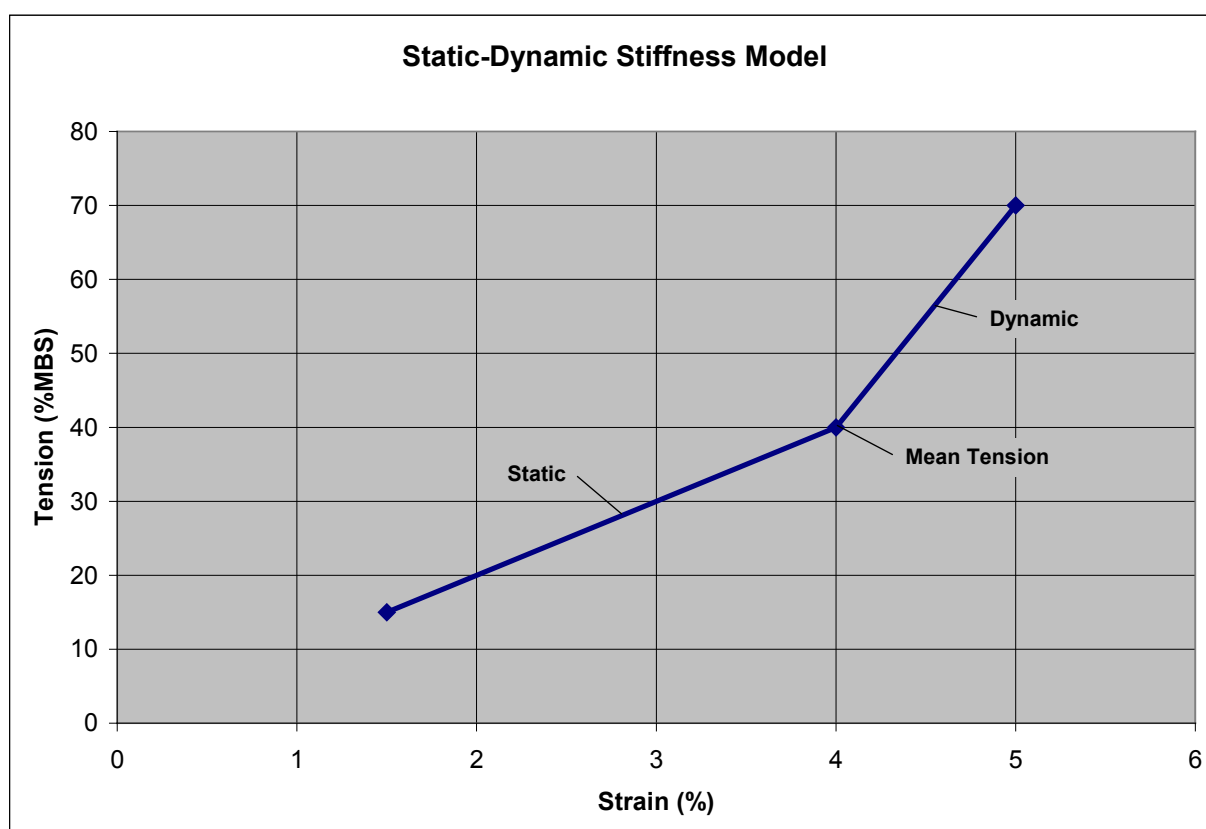
where ΔF is the change in load, $\Delta \varepsilon$ is change in strain, and EA is the stiffness or the modulus times the cross-sectional area of the rope. The stiffness is usually expressed in units of force such as kN or kips. Equivalently, a non-dimensional stiffness K_r can also be expressed as:

$$K_r = \frac{EA}{MBS} \dots\dots\dots (3.2)$$

where MBS is the Minimum Breaking Strength.

In addition, these Guidance Notes deal with two types of stiffness, dynamic and static and the non-dimensional dynamic stiffness is denoted as K_{rd} and the non-dimensional static stiffness is denoted as K_{rs} .

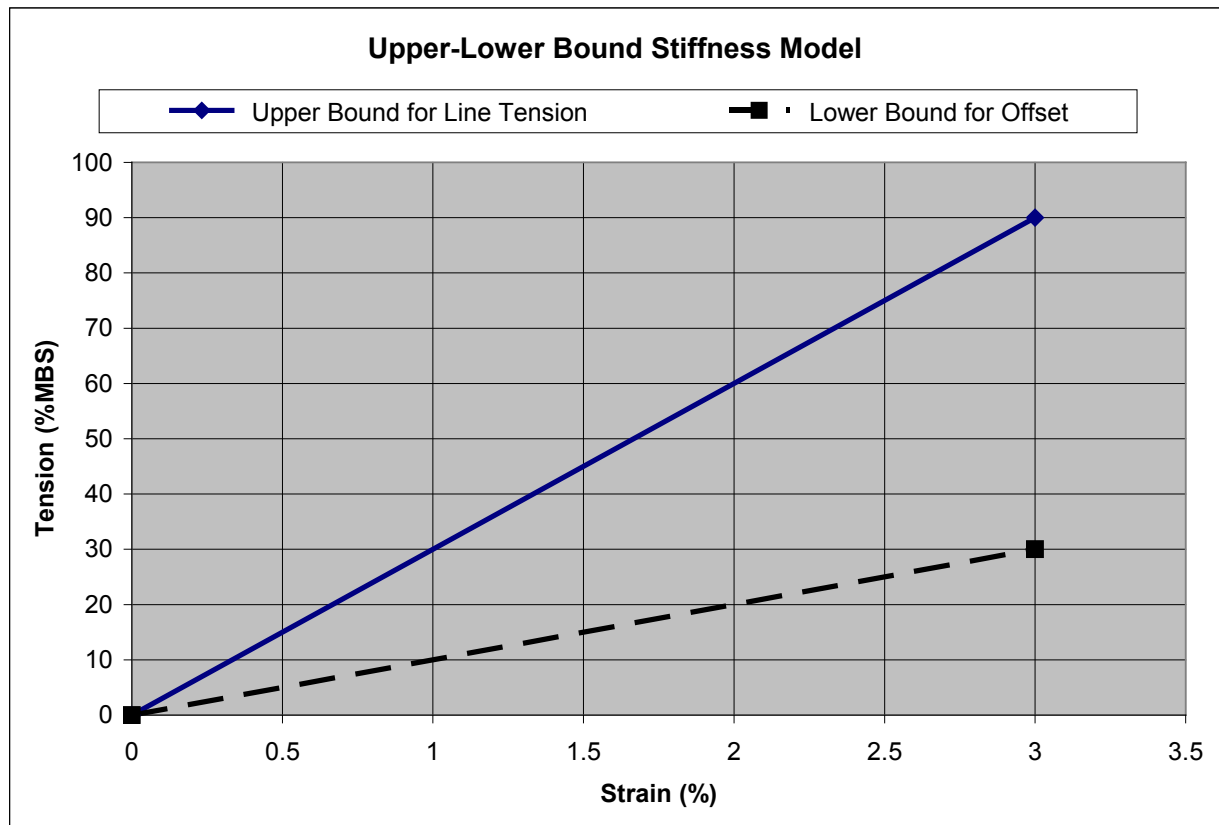
FIGURE 1
Static-Dynamic Stiffness Model



3.2 Upper-Lower Bound Model

The upper-lower bound model was first introduced in 1999 in response to the growing needs of the industry for a practical stiffness model for polyester mooring systems [5]. This model defines a lower bound (post-installation) and upper bound (storm) stiffness values as a first approximation. These lower and upper bound values are then used to calculate maximum offsets and line tensions, respectively. A plot of typical upper bound (storm) stiffness and the lower bound (post-installation) stiffness values is shown in Section 3, Figure 2.

FIGURE 2
Upper-Lower Bound Stiffness Model



The upper-lower bound model has been widely used in the industry due to its simplicity and unavailability of a better model. However, it does have certain shortcomings such as:

- There is no systematic method to determine the upper and lower bound stiffness, and therefore these values are often arbitrarily determined
- Polyester rope has a very complicated stiffness property, which is a function of load type, amplitude, duration, and history. Using 2 limiting values to represent the complicated behavior often results in overly conservative or non-conservative analysis results, depending on the design parameter being considered. To avoid this situation, many designers use some intermediate values, but again the selection of these values is rather arbitrary, resulting in more confusion over this issue.

Although the upper-lower bound model is a simple and widely used model, determination and use of the upper and lower bound values requires careful consideration.

3.3 Other Stiffness Models

Other stiffness models can be acceptable if they meet the following criteria:

- The model reflects the basic elongation behavior of polymer material as discussed in 3/3.1.1
- The model produces realistic line tension and vessel offset predictions under various conditions
- The model properly accounts for line length changes due to creep and permanent elongation

4 Dynamic Stiffness

4.1 Equation for Dynamic Stiffness

The three-parameter equation [8] is recommended for dynamic stiffness:

$$K_{rd} = \alpha + \beta L_m + \gamma T + \delta \log(P) \dots \dots \dots (3.3)$$

where

- L_m = mean load as % of MBS (i.e., 20 is 20% of MBS)
- T = load amplitude as % of MBS
- P = loading period in seconds

There is a trend in the industry to take out the tension amplitude and loading period in the equation, claiming their impact is negligible. This leaves a simplified dynamic stiffness model depending on mean load only. Investigations reveal that this simplified model is a poor fit to the test data. To have a general model for all polyester ropes, all 3 parameters should be kept, unless data are available to justify the use of a simpler formulation.

4.2 Effect of Load Amplitude

The tension amplitude T in Equation 3.3 is based on test data for sinusoidal loading with constant amplitude. Industry studies indicate that the effect of tension amplitude can be significantly less for the extreme response under stochastic loading [9]. Under fatigue loading, the effect of tension amplitude can be negligible. Based on this, the following practice is recommended:

- For sinusoidal loading such as Spar VIM in the lock-in region, T is the maximum tension amplitude for strength and fatigue analysis
- For strength analysis under stochastic loading such as storm loads or Spar VIM in the transition region, T is 0.5 times the maximum tension amplitude.
- For fatigue analysis under wave loading, T is negligible

4.3 Effect of Loading Period

For WF response, the loading period P can be taken as the response (or spectral as approximation) peak period. For LF response including VIM, it can be taken as the natural period of the moored system. Dynamic stiffness is not very sensitive to loading period since it is a function of $\log(P)$.

4.4 Effect of Load History

To investigate the impact of load history, the rope conditions are classified in 3 categories:

1. *Pre-installation:* The rope has not been preloaded and therefore has the lowest stiffness
2. *Post-installation:* The rope has been preloaded during installation and achieved an initial bedding in
3. *Aged:* The rope has experienced severe loadings beyond the preload to reach a fully bedded in condition

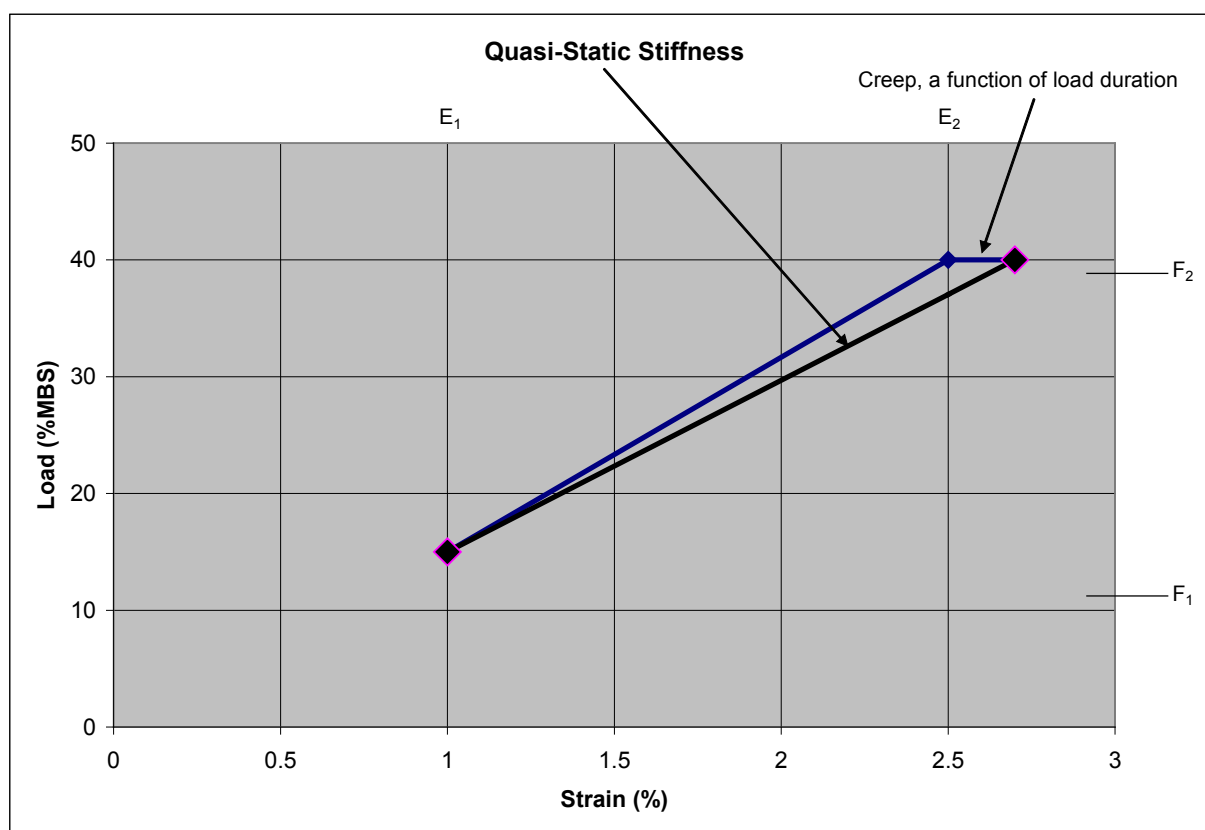
Available test data indicate that the difference between dynamic stiffness for post installation and aged rope is small. Therefore dynamic stiffness for the aged rope can be used conservatively for the project, and testing for both post-installation and aged rope is not necessary. Dynamic stiffness data for the pre-installation rope are not available at this point.

5 Static Stiffness

5.1 Recommended Static Stiffness Model

Based on industry investigations [5][10][11][12], a “quasi-static stiffness” model is recommended. As shown in Section 3, Figure 3, after pre-conditioning the rope, the static test started at the pre-tension, and a creep plateau is placed at the load level of interest. The quasi-static stiffness is taken as the secant stiffness connecting the point at the pre-tension with the point at the end of the creep plateau for the load level. The creep, which is a function of load or storm duration, can be represented by a linear function of log time. Therefore the quasi-static stiffness can be determined by Equation 3.4.

FIGURE 3
Definition of Quasi-Static Stiffness



$$K_{rs} = (F_2 - F_1) / [E_2 - E_1 + C \cdot \log(t)] \dots\dots\dots (3.4)$$

where

- F_1 = starting test tension, typically pre-tension of mooring line (%MBS)
- F_2 = ending test tension, typically storm mean load (%MBS)
- E_1 = starting strain (%)
- E_2 = ending strain (%)
- C = creep coefficient
- t = duration of the environmental event

The coefficient C can be determined by regression analysis as shown in A2/2.2.

5.2 Alternative Static Stiffness Model

Some designers prefer to use the elastic stiffness instead of the quasi-static stiffness. The non-elastic elongations such as permanent elongation and creep are determined and input to the mooring analysis software separately. This approach can be acceptable if the elastic stiffness is properly defined and all non-elastic elongations are properly accounted for. A specialized test program is required to provide appropriate test data for this approach. These Guidance Notes provide no guidance for this model.

5.3 Effect of Load History

Available test data indicate that the difference between quasi-static stiffness for pre-installation, post-installation, and aged rope can be large. For example the difference between quasi-static stiffness for post-installation and aged rope is in the range of 30% to 60% based on test data for recent projects [5]. Therefore quasi-static stiffness testing for pre-installation, post-installation, and aged rope should be done separately, if applicable.

5.4 Effect of Preload Level

The effect of preload level is also noticeable. For example some test data indicate that reducing the preload from 40% MBS to 30% MBS may result in about 10% reduction in quasi-static stiffness.

6 Stiffness Values for Preliminary Design

During preliminary design, there is a need to use approximate stiffness values since the rope manufacturer for the project may have not been determined. More accurate stiffness values based on rope specific testing are not available at this stage. In the absence of better information, guidance provided in Subsection A2/1 can be used to determine stiffness values for preliminary design.

7 Determination of Stiffness Based on Test Data

Project specific test data, if available, should be used to determine quasi-static and dynamic stiffness for the final design. The stiffness testing should be conducted according to guidance provided in Subsection 8/5. The examples in Subsection A2/2 illustrate procedures to develop the dynamic stiffness coefficients and quasi-static design curves based on test data.

8 Mooring Analysis Procedure

Analysis procedure for fiber rope moorings is similar to that for steel moorings as presented in API RP 2SK. An exception is the treatment of fiber rope stiffness, which is much more complicated than the linear stiffness for steel components. This Section provides guidance only for handling fiber rope stiffness in the mooring analysis, and the designers should refer to API RP 2SK for general mooring analysis procedure.

8.1 Major Conclusions from Parametric Studies

Two parametric studies have been conducted in the DeepStar 6403 study [10] and in the ABS JIP [5] to investigate the impact of stiffness models and parameters on mooring analysis results under various conditions. The conclusions from these studies are presented in Subsection A2/3, which can serve as guidance for practical and conservative fiber rope mooring analysis.

8.2 Analysis Procedure Based on the Static-Dynamic Model

Commercial mooring analysis software is normally not designed to handle the 2-slope static-dynamic model directly and therefore some approximations are needed. In typical industry practice, the mooring analysis is performed twice, one with the quasi-static stiffness and another one with the dynamic stiffness. Then the mean responses (tension and offset) from the first run are combined with the dynamic responses from the second run to yield the final results. The pre-tension for both runs should be the same. To achieve this, the line length or anchor location may have to be adjusted in the second run when the quasi-static stiffness is changed to dynamic stiffness. This procedure applies to both FD and TD analysis.