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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

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- 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

CONTENTS

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 FPUs

- 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_r): 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:

$$EA = \frac{\Delta F}{\Delta \varepsilon}$$ ....(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:

$$K_r = \frac{EA}{MBS}$$ ....(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
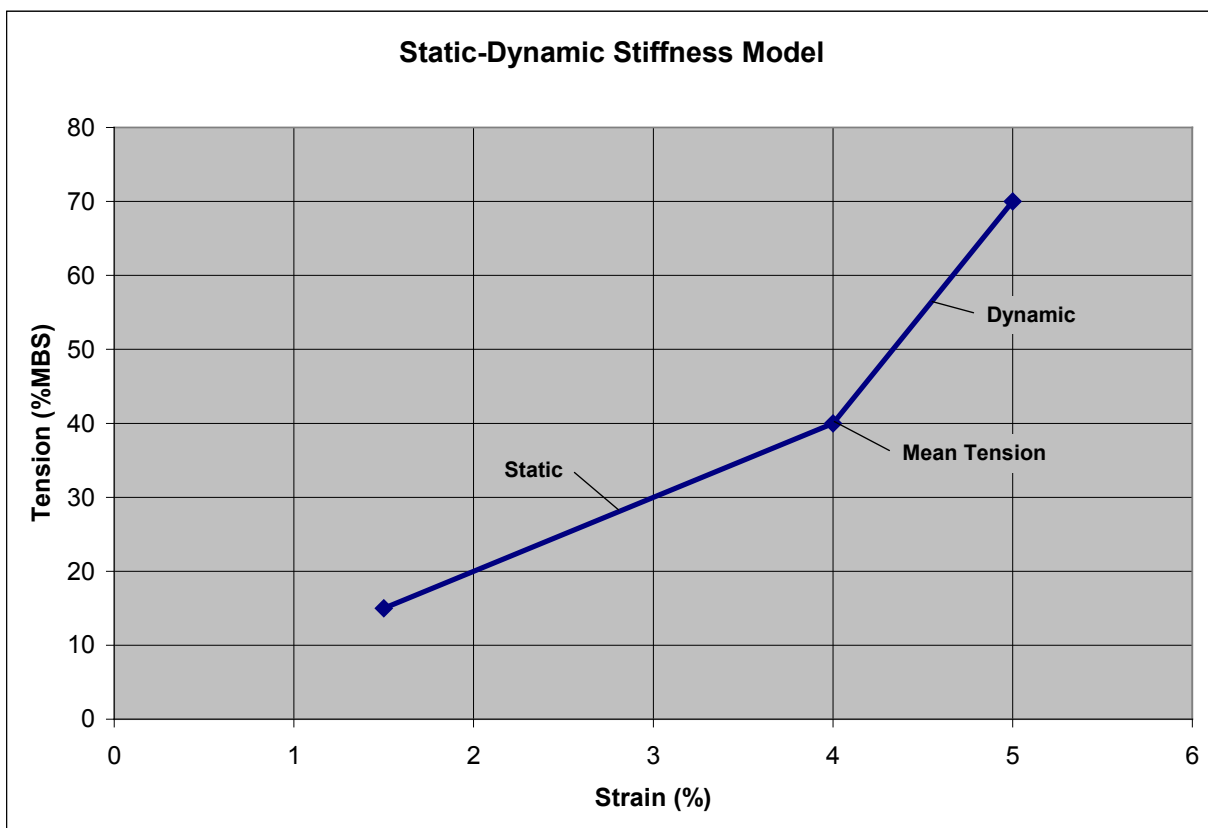
3.2 Upper-Lower Bound Model

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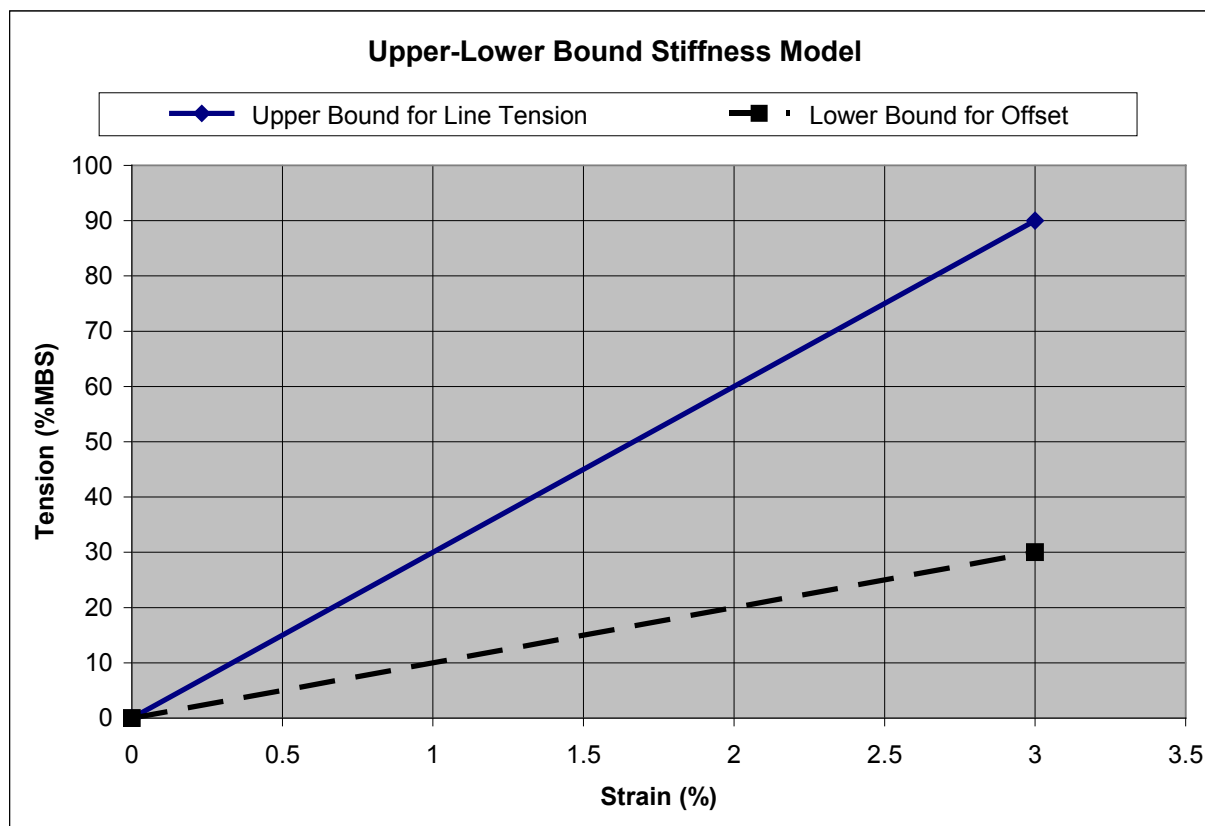
The upper-lower bound model has been widely used in the industry due to its simplicity and unavailability of a better model. However, it does have certain shortcomings such as:

- 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:

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

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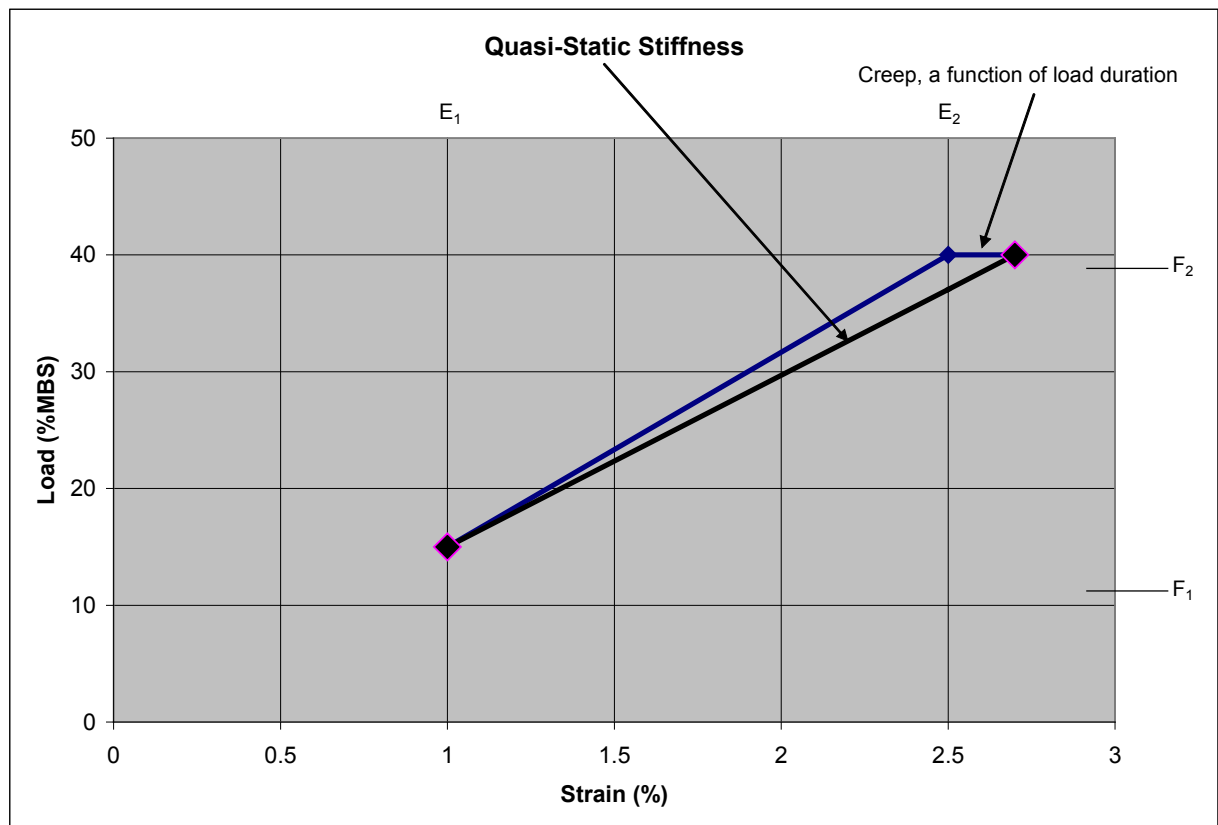
$$K_{rs} = (F_2 - F_1)/[E_2 - E_1 + C.\log(t)] \dotfill (3.4)$$

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.

8.3   Analysis Procedure Based on the Upper-Lower Bound Model

The analysis procedure is similar to that for the static-dynamic model. The mooring analysis is performed twice, one with the lower bound stiffness and another one with the upper bound stiffness. Then the maximum offset is determined by the first run, and the maximum line tension is determined by the second run. Again 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 lower bound stiffness is changed to the upper bound stiffness. This procedure applies to both FD and TD analysis.

9   Mooring Analysis Examples

Examples of stiffness determination, strength and fatigue analysis are provided in Subsection A2/4.

10   Creep

Polyester ropes are not subject to significant creep at loads normally experienced in mooring applications and thus are not normally subject to failure due to creep rupture. Therefore creep or creep rupture analysis is not required for mooring design. However, mooring line adjustments may be needed during design service life due to rope creep, and sufficient upper chain segment length should be retained to allow future line adjustments. Estimate of future line adjustments can be carried out using the creep rates at the creep plateaus from the quasi-static stiffness test.

11   Fatigue

11.1   Tension-Tension Fatigue

The recommended polyester fatigue design curve is the "mean minus two standard deviation" curve from the JIP investigating the durability of polyester ropes [13]. This design curve is represented by the following design equation and the plot in Section 3, Figure. 4. Polyester ropes have much better fatigue resistance than chain and steel wire ropes, and therefore fatigue evaluation is typically focused on the upper chain segment, which has the shortest fatigue life.

$$NR^M = K \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (3.5)$$

where

N	=	number of cycles
R	=	ratio of tension range (double amplitude) to MBS
M	=	5.2 (slope of T-N curve)
K	=	25,000 (intercept of T-N curve)

FIGURE 4
Polyester Fatigue Design Curve
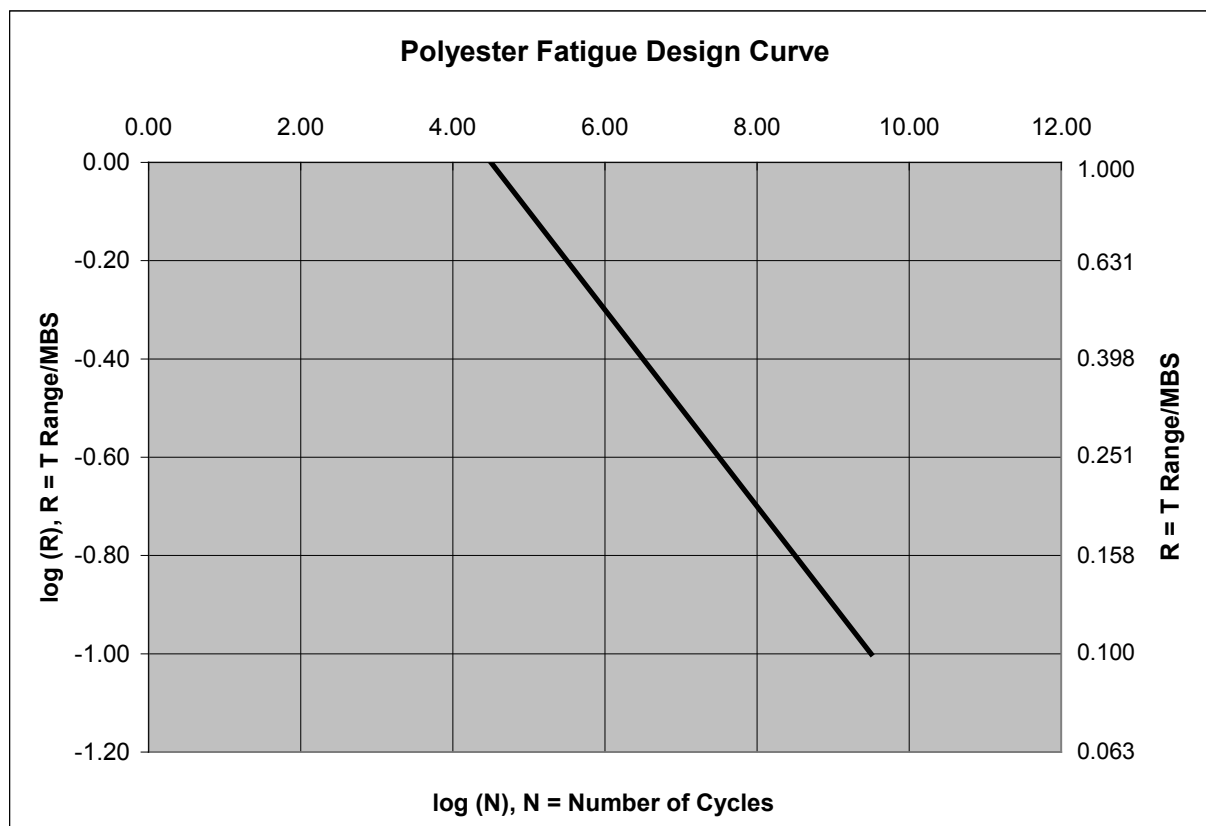
As per the ABS *FPI Rules* [1], tension-tension fatigue life design criteria can be summarized in the following table for permanent installations. For temporary installations, fatigue analysis can be waived provided that inspection of the mooring is conducted according to API RP 2I [14].

TABLE 1
Fatigue Life Factor of Safety

Area	Component Fatigue Life/Design Service Life
Inspectable Areas	3
Non-Inspectable and Critical Areas	10

11.2 Axial Compression Fatigue

Axial compression fatigue is not a concern with polyester ropes, and therefore axial compression fatigue analysis and testing are not required.

12   Torque Compatibility

Torque compatibility should be considered between polyester rope and other components such as chain and wire rope. There are 2 torque categories for mooring components:

- Torque component: Twist is generated due to tension variation, such as 6-strand or 8-strand wire rope

- Non-torque component: 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.

Laboratory testing demonstrates that a 6- or 8-strand wire rope's fatigue performance, when connected with a non-torque polyester rope, could be significantly degraded, although the scale effect of such testing is yet to be quantified. Following is some guidance to address this issue.

12.1   Permanent Mooring

Non-torque polyester rope should generally be used with non-torque steel components such as chain or spiral strand to achieve a non-torque mooring line. Should special situation dictate the use of a polyester rope with a torque steel component such as 6- or 8-strand wire rope, the polyester rope should be designed to have similar torque characteristics as the steel component to achieve a torque-matched mooring line. A torque match test should be conducted for the polyester rope and the wire rope according to the test procedure presented in Subsection 8/8, and the angular rotation in the wire rope should not exceed 5° per rope lay length.

12.2   MODU Mooring

A large number of MODUs use torque steel components, mostly 6-strand wire rope, especially for deepwater operations. Special considerations should be given to MODU operations, which are typically of short duration and in different water depths and environments. Industry experience indicates that there are at least two viable design approaches for MODU moorings.

12.2.1   Torque-matched Approach

A steel wire rope's fatigue life is best preserved by connecting to a torque-matched polyester rope. A rope is considered torque matched if its torsion characteristics over the design load range are essentially the same as that of the connected wire rope. Due to the inherent difference in material properties, a polyester rope typically can only match a wire rope's torsion characteristics at a pre-determined tension range. The difference between the torque of the polyester rope and wire rope increases as the line tension deviates from the match point with changing environmental loading or heading. Other factors to be considered in the torque-matched design include torque characteristics, lay direction, presence of swivels in the mooring lines, swivel lock-up load, and the presence and length of chain segments.

If this approach is used, a torque match test should be conducted (see 3/12.1).

12.2.2   Non-torque-matched Approach

Available non-torque polyester ropes can be used for short term MODU mooring systems if the dynamic torsion of the steel wire could be restrained at the interface between the fiber rope and wire rope [15]. A properly designed submersible buoy could provide such restraint. Available experience shows that wire rope fatigue damage in such a system is lower than some of the earlier scaled test data suggest [15]. The fatigue damage to wire rope tends to be concentrated near the interface with the polyester rope. The wire rope can be returned to service after the damaged end is re-terminated during a MODU move. It is also possible to insert a short wire rope insert (200 ft to 300 ft) between the wire rope and the polyester rope to minimize the need for re-socketing wire ropes in the field.

13   Delayed Preloading

The preloading operation to achieve initial bedding-in of the polyester ropes should be carried out immediately after the mooring installation. If this operation is delayed for an extended period during which severe environments can be encountered, a mooring analysis should be conducted using the stiffness values for a pre-installation rope. Vessel offsets and motions from this analysis should be used to check that riser stress and fatigue life are sufficient to provide riser integrity under this condition.

14   MODU Mooring Considerations

The guidance in this document is mainly based on the industry experience from permanent mooring projects, and most of the guidance is expected to be applicable to MODU moorings. However, there are areas where a MODU mooring is different from a permanent mooring, and special attention should be paid to these areas, such as:

- The requirements for the top and bottom steel section can be different (Subsection 3/1)

- Polyester rope for MODU moorings is often not preloaded or preloaded with a much lower tension. This may result in a very soft rope when it is new, but the rope becomes stiffer as it ages. This should be taken into consideration when conducting stiffness test and mooring analysis. This is particularly important for deepwater operations where stroking out of the riser slip joint is possible due to large vessel offset.

- The practice for torque compatibility is different (Subsection 3/12)

- Determination of dynamic and quasi-static stiffness values is based on a few design parameters, such as mean tension, tension amplitude, duration of the environmental event, natural period of the moored system, etc. MODU operations are typically of short duration and in different water depths and environments, and therefore these design parameters are often uncertain. Simplified and conservative assumptions should be used to determine these parameters.

SECTION 4 **HMPE Mooring Design and Analysis**

The guidance for polyester mooring design and analysis is generally applicable to HMPE moorings. The major issue of HMPE is its tendency to creep, which should be properly addressed, as discussed in the following sections.

1 HMPE Rope Strength and Stiffness Properties

HMPE possesses several desirable properties for mooring operations. They are naturally buoyant, have high abrasion resistance and possess a strength-to-diameter ratio much higher than that of polyester rope, as shown in Section 4, Table 1 [28]. Note the values in this table are indicative only and should not be used for design. Additionally, HMPE possesses higher static and dynamic stiffness over aramid and polyester as seen in Section 4, Figure 1 [16][17]. However, quasi-static stiffness of HMPE is strongly dependent on storm duration as discussed in Subsection 4/3.

TABLE 1
Typical Rope Weights and Sizes for 10,000 kN Break Strength

Rope Property	Polyester	Aramid	HMPE	Steel (for comparison)
Total weight in air (kg/m)	23.0	12.0	8.4	57.0
Total weight in water (kg/m)	5.9	3.3	Buoyant	48.0
Typical overall diameter (mm)	175.0	120.0	125.0	108.0

FIGURE 1
Comparison of Static and Dynamic Stiffness of Three Fiber Materials
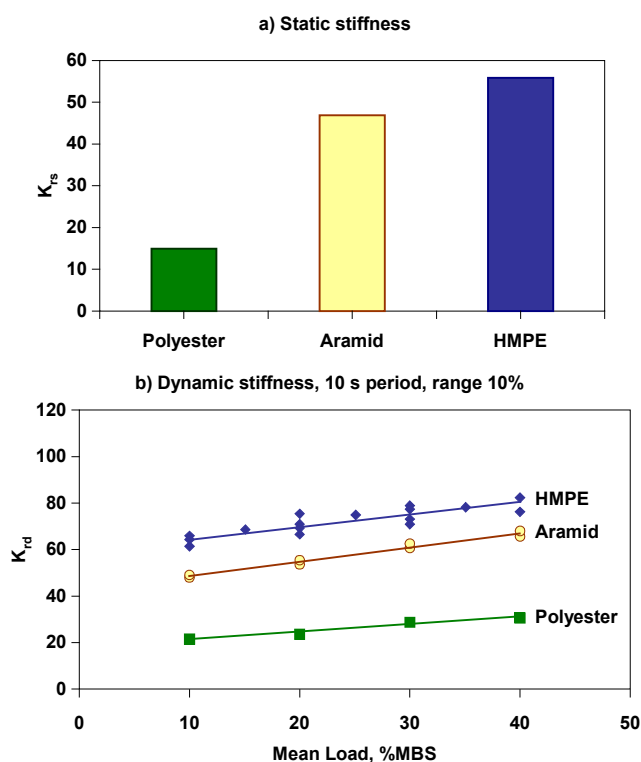
2   HMPE Creep

The major issue of HMPE is its tendency to creep, which should be addressed in the design of permanent moorings. One of the main concerns with HMPE's high creep rate is the potential for failure via creep rupture. As a HMPE rope creeps under tension, eventually it stretches to the point of complete failure. Another concern is the need for re-tensioning because of HMPE's high creep rate. Furthermore the high creep rate can lower the quasi-static stiffness over long storm duration. Factors affecting HMPE creep behavior are fiber type, applied load, time, and temperature, as discussed below.

Similar considerations should also be given to MODU moorings, but the concern for creep and creep rupture is less for MODU operations because of the short duration of these operations.

2.1   Effect of Time and Creep Regimes

Section 4, Figure 2 shows a typical creep curve of HMPE, where the strain is plotted as a function of time. The logarithmic creep rate of this experiment, which is the slope of this curve, is shown in Section 4, Figure 3. Three regimes can be clearly distinguished by a different behavior of the creep rate [18].

- *Regime I "primary creep":* In this regime the amorphous realignment takes place, and the high creep rate at start reduces to a plateau level at the end. The strain is reversible with the use of an elastic and delayed elastic component.

- *Regime II: "steady state creep":* In this regime the sliding of molecular chains takes place. The creep rate increases slightly because under a constant load the yarn stress actually increases slightly as creep continues. For practical purpose the creep rate can be considered constant for this regime. The strain is called "plastic creep", which is irreversible.

- *Regime III: "tertiary creep":* In this regime molecular chains start to break. High strains will start to cause necking in the filaments and will increase the local stress that further accelerates the strain until breakage.

FIGURE 2
Typical HMPE Creep Curve
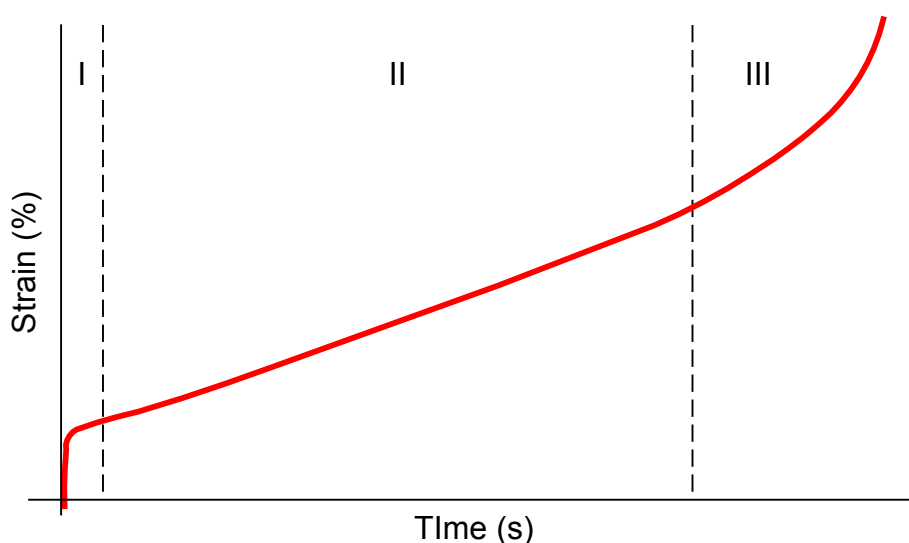
FIGURE 3
Typical HMPE Creep Rate Curve
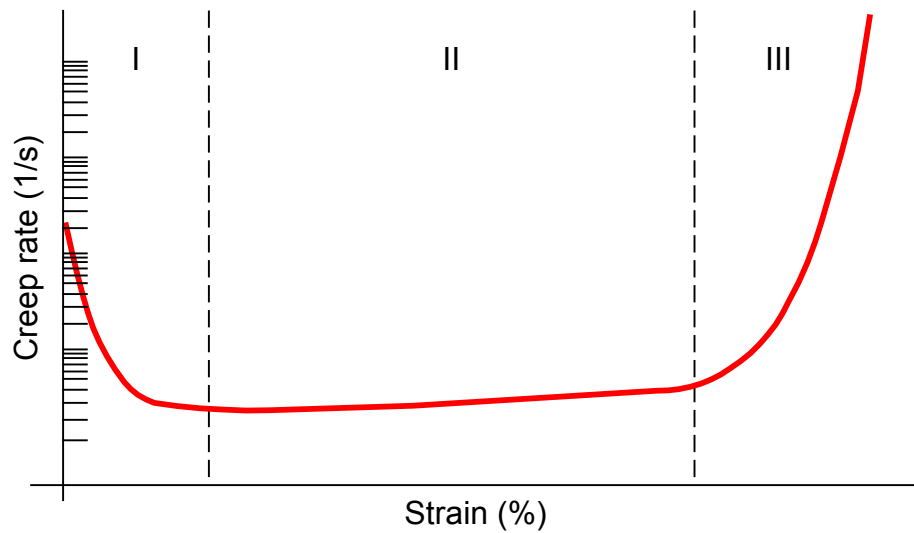
2.2   Effect of Applied Load and Temperature

The creep rate of HMPE yarn is also dependent upon the applied load and temperature. Section 4, Figure 4 shows an example of creep rate as a function of applied load and temperature based on yarn creep test for a specific HMPE fiber [18].

FIGURE 4
Impact of Load and Temperature on Creep Rate
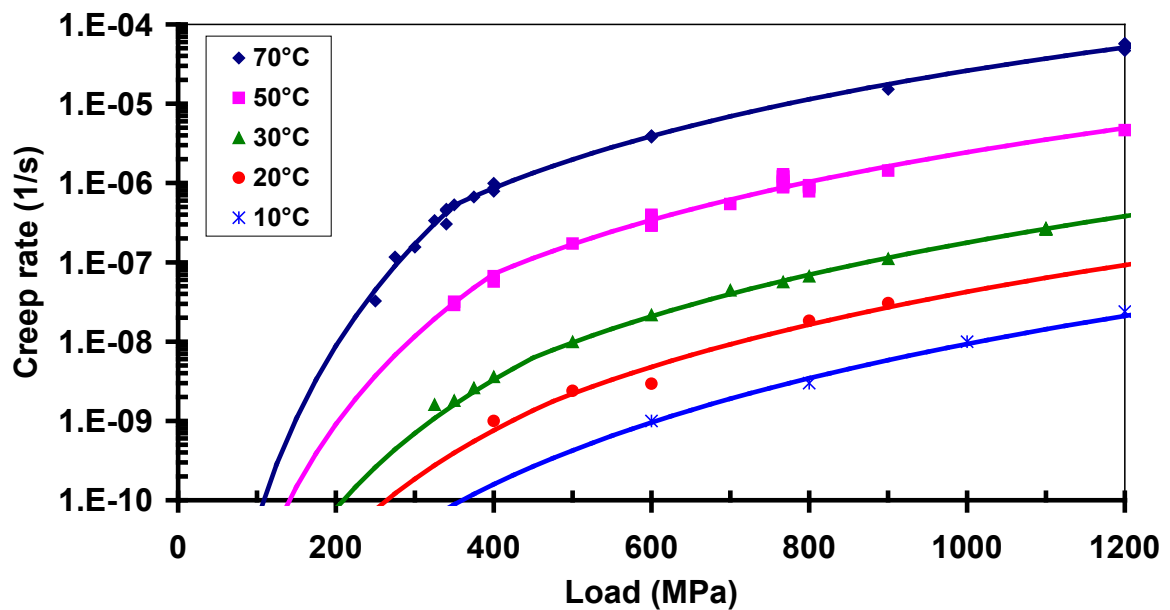
It can be seen that creep rate increases with increasing temperature. Section 4, Figure 5 shows the mean annual water temperature as a function of water depth for GOM [19]. To avoid excessive creep, HMPE ropes should be placed at a depth where the creep performance meets the design criteria.

FIGURE 5
GOM Water Temperature Distribution
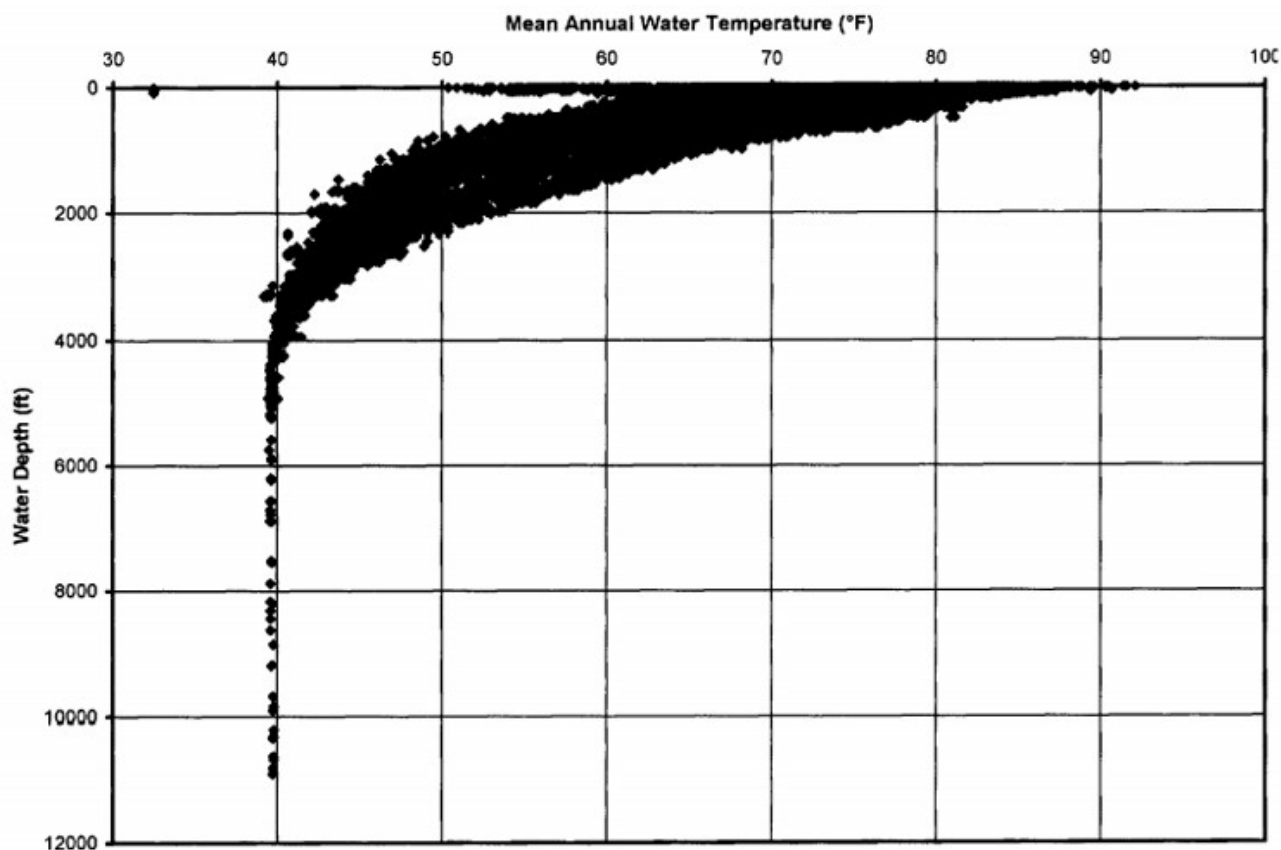
2.3   Creep Analysis

A creep analysis should be performed for an intact mooring to estimate the total creep strain during the design service life, which should be limited to 10% for the total length of the HMPE rope. To simplify the analysis, the following assumptions are made:

- Regime I is of short duration compared with design service life and therefore creep in this regime can be neglected

- The creep in Regime II is estimated using a constant creep rate for time, but the creep rate is still a function of applied load and temperature

- Creep rates as a function of yarn stress and temperature relevant to the project are available. These rates are typically generated based on yarn test data and a creep model

- Information about the rope design and unit mass is available so yarn stress can be converted to rope tension (%MBS) by a conversion factor for a particular rope

- The strain in Regime II is defined as plastic creep that is irreversible, and therefore creep is cumulative. The annual cumulative creep strain, G_t can be calculated by the following equation for a specific temperature:

$$G_t = \sum h_i\, H_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.1)$$

where

h_i = duration per year within the tension interval i,

H_i = creep rate for the tension interval i

The recommended procedure for a creep analysis is described below.

i)   The long-term environmental events can be represented by a number of discrete design conditions. Each design condition consists of a reference direction and a reference sea state characterized by significant wave height, peak spectral period, spectral shape, current velocity, and wind velocity. The probability of occurrence of each design condition should be specified.

ii)   For each design condition, determine the mean tensions for all mooring lines.

iii)   Compute the annual creep strain from one design condition (one sea state in one direction) using Equation 4.1.

iv)   Repeat *iii)* for all sea states and directions and compute the annual creep strain G_t, which is the sum of creep strain from all sea states and directions.

v)   The predicted total creep strain of the mooring line for a design service life *M* (year) is:

$$G = M\,G_t \dotfill (4.2)$$

Special attention should be given to the high current event such as the Loop current event in the Gulf of Mexico, which can impose high steady loads of long duration on the floating structure. Such an event should be included in the design conditions for creep analysis.

A creep analysis example is provided in A2/5.1.

2.4   Creep Rupture Analysis

A creep rupture analysis should be performed for an intact mooring to estimate the creep rupture life, which should be greater than 5 times the design service life if creep is monitored. The creep rupture life should be greater than 10 times the design service life if creep is not monitored. To simplify the analysis, the following assumptions are made:

- Regime III is of short duration compared with design service life and therefore creep rupture is conservatively assumed at the start of Regime III.

- Creep rupture time as a function of yarn stress and temperature relevant to the project are available. This information is typically generated based on yarn test data and a creep model

- Information about the rope design and unit mass is available so yarn stress can be converted to rope tension (%MBS) by a conversion factor for a specific rope

- Similar to the Miner's rule for fatigue analysis, the annual cumulative creep rupture damage ratio *B* can be calculated by the following equation:

$$B = \sum c_i/C_i \dotfill (4.3)$$

where

    c_i = duration per year within the tension interval *i*,

    C_i = creep rupture time for the tension interval *i*

The predicted creep rupture life for the mooring component is 1/*B*.

The recommended procedure for a creep rupture analysis is described below.

i)   The long-term environmental events can be represented by a number of discrete design conditions. Each design condition consists of a reference direction and a reference seastate characterized by significant wave height, peak spectral period, spectral shape, current velocity, and wind velocity. The probability of occurrence of each design condition should be specified.

ii)   For each design condition, determine the mean tension for all mooring lines.

iii)   Compute the annual creep rupture damage from one design condition (one seastate in one direction) using Equation 4.3.

iv)   Repeat *iii)* for all seastates and directions and compute the total annual creep rupture damage B_t, which is the sum of creep rupture damage from all seastates and directions.

v)   The predicted creep rupture life of the mooring line is:

$$L = 1/B_t \text{ (years)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.4)$$

Unlike fatigue damage that is mainly caused by cyclic loading from waves, creep rupture damage can be significantly contributed by all environmental parameters including wind, waves, and current. Special attention should be given to the high current event such as the Loop current event in the Gulf of Mexico, which can impose high steady loads of long duration on the floating structure. Such an event should be included in the design conditions for creep rupture analysis.

A creep rupture analysis example is provided in A2/5.2.

2.5   Creep Model Verification

The creep model generating design data for creep and creep rupture analysis should be verified by a verification test for rope creep rate at least one load and one temperature according to the procedure specified in Subsection 8/9. If the design data used in the analysis are found to be non-conservative, they should be adjusted using the verification test results, and the creep and creep rupture analysis should be repeated. To properly adjust the design data, additional tests for rope creep rate may be necessary.

3   Quasi-Static Stiffness

Creep has much higher impact on the quasi-static stiffness for HMPE than for polyester. Equation 3.4 in 3/5.1 should be modified to the following equation for HMPE:

$$K_{rs} = (F_2 - F_1)/(E_2 - E_1 + C\,t) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.5)$$

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

An example for HMPE quasi-static stiffness is provided in A2/5.3.

4   Fatigue

4.1   Tension-Tension Fatigue

Limited fatigue test data for HMPE rope indicates that HMPE rope may have comparable fatigue resistance to polyester rope, but the fatigue design curve cannot be generated at this point. Fatigue analysis should be focused on the upper chain segment, and the tension range for the upper chain should be based on proper stiffness values for the HMPE rope.

4.2   Axial Compression Fatigue

Axial compression fatigue is not a concern with HMPE ropes, and therefore axial compression fatigue analysis and testing are not required.

SECTION 5 Aramid Mooring Design and Analysis

The guidance for polyester mooring design and analysis is generally applicable to aramid moorings. The major issue for aramid is its susceptibility to failure from axial compression fatigue under low tension, which should be properly addressed, as discussed in the following sections.

1 Aramid Rope Strength and Stiffness Properties

The main characteristics of aramid that make it attractive for mooring applications are its high strength, high modulus, and low creep. Aramid rope possesses a strength-to-diameter ratio much higher than that of polyester rope, as shown in Section 4, Table 1. Additionally, aramid rope has higher static and dynamic stiffness over polyester as seen in Section 4, Figure 1 [16][17].

2 Axial Compression Fatigue

2.1 Past Experience and Current Status

Early experience with aramid rope in mooring applications has not been favorable because of the failure mechanism of axial compression fatigue. It was once believed that this problem could be overcome by keeping the rope in tension. Laboratory tests showed, however, some fibers at the splice can still be subjected to axial compression fatigue even though the whole rope is in tension. This caused the industry to turn away from aramid rope for an extended period. Industry studies indicate however that this problem can be overcome by the following measures [20]:

i) Improved rope design in the areas of splice, marine finish, and jacket

ii) Establishing proper minimum tension criteria and analysis procedure

iii) Conducting axial compression fatigue test to provide for adequate resistance to axial compression fatigue failure

Below the second and third measures are addressed.

2.2 Acceptance Criteria

2.2.1 Recommended Criteria

i) The predicted minimum tension at the bottom of the aramid segment for the leeward lines should be more than 2% MBS for an intact mooring under the severe storm environment (typically 100-year return period)

ii) The rope should maintain a minimum residual strength of 95% MBS after being subjected to 2000 cycles of dynamic load with a tension range of 1% to 20% MBS. The axial compression fatigue test procedure is provided in Subsection 8/10.

iii) The aramid rope should maintain a minimum tension of 2% MBS if it is suspended by a buoy after pre-installation

2.2.2   Alternative Criteria

The criteria in 5/2.2.1i) and 5/2.2.1ii) can be modified based on project specifics, but there should be no significant deviation from the principles behind these criteria. The designer should provide the following information for review on a case by case basis:

i)   Minimum tension design criteria

ii)   Axial compression fatigue test procedure: tension range, number and frequency of test cycles

iii)   Residual strength after test

iv)   Basis for the design criteria and test procedure

2.3   Mooring Analysis

Frequency domain analysis may not yield an accurate prediction for minimum tension in leeward lines, and time domain analysis is preferred. If frequency domain analysis is used, it should be first verified by time domain analysis.

3   Tension-Tension Fatigue

Tension-Tension fatigue design curve cannot be generated at this point because of lack of data. Fatigue analysis should be focused on the upper chain segment, and the tension range for the upper chain should be based on proper stiffness values for the aramid rope.

4   Creep and Creep Rupture

Aramid rope has better resistance to creep than polyester and HMPE rope, and therefore creep and creep rupture analysis are not required for mooring design.

SECTION 6 Design and Analysis for Other Fiber Ropes

There are fiber materials other than polyester, HMPE, and aramid that can be considered for mooring applications. These Guidance Notes cannot give specific guidance for them at this point because of lack of technical data. Some of the guidance in this document may be applicable to other fiber materials, but the user should exercise caution and sound judgment in such applications.

SECTION 7 Summary of Design Criteria

1 Tension Criteria

Tension limits and factors of safety for intact and one line damaged condition for the most loaded line based on dynamic analysis are provided in Section 7, Table 1.

TABLE 1
Tension Limit and Factor of Safety for Dynamic Analysis

	Tension Limit (% MBS)	*Equivalent Factor of Safety*
Intact	55	1.82
Damaged	70	1.43

2 Fatigue Criteria

Factors of safety for fatigue life are as follows:

TABLE 2
Factor of Safety for Fatigue Life

	Component Fatigue Life/Design Service Life
Inspectable Areas	3
Non-Inspectable & Critical Areas	10

3 HMPE Creep

- Creep strain limit for design service life: 10%

- Factor of safety against creep rupture: 5 (creep is monitored) or 10 (creep is not monitored)

4 Aramid Axial Compression Fatigue

- Minimum tension for leeward line under intact condition: 2% MBS

- Minimum residual strength of 95% MBS after 2000 cycles of dynamic load with a tension range of 1% to 20% MBS.

- Minimum tension of 2% MBS if it is suspended by a buoy after pre-installation

5 Torque Match with Torque Steel Wire Rope

The angular rotation in the steel wire rope should not exceed 5 degrees per rope lay length based on the test procedure specified in Subsection 8/8.

SECTION **8 Testing of Rope**

1   General

This Section provides guidance for conducting rope tests to determine fiber rope properties.

1.1   Test Requirements

A summary of test requirements for different fibers and operating conditions is given in Section 8, Table 1.

TABLE 1
Test Requirements

Subsection	Test Type	Fiber Type	Requirement
8/4	Minimum Breaking Strength	All	Required
8/5	Elongation and Stiffness	All	Required
8/6	Splice Qualification	All	Required
8/7	Particle Ingress Resistance	All	*
8/8	Torque Match with Steel Wire Rope	All	**
8/9	HMPE Creep Rate Verification	HMPE	Required
8/10	Aramid Axial Compression Fatigue	Aramid	Required

Notes:

* Required for rope preset on seabed and reuse of an accidentally dropped rope

** Required for fiber rope connected with torque wire rope (6- or 8-strand) for permanent mooring

1.2   Group Approval

Approval for a group of different sizes of rope of the same design based on 1 or 2 rope tests is acceptable in some cases, as indicated in Section 8, Table 2.

TABLE 2
Group Approval

Subsection	Test Type	Group Approval
8/4	Minimum Breaking Strength	No
8/5	Elongation and Stiffness	Dynamic stiffness only
8/6	Splice Qualification	Yes
8/7	Particle Ingress Resistance	Yes
8/8	Torque Match with Steel Wire Rope	No
8/9	HMPE Creep Rate Verification	No
8/10	Aramid Axial Compression Fatigue	Yes

Conditions for group approval are as follows:

i)   Group approval is effective for no more than 5 years from the test date

ii)   One sample: qualify ropes within ±20% of MBS of the test sample

iii)   Two samples: qualify ropes between 80% MBS of the small and 120% MBS of the large test sample. The 2-sample approach is not applicable to dynamic stiffness test.

iv)   Group approval applies only to ropes with same design parameters as indicated below:

- Subrope construction
- Yarn type
- Number of layers in eye configuration
- D/d ratio for hardware
- Shape of hardware bearing surface
- Splice lengths (number of strand tucks and tapered tucks)
- Chafe protection material and application in the eye
- Soil filter material and design (for "Particle Ingress Resistance" test only)

2   Rope Test Practice

2.1   Rope Sample

The rope tests may be performed on a prototype rope after the rope design is documented by the manufacturer before an order is received or on a sample rope taken before, during or after production of an order. The ropes to be tested should be identical in material and construction to the production ropes, except as noted. Test sample requirements are summarized in Section 8, Table 3

TABLE 3
Test Sample Requirements

Subsection	Test Type	Subrope Sample Allowed for Parallel Construction?	Same Splice as Production Rope Required?	Minimum Sample Length
8/4	Minimum Breaking Strength	No	Yes	40*D*
8/5	Elongation and Stiffness	Yes	No	5 m
8/6	Splice Qualification	No	Yes	40*D*
8/7	Particle Ingress Resistance	No	Yes	40*D*
8/8	Torque Match with Steel Wire Rope	No	Yes	Same length as steel wire rope
8/9	HMPE Creep Rate Verification	Yes	No	5 m
8/10	Aramid Axial Compression Fatigue	No	Yes	40*D*

Notes:

1   All samples should be full rope samples with 2 exceptions for tests of parallel construction ropes. Subrope samples can be used for these 2 tests, and the subrope MBS can be taken as the full rope MBS divided by the number of subropes.

2   The sample length is the length between the bearing points (Section 8, Figure 1). *D* is sample diameter

3   The samples should be terminated in the same manner as the production with exception for 2 tests. For these two tests the terminations should be of sufficient strength to safely withstand at least 70% of the rope MBS. The sample length should be at least 5 m. The gage marks should be no closer than 3 times rope diameter from the last tuck of rope splices.

4   In general, the sample should not have been previously tensioned to more than 5% of its estimated breaking strength nor have been maintained under steady or cyclic tension except as noted. This criterion does not apply to the test for used ropes.

5   The entire sample including terminations should be soaked in fresh water for 4 hours (subrope) or 12 hours (full rope) before testing. The sample should be tested as soon as practical after being removed from the water. If there is a delay of more than 16 hours after soaking, the sample should be soaked again for 4 hours (subrope) or 12 hours (full rope).

FIGURE 1
Typical Test Setup
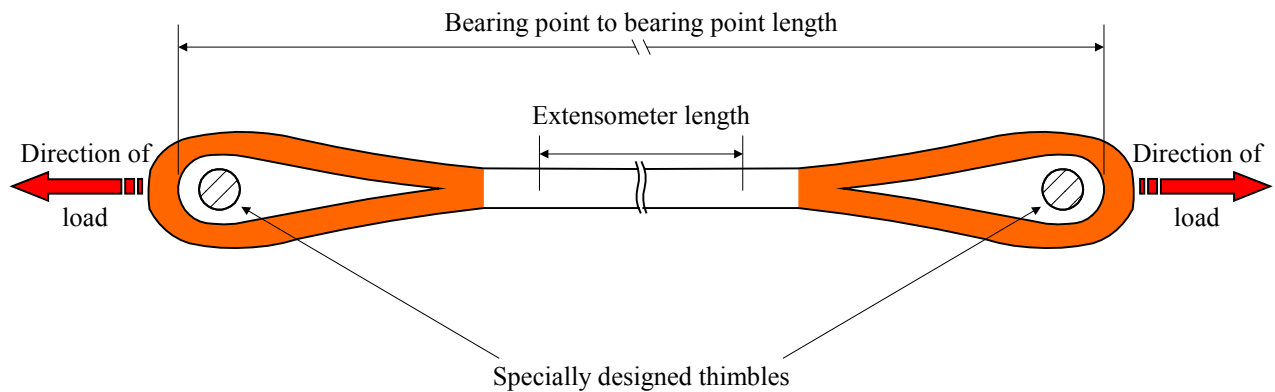
2.2   Test Machine

The test machine should have sufficient bed length, stroke, rate of loading, and force producing capacity to carry out the test as described in the following sections. It should be equipped with a force measuring and indicating/recording device which is accurate to within ±1% of the estimated MBS for the rope sample. The force measuring and indication/recording device should be calibrated by a recognized independent calibration agency, using a reference load cell traceable to applicable national standards. This calibration should have been done within one year before testing. An original calibration certificate should be available for examination, and a copy of this certificate should be attached to the test report.

For the "Elongation and Stiffness" (Subsection 8/5) and "Torque Match with Steel Wire Rope" (Subsection 8/8) test, the test machine should be equipped with an elongation or rotation measuring device and data collection system capable of measuring and recording the elongation or rotation over the gage length. The accuracy of these measurements should be established according to the guidance provided in Appendix A of CI Standard 1500-2 [21]. The data collection system should be capable of recording sufficient data points during a load cycle.

Preferably, the entire rope section including terminations is immersed in fresh water during the test. Alternatively, the entire length of rope between ends at terminations can be sprayed with fresh water during the test at a minimum rate per minute calculated by the following formula:

$$W_R = 0.0004 W_L D^2 \dotfill (8.1)$$

where

W_R =   rate of water application, liters/minute

W_L =   length of rope over which water is applied, in meters

D =   rope diameter, in mm

2.3   Test Temperature

The sample internal temperature should be monitored by thermal couples or other suitable temperature measuring devices. For polyester, the sample internal temperature should be kept below 40°C. HMPE rope properties are more sensitive to temperature and therefore sample temperature should be carefully selected and recorded so the test results can be interpreted for application to the project. Aramid can tolerate higher internal temperature (70°C or even higher).

Special attention should be paid to testing with dynamic loads such as fatigue and splice qualification test. When rope temperature indicates a risk of overheating, the following measures should be considered:

i)   Stop the test and resume the test after the temperature is lowered to an acceptable level

ii)   Increase the period of the dynamic load

iii)   Increase the water flow

2.4   Rope Design for Parallel Construction

Ropes of parallel construction are typically made up with subropes using two different methods:

*   Method A: The rope is made up with a fixed number of subropes. In this case, the subrope size changes as the full rope size changes.

*   Method B: The rope is made up with subropes of the same size. In this case, the number of subrope changes as the full rope size changes.

In general, the test and data interpretation procedures given below apply to both Method A and B unless noted in the following sections.

3   Interpolation and Extrapolation of Data

Interpolation or extrapolation is acceptable only as noted in the following sections. As a general guide, it is recommended that full scale testing should be performed wherever possible. Any interpolation or extrapolation other than that given here should be fully documented and justified, and will be considered on a case by case basis.

4   Minimum Breaking Strength

4.1   Test Procedure

Either one of the following test procedures can be used. Procedure A is based on the CI Standard 1500-02 [21] and procedure B is based on BS ISO 18692 [22].

4.1.1   Procedure A

i)   A cycling tension between 1% and 50% of the rope MBS should be applied 10 times at a period of 12 – 35 sec.

ii)   On the last cycle, the rope is pulled to failure, at a loading rate of approximately 20% MBS per minute.

iii)   Record the breaking force (maximum force applied to the rope). Record the location where the rope broke (e.g., between splices, at end of a splice, at crotch of a splice, in back of an eye, or other breaking locations).

4.1.2   Procedure B

i)   A tension of 50 % of the rope MBS should be applied at a rate of 10% MBS per minute and held for 30 min.

ii)   The tension should be reduced to 10% of the rope MBS, at a rate of 10% MBS per minute.

iii)   A cycling tension between 10% and 30% of the rope MBS should be applied 100 times at a period of 12 to 35 sec.

iv)   On the last cycle, the rope is pulled to failure, at a loading rate of approximately 20% MBS per minute.

v)   Record the breaking force (maximum force applied to the rope). Record the location where the rope broke (e.g., between splices, at end of a splice, at crotch of a splice, in back of an eye, or other breaking locations).

4.2   Recommended Procedure to Determine MBS

i)   Five full rope samples should be tested, and the MBS will be accepted if all 5 break loads are above the MBS

ii)   If one break load is below the MBS, an investigation should be conducted to identify causes. If the investigation indicates an isolated event, two more samples can be tested, and the MBS will be accepted if both break loads are above the MBS.

Note: The above procedure applies to each project and group approval is generally not acceptable for MBS. However, if after the first project, the same rope (same design and MBS) is produced for other applications, the number of tests can be reduced according the following guidance:

1   Number of break tests for the first project: 5

2   Number of break tests for subsequent applications: 1 additional test for every 25 segments including test inserts

4.3   Alternative Procedure to Determine MBS

For ropes of parallel construction with MBS greater than 2000 MT, a procedure for a combination of subrope and full rope tests can be considered, as illustrated in Appendix 3. This procedure should be used only when serious limitations such as unavailability of large test machine are encountered. ABS has not developed detailed test specification and specific acceptance criteria for this procedure, and only general guidance is provided in Appendix 3. Should the situation dictate that this procedure must be used, detailed testing specifications should be developed based on the principles provided in Appendix 3 or other valid principles. Also documentation supporting the reliability of the testing and data analysis procedures should be submitted in a timely manner to allow review well in advance of their implementation.

5   Elongation and Stiffness

5.1   Installation Pre-loading Test

This test is to simulate the installation pre-loading and pre-tensioning sequence which removes as much permanent elongation as possible during installation and to increase stiffness of the rope. The results can be used to determine the relationship between the as-installed length at pre-tension and the manufactured rope length (typically at 2% MBS). The test should simulate the planned installation pre-load sequence. The following is an example, which can be modified according to project specifics.

1.   The test should be done on at least two rope samples. The test should also precede all rope tests intended to determine design rope properties for elongation, quasi-static stiffness, and dynamic stiffness.

2.   Detailed test procedure is as follows:

a)   Tension the rope to 2% MBS. Measure and record the initial rope length.

b)   Increase the tension to the specified pre-tension and hold at this tension for at least two hours. Record the elongation at 1, 10, and 100 minutes, and at the end of the duration.

c)   Increase the tension to the specified preload tension and hold for the planned duration during installation at this tension (at least one hour). Record the elongation at 1, 10, and 100 minutes, and at the end of the duration.

d)   Decrease the tension to pre-tension and hold at this tension for at least 6 hours. Record the elongation (at least) at 1, 10, and 100 minutes, and at the end of the duration.

3.   Report the difference in length from the end of step 2a to the end of step 2d above. This is the permanent post-installation elongation.

The data from this test can also be used to determine the quasi-static stiffness for pre-installation rope.

5.2 Quasi-Static Stiffness for Post-Installation Rope

This test is used to determine the quasi-static stiffness and elongation of a post-installation rope, which has been subjected to the installation pre-loading. This test should be carried out on the test segment that has been tested in the installation pre-loading test and has been kept at the pre-tension for at least 6 hours. The sample is loaded from pre-tension to 3 load levels with a creep plateau at each load level. Following is the recommended procedure.

1.   Increase the tension from pre-tension to 30% MBS at a rate of approximately 10% MBS per minute and hold at this tension for 100 minutes. Record the extension at 1, 10 and 100 minutes.

2.   Increase the tension from 30% to 45% MBS at a rate of approximately 10% MBS per minute and hold at this tension for 100 minutes. Record the elongation at 1, 10, and 100 minutes.

3.   Increase the tension from 45% to 60% MBS at a rate of approximately 10% MBS per minute and hold at this tension for 100 minutes. Record the elongation at 1, 10, and 100 minutes.

4.   Reduce the tension from 60% MBS to pre-tension at a rate of approximately 10% MBS per minute and hold at this tension for at least 200 minutes. Record the elongation at 1, 10, and 100 minutes and at the end of the duration.

The data from this test should be used to determine quasi-static stiffness for the post-installation rope (A2/2.2). For HMPE, additional holding time may be required in steps 1 through 3 to make sure that the sample has entered Regime II in Section 4, Figure 3.

5.3 Quasi-Static Stiffness for Aged Rope

This test is used to determine the quasi-static stiffness and elongation of an aged rope. This test should be carried out on the test sample that has gone through the test for quasi-static stiffness for post-installation rope in 8/5.2. The sample is first loaded with static and dynamic loadings for fully bedding in the rope, and then the quasi-static stiffness test outlined in 8/5.2 is repeated. The procedure for fully bedding in the rope is as follows:

1.   Increase the tension from pre-tension to 65% MBS at a rate of approximately 10% MBS per minute and hold at this tension for 100 minutes. Record the elongation at 1, 10 and 100 minutes.

2.   Apply 1000 cycles of dynamic load with a tension range of 35% to 65% MBS and a period of 12 to 35 seconds.

3.   In the last cycle reduce the tension from 65% MBS to pre-tension at a rate of approximately 10% MBS per minute and hold at this tension for 100 minutes. Record the elongation at 1, 10, 100 minutes.

An alternative to the above procedure for fully bedding in the rope is to use a rope sample that has been subjected to the dynamic loading in the splice qualification test (Subsection 8/6).

The quasi-static stiffness test outlined in 8/5.2 should be repeated after above loading, and the data from this test can be used to determine quasi-static stiffness for aged rope.

5.4 Dynamic Stiffness

5.4.1 Test Matrix

This test is used to determine the dynamic stiffness (under wave frequency and low frequency loading) of a bedded-in rope at different mean tensions and tension ranges. The test should be carried out on the rope sample that has gone through the test for quasi-static stiffness for aged rope outlined in 8/5.3. Section 8, Table 4 provides a test matrix that should be applicable to a wide range of applications such as LF and WF dominating and VIM responses. A project specific test matrix can be developed using the guidance in Subsection A2/6.

TABLE 4
Dynamic Stiffness Test Matrix for General Applications

Case Number	T_{mean} (%MBS)	T_{amp} (%MBS)	T_{min} (%MBS)	T_{max} (%MBS)	Period (sec)
1	15	5	10	20	250
2	20	3	17	23	12 to 35
3	20	3	17	23	250
4	23	16	7	39	250
5	30	16	14	46	12 to 35
6	30	16	14	46	250
7	30	28	2	58	250
8	35	8	27	43	12 to 35
9	35	8	27	43	250
10	40	30	10	70	12 to 35
11	40	30	10	70	250
12	50	20	30	70	12 to 35
13	50	20	30	70	250
14	60	10	50	70	250

5.4.2   Test Procedure

i)   Cycle the rope 10 times between pre-tension and 55% MBS with a period of 12 to 35 sec. and then return to pre-tension and hold for at least 100 minutes.

ii)   For each WF test case (12 to 35 sec. period), cycle the rope between T_{min} and T_{max} 40 times; record the load and elongation with frequency of at least 1 Hz.

iii)   For each LF test case (250 sec. period), cycle the rope at tension between T_{min} and T_{max} 20 times; record the load and elongation with frequency of at least 0.25 Hz.

iv)   The sequence of the test cases can be selected to best facilitate the tests

v)   The test for the whole matrix should be continuous without significant interruption. If necessary, a short pause can be placed between each test case

5.4.3   Determination of Dynamic Stiffness

i)   Dynamic stiffness should be calculated by Equation 3.1 using the peak and trough points of the cycle, and the strain should be based on the average rope length during the cycle.

ii)   For each test case, calculate the dynamic stiffness for each cycle, and report the average stiffness of the last three cycles as the dynamic stiffness for the test case.

5.5   Group Approval

Group approval is not applicable for quasi-static stiffness test since pre-tension and preloading level and duration are project specific. Group approval is acceptable for dynamic stiffness. Dynamic stiffness test results for a full rope or subrope sample can be applicable to ropes within ±20% of MBS of the test sample.

6   Splice Qualification

This test is intended to demonstrate that the splice of the rope is properly designed and made. The test procedure is as follows:

i)   Apply either one of the following cyclic loadings at a period of less than 1 minute per cycle.

   • Tension range of 10% - 50% MBS for 17,000 cycles

   • Tension range of 5% - 55% MBS for 5,500 cycles

ii)   After cycling, examine the entire length of the rope including terminations in detail for any pending failure.

iii)   Record the load range, number of applied cycles, and signs of deterioration, if any.

7   Particle Ingress Resistance

This test is required for rope preset on the seafloor and reuse of rope that has been accidentally dropped on the seafloor. The test is intended to demonstrate that the soil filter incorporated in the rope body and splice is efficient in blocking harmful soil particles. These Guidance Notes provide only general guidance since detailed test specification has not been developed.

7.1   Test Procedure

7.1.1   Offshore Test Approach

In this approach, the test sample is deployed at an offshore location that has a soil condition representative of the project site. The rope is dragged, lifted up and put down to simulate the rope movements during installation and impact of a dropped rope. The rope sample stays on the seafloor for at least 24 hours before it is retrieved for inspection and testing. This approach has been used in some GOM projects.

7.1.2   Laboratory Test Approach

In this approach, the sample is tested in an open test tank filled with water and soil under the following conditions:

i)   The soil grading should contain 30% to 40% clay (less than 2 microns) and 50% to 60% silt (2 to 63 microns). An example of soil grading is shown in Section 8, Figure 2.

ii)   Horizontal (back and forth) and vertical (pick up and drop) movements (minimum 1 m) should be imposed on the rope sample at least 20 times each to simulate rope movements during installation and impact of a dropped rope

iii)   After the simulations, the rope should stay in the tank for at least 24 hours

FIGURE 2
Example Soil Grading
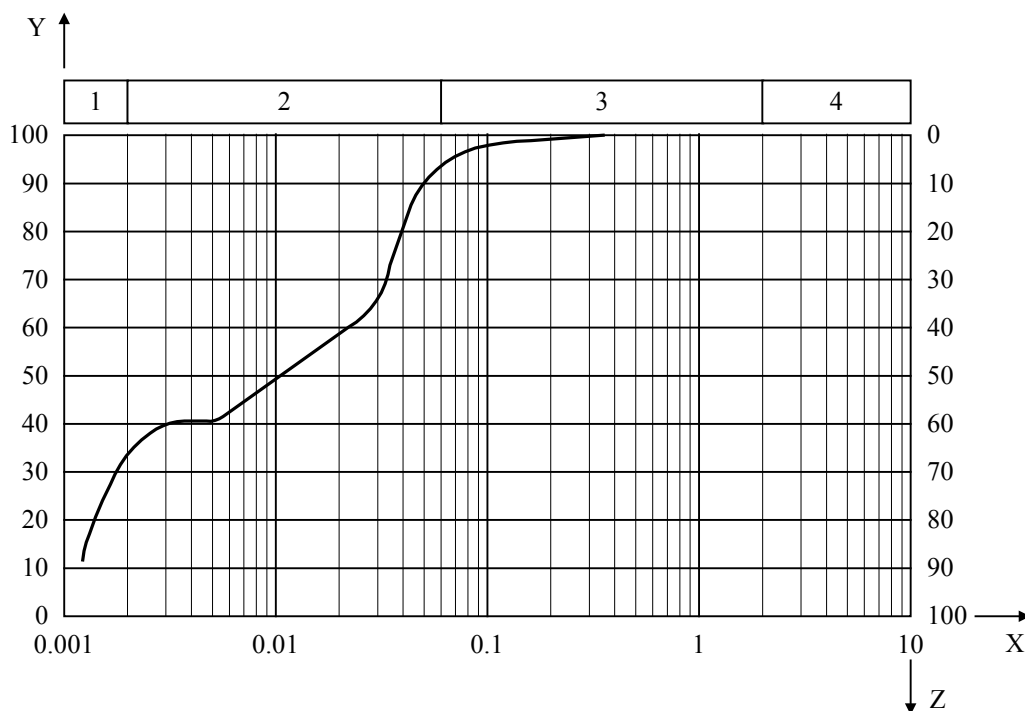
Key
1   clay $\leq$ 2 μm
2   silt > 2 μm and $\leq$ 63 μm
3   sand > 63 μm and $\leq$ 2 mm
4   gravel > 2 mm and $\leq$ 63 mm
X   particle size (mm)
Y   passing percentage (%)
Z   retained percentage (%)

7.2   Inspection and Testing

The following tests and inspections should be conducted after retrieving the sample:

i)   Perform visual inspection of the full rope sample

ii)   Open the outer jacket and inspect the soil filter layer by layer

iii)   Examine the yarn of one subrope just beneath the soil filter by scanning electron microscope (SEM) to determine the efficiency of the filter. In general the yarn should not contain particles greater than 5 microns. (Existence of a few particles larger than 5 micron may not indicate deficiency of the filter because these particles could be within the rope prior to contact with the soil).

iv)   Conduct break tests for a minimum of 4 outer subropes. The average of the break loads should be more than 90% of the average of the break loads for new subropes.

v)   Residual fatigue life should be checked on at least one outer subrope by applying either one of the following cyclic loadings at a period of less than 1 minute per cycle. The subrope should show no sign of imminent fatigue failure.

•   Tension range of 10% - 50% MBS for 17,000 cycles

•   Tension range of 5% - 55% MBS for 5,500 cycles

8   Torque Match with Steel Wire Rope

This test is required for fiber rope connected with a torque steel wire rope (6-strand or 8-strand) in a permanent mooring. The test is intended to demonstrate that the torque characteristics between the fiber rope and the steel wire rope are compatible. The test procedure is as follows:

i)   Equal length full rope samples of the fiber rope and the wire rope should be connected and arranged in a test machine with both outer ends fixed.

ii)   The samples should be loaded to 2% of the wire rope MBS, and the length of each rope and the lay length of the wire rope should be measured.

iii)   The samples should be cycled 10 times between 2% and 20% of wire rope MBS at a period of 20 to 30 sec.

iv)   The samples should be held at the 20% wire rope MBS and the connection between the two ropes should be provided with means to measure any rotation of the connection, such as a lever.

v)   The samples should be cycled 10 times with a load range of 10% to 30% of wire rope MBS at a period of 20 to 30 sec., and the angular rotation of the connection for each cycle should be recorded.

The average cyclic degree of rotation per lay length of the wire rope should be calculated and should not exceed 5° as specified in 3/12.1.

9   HMPE Creep Rate Verification

This test is required for HMPE rope only and is intended to demonstrate that the creep model generating creep data for HMPE creep analysis (4/2.3) and creep rupture analysis (4/2.4) is appropriate. The test procedure is as follows:

i)   The test should be performed for a constant load and a constant temperature. The load level and temperature should be selected to be relevant to the project where the rope will be applied, so that the creep rate in Regime II (4/2.1) can be established with confidence.

ii)   The duration is such that the sample shows a constant creep rate with time for at least 24 hours, and the load level and temperature should be kept as constant as possible within the duration. Load and elongation should be recorded during the entire duration at least hourly.

iii)   The creep rate is obtained from the strain versus time data over the end of the test period (e.g., the last 24 hours), which should be compared with the creep rate generated by the creep model for the specific load and temperature.

iv)   The total strain measured during Regime I of the test should also be reported.

10   Aramid Axial Compression Fatigue

This test is required for aramid rope only and is intended to demonstrate that the aramid rope has adequate resistance against axial compression fatigue failure.

10.1   Test Procedure

The cyclic load test should be conducted as follows:

i)   Cycle the rope from a trough tension of 1% of MBS to a peak tension of 20% of MBS at a period of less than 1 minute per cycle for at least 2,000 cycles.

ii)   Tension the rope to break, using the test procedure of 8/4.1, to determine residual strength.

10.2   Data Reporting

Report the residual strength, both in absolute terms and as a percentage of new MBS and the number of applied cycles.

If the residual strength is greater than 95% MBS, then the rope is considered to pass the axial compression fatigue test.

SECTION 9 Testing of Yarn

Yarn testing should be conducted according to Subsection 9/1 to 9/3 before rope production. Some yarn properties should be verified during production according to Subsection 9/4.

1 Testing of Yarn Dry Breaking Strength and Elongation

Four samples of basic yarn should be taken and tested. The samples should be conditioned to equilibrium at a temperature between 15° and 25° C and a relative humidity between 60% and 70%.

The samples should be loaded to break in accordance with ASTM D 885 "Tire Cords, Tire Cord Fabrics, and Industrial Filament Yarns Made From Man-Made Organic-Based Fibers" [21], BS EN ISO 2062 "Methods of Determination of Breaking Strength and Extension" [24], or an equivalent method. The testing method to be used should be identified in the rope design documentation. The same method is then to be used whenever the yarn is tested.

The average yarn dry breaking strength and dry elongation should be determined and recorded.

2 Testing of Yarn Dry Creep for HMPE

A sufficiently large number of HMPE yarn tests should be conducted to provide test data for developing models for HMPE creep and creep rupture analysis (Subsection 4/2). Test variables include yarn stress, temperature, creep versus time (creep model), and time to creep rupture (creep rupture model).

3 Yarn-on-Yarn Abrasion Performance

Marine grade fibers such as polyester and aramid should meet the requirements specified in 9/3.1 and 9/3.2. Other fibers such as HMPE, if not marine grade, should pass the yarn-on-yarn test specified in 9/3.1.

3.1 Efficiency of Marine Finish

When the fiber is specified to be "marine grade", qualification testing for efficiency of finish should be performed on wet yarns in accordance with CI 1503 [25]. The tests should be performed at least at three load levels, including one in each of the following ranges:

* 20 to 30 mN/tex;

* 35 to 45 mN/tex;

* 55 to 60 mN/tex.

  Note: Tex is a unit for expressing linear density, equal to the weight in grams of 1 kilometer of yarn, filament, fiber, or other textile strand. 1 kg/m = 1,000,000 tex.

A minimum of 8 yarns should be tested for each level. The results at each load level should be obtained and reported in accordance with the procedure in CI 1503. The mean number of cycles to failure as defined in CI 1503, at each load level should be above the minimum number of cycles given in Section 9, Figure 1 for that level. The number of cycles to failure, *N*, shown in Section 9, Figure 1, is given by the equation:

$$\log N = 4.5 - F_{test}/30 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (9.1)$$

where F_{test} is the test load, expressed in millinewtons per tex (mN/tex).

3.2   Persistence of Marine Finish

The persistence of the marine finish in a marine environment should be demonstrated. The assessment method should be duly documented by the fiber producer. Yarn-on-yarn abrasion tests after artificial aging may be used.

FIGURE 1
Minimum Requirement for Yarn-on-Yarn Abrasion Test
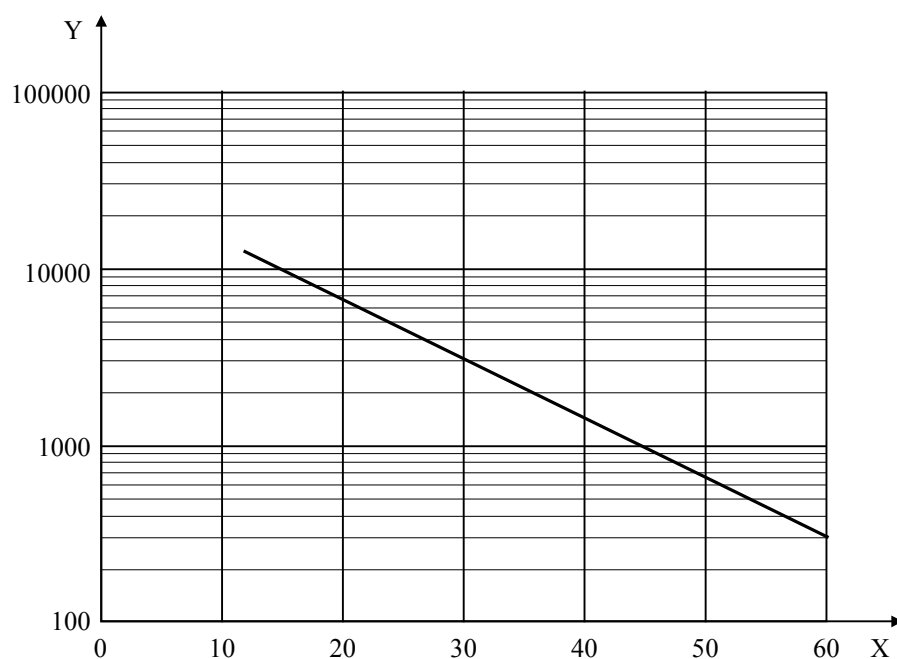
Key
X   test load, F_{test}, in millinewtons per tex (mN/tex)
Y   number of cycles to failure, N

4   Yarn Testing during Production

Yarn properties should be verified during production as follows:

i)   At least one yarn sample should be taken randomly from each 2 MT of material and tested for yarn size, dry break strength, and dry elongation to break.

ii)   At least one wet yarn-on-yarn abrasion test should be performed from each 20 MT of material. Each test should be carried out at least at one load level, on a minimum of four yarns, with an acceptance level not less than the one given in Section 9, Figure 1 for that level.

![ABS logo](FOUNDED 1862)

SECTION **10 Rope Design**

1   General

The most commonly used type of fiber rope for offshore moorings consists of parallel subropes held together by a braided jacket (parallel construction). The subropes consist of strands in helical (laid) or braided arrangement. The strands are made up with yarns. Rope constructions resembling steel wire rope are also used, either as subropes or as full rope (wire rope construction). Soil filter is typically incorporated between the jacket and the rope core to block harmful soil particles. Fiber ropes are terminated with spliced eyes.

Most fiber ropes are non-torque type, i.e. the rope does not exert torque when loaded. When a fiber rope is connected to a torque steel wire rope such as 6-strand wire rope, a "torque-matched" rope is sometimes used (Subsection 3/12).

2   Load Bearing Fiber

Polyester, HMPE, and aramid are the primary fibers considered by these Guidance Notes. Polyester fibers should be high tenacity and marine grade. Aramid fibers should be marine grade. Other fibers can be considered by ABS based on their properties and intended application. All fibers should pass the yarn-on-yarn abrasion test specified in Subsection 9/3.

3   Rope Jacket

Rope jacket should be sufficiently dense to protect the rope from mechanical damage during handling and service. It should be permeable for water to flood the rope core. Visible marking such as colored strands or brightly colored longitudinal stripes should be incorporated in the rope jacket for monitoring rope twist during installation.

4   Soil Filter

Soil filter should be effective to prevent ingress of particles exceeding 5 microns, based on standard filtering test such as ASTM D 4751 [26]. For ropes preset on the seafloor or reuse of rope accidentally dropped on the seafloor, the requirement and testing specified in Subsection 12/3 should be met.

5   Termination

Fiber ropes should be terminated with spliced eyes. For terminations other than spliced eye, detailed design and testing information should be submitted for approval on a case by case basis. Important factors for spliced eyes are D/d ratio and protection of the rope eye. If the spliced eyes are fitted on thimbles, the thimble should be a neat fit on the connecting (shackle or H-link) pin, and the root diameter should be specified.

Rope jacket and soil filter should be restored to cover splice after splicing. Protective cloth should be provided between the splice eye and the termination hardware that fits through the eye. Such cloth should provide low friction and high wear resistance. The splice should be covered by elastomeric material such as polyurethane coating to protect against chafing. The coating can be omitted for test samples.

A subrope should be spliced back to itself or in a matched pair.

6   Rope Continuity

Strand or subrope should be manufactured continuously for each rope segment without interchange or splice. Long rope segments consisting of strand splices will be specially considered based on detailed information of design, testing, and manufacturing.

Rope cover may include properly staggered strand interchanges.

![ABS logo]

SECTION **11 Rope Production and Certification**

This Section provides guidance on manufacturing the rope, including design documentation, quality control and assurance, termination, assembly, and product documentation.

1   Rope Design Documentation

The rope manufacturer is responsible for preparing and following detailed documents which completely and accurately describe how the rope is made, including a Rope Design Specification, a Yarn Specification, a Manufacturing Specification, and a Termination Specification.

2   Quality Control and Assurance

2.1   Quality Assurance Manual

The rope manufacturer should prepare a Quality Assurance Manual which completely and accurately describes the Quality Control and Assurance Program. This document should be made available for examination by the attending ABS Surveyor during rope inspection.

2.2   Quality Control Data Sheets

The rope manufacturer should prepare Quality Control Data Sheets for the processes of yarn assembly, strand assembly, rope making, rope jacketing, splicing, and other processes as applicable.

2.3   Quality Control Report

For each rope and rope assembly, the rope manufacturer should prepare a Quality Control Report based on OCIMF, "Guidelines for the Purchasing and Testing of SPM Hawsers" [27] or an equivalent practice. This Report is to include the Quality Control Data Sheets, Material Certificates, yarn test results, rope inspection and test reports as applicable. This Report should be available for examination by the attending Surveyor at the rope manufacturer's offices at any time upon request.

3   Material Certification

The rope manufacturer should certify that the fiber material used in making the rope is that specified in the Rope Design Specification. The yarn producer should certify the type and grade of fiber material, including finish designation, merge number, and other identifying information. Either the rope manufacturer or the yarn producer should certify the following yarn properties, using the test methods specified in Section 9:

- Yarn size

- Dry break strength

- Dry elongation to break

- Dry creep

- Wet yarn-on-yarn abrasion

4   Rope Production Report

The rope manufacturer should prepare a Rope Production Report. This Report should include a complete and accurate description of the rope product, rope and termination design, and the manner in which the length was determined, and the quality control report. The rope production report should be available for examination at the rope manufacturer's offices. One copy of this Rope Production Report should be shipped with the rope and one copy of this Report should be submitted to the attending ABS Surveyor.

5   Testing, Inspection, and Certification

5.1   General

This Subsection provides guidance on inspection, testing, and certification of the finished rope product. Specific survey requirements during prototype testing and production are summarized in Section 14.

The inspection should be carried out by the attending ABS Surveyor. Testing of components and samples of the produced rope should be witnessed by the attending ABS Surveyor.

5.2   Inspection, Examination, and Testing during Rope Production

Notification of the beginning of rope production should be given to ABS prior to the beginning of production. Access to the rope making and assembling facilities at any time while rope production and assembly are in process should be provided to the attending ABS Surveyor. This includes operations of assembling yarns, assembling strands, making ropes, terminating ropes, and testing materials.

The attending Surveyor may carry out reasonable inspections of the rope making and assembly processes and question production and quality assurance personnel prior to, during, and after rope production and assembly. He may at any time review the applicable Yarn Specifications, Manufacturing Specifications, Termination Specifications, prototype rope test results, quality control check lists, material certificates, and fiber certificates.

At any time during rope production or termination, the attending Surveyor may take reasonable quantities of yarn samples from production and have them tested, in accordance with Section 9.

5.3   Inspection of Completed Rope Product

The attending Surveyor may examine and inspect each continuous length of rope after it is produced. At the conclusion of rope production, the attending Surveyor will review rope production documentation for completeness.

5.4   Examination and Inspection of Terminations

Notification of the beginning of application of rope terminations should be given to the attending Surveyor prior to the beginning of application of terminations. The attending Surveyor will have access to the location where terminations are applied at any time while terminations are being applied. The Surveyor may carry out reasonable inspections of the rope termination process and question termination and quality assurance personnel prior to, during, and after termination application.

The Attending Surveyor should thoroughly inspect the assembled rope, after application of terminations and as appropriate before or after the application any other appliances and accessories. Traceable rope assembly markings in accordance with Subsection 11/6 should be identified during the inspection.

5.5   Determination of Finished Rope Length

If a method of determining the finished rope length is specified and agreed to in the purchase order, the rope manufacturer will carry out that test in the presence of the attending Surveyor to demonstrate the specified length.

6 Marking

Each fiber-rope assembly should be marked at each end with a durable and unique identifier traceable to appropriate certification with at least the following information:

- Manufacturer identification

- Order and part number

- Rope MBS

- Month and year of production

- ABS certification number

SECTION **12 Handling and Installation**

1 General

This Section provides guidance for handling and installation of fiber ropes. In general, the guidance in Appendix G of API RP 2SM (May 2007) [28] should be followed to minimize damage during handling and installation. Other guidance is included in the ABS *FPI Rules* [1] and the applicable sections of the ABS *MODU Rules* [3].

2 Minimum Tension for Aramid Rope

The aramid rope should maintain a minimum tension of 2% MBS if it is suspended by a buoy after pre-installation

3 Contact with Seabed

3.1 Preset Mooring

In general, contact of fiber rope with seabed should be minimized during deployment. However, in some instances, it is necessary for the mooring line to be preset prior to hook-up with the installation. Presetting of fiber rope on seabed is acceptable if the rope passes the test for particle ingress resistance as outlined in Subsection 8/7.

3.2 Dropped Rope during Deployment

A rope accidentally dropped on the seafloor during deployment can be reused under the following conditions:

i)   The rope passes the test for particle ingress resistance as outlined in Subsection 8/7, and

ii)   The rope is retrieved quickly and inspected according to API RP 2I. There is no damage exceeding the API RP 2I discard criteria.

4 Preloading Operation

The preloading operation to remove as much permanent elongation as possible and to increase stiffness of the rope should be carefully planned before installation. The preload level and duration should be determined based on a number of considerations including amount of permanent elongation to be removed, limitation of preloading equipment, and time required to complete the preload operation. The preload duration should not be less than one hour. The preload level and duration achieved and rope elongation should be recorded for each step and compared with the expected values.

SECTION **13 Surveys During and After Installation**

1 General

Surveys during and after installation should generally be based on the following documents:

- API RP 2I [14] (fiber rope and steel components)

- ABS *FPI Rules* [1] (steel components)

- ABS *MODU Rules* [3] (steel components)

A typical fiber rope mooring system consists of steel components at the floating vessel and anchor ends, and therefore inspection procedures for fiber rope moorings and steel moorings are closely related. The inspection objective, type, and schedule established for steel moorings in the above documents are generally applicable to fiber rope moorings. The following sections address only inspection schedule and additional issues unique to fiber ropes.

The decision to retire a fiber rope during a survey should be based on the fiber rope discard criteria specified in API RP 2I [14].

Monitoring of fiber rope mooring may require additional information, such as rope elongation, time period between re-tensioning, removal and testing of inserts if applicable, and inspection techniques. Methods to acquire this additional information should be included in the operations, maintenance, and in-service monitoring plan for ABS review.

2 Permanent Mooring

2.1 Survey During Installation

A survey should be conducted within 3 months or as soon as practical after completion of initial hookup of the mooring system with the floating vessel. If needed, additional survey should be performed after subsequent installation activities (riser hookup, etc.) that may have significant impact on the mooring system.

The mooring line should be inspected for any external damage by ROV (Remotely Operated Vehicle) or diver. Twist can be verified at installation by ROV/diver monitoring of the marking that runs externally on the jacket. Particular attention should be made to the condition of fiber ropes terminations. Other design aspects which should be verified immediately following hook-up are the fiber rope near surface termination position and the preloading. Estimated elongation should be recorded for all lines during the preloading operation. The purpose of the survey is to establish the initial condition, which will be compared with future inspection results.

2.2 Surveys After Installation

The requirements for surveys after installation specified by the ABS *FPI Rules* [1] and API RP 2I [14] are summarized below. Refer to Part 7 of the ABS *FPI Rules* for detailed requirements.

2.2.1 Annual Surveys

Annual Surveys of mooring system should be made within three (3) months before or after each annual anniversary date of the crediting of the previous Special Periodical Survey or original installation date. The survey is limited to above water components. In addition to requirements specified in Part 7 of the *FPI Rules* [1], these Guidance Notes recommend the following:

- The Surveyor should review the records of anchor leg re-tensioning caused by creep, and confirm with designer that adequate chain/wire segments are available for further re-tensioning due to creep such that the fiber rope does not come into contact with the chain stoppers, fairleads, etc., and stays below the water surface. See 3/1.1 for determination of lengths of chain/wire segments.

- The Surveyor should verify that recorded values of creep are in accordance with the anticipated design values. Any deviance from design values should be justified by the designer, and appropriate remedial action should be taken accordingly.

- The pre-tension of mooring lines should be within the designer recommended limits. It should be noted that the measurement of catenary angles as indicated in the *FPI Rules* may not be sufficient for TLMs (Taut Leg Moorings). Other means should be used to determine the mooring line tensions to the satisfaction of the attending Surveyor.

2.2.2   Special Periodical Surveys

A Special Periodical Survey should be completed within five (5) years after the date of build or after the crediting date of the previous Special Periodical Survey. The survey scheme should include methods and techniques used to verify that the system is operating as designed. In accordance with Part 7 of the *FPI Rules*, Special Periodical Survey should include a dry-docking or underwater inspection (ROV or diver), and all components of mooring system should be examined to the satisfaction of the attending Surveyor. In addition, particular attention should be given to the examination of the following for fiber ropes:

- Records of anchor leg re-tensioning caused by non-recoverable elongation should be reviewed, and confirmed with the designer that adequate lengths of chain/wire segments are available for further re-tensioning due to non-recoverable elongation such that the fiber rope does not come into contact with the fairlead and stays below the water surface. See 3/1.1 for determination of lengths of chain/wire segments.

- The pretensions of mooring lines are within the designer's recommended limits. The measurement of catenary angles may not necessarily be very accurate for taut leg moorings. Thus other means should be used to determine the mooring line tensions.

- Conditions of the terminations are checked

- Foreign particles in way of rope body and crevices are examined and removed if possible.

- Marine growth, if affecting the condition of the rope, should be removed if possible, by a method which will not damage the rope.

2.2.3   Special Event Survey

A special event survey should be considered after severe storms or other events that warrant inspection (dropped objects, collision, and contact with work wire, etc.). The scope of Special Event Survey should be determined based on the purpose of the survey. For example if the survey is needed because of dropped object, the survey may be limited to the area that can be damaged by the dropped object. After a severe storm, which is defined as environmental conditions approaching the design storm conditions, the measures recommended for the Annual Survey should be followed as minimum. Some of the measures recommended for the Special Periodical Survey should be considered, if applicable.

3   MODU Mooring

For MODU moorings, reference should be made to the applicable sections of the ABS *MODU Rules* [3].

Regular inspection of fiber mooring ropes may be feasible, while the fiber rope moorings are recovered and before they are redeployed at a new location. In general before a fiber rope is reinstalled it should be carefully inspected for damage to the jacket, rope core, terminations, and termination hardware. Such inspection can be performed during recovery of the moorings on board the recovery vessel(s), or it can be performed at a base port facility.

After a severe storm, which is defined as environmental conditions approaching the design storm conditions, inspection of the fiber mooring line should take place immediately or at the next rig move.

In the areas of tropical cyclone (hurricane, typhoon, etc.), MODUs may encounter environmental loads much higher than the design loads, and mooring failures are possible. Rigorous mooring inspection is more critical for operations in these areas to address the integrity of the mooring system and minimize the probability of mooring failures. Also guidance is needed to address the reuse of the components from a mooring damaged by a tropical cyclone. Appendix B of API RP 2I [14] should be followed for additional guidance for MODU mooring inspection in these areas.

4   Test Insert

4.1   The Tradeoff of Test Insert

Some permanent moorings contain fiber rope test inserts, which are short segments typically 10 m to 15 m long, placed at the top of the fiber mooring line just below the fairlead chain. A test insert can be taken out periodically for detailed inspection and testing. This inspection method may provide information on the in-service condition of the fiber rope such as present strength and fatigue life, ingress of soil particles or marine growth, changes in yarn or fiber properties, and loss of marine finish, etc., for the insert tested. There are concerns regarding the negative impact of this practice. Therefore the placement and inspection of test inserts need careful evaluation, which should consider the following factors.

i)   The use of test inserts increases the number of terminations, which are potential weak points in the mooring.

ii)   Currently there is no standard methodology to apply the test insert data to the rest of the mooring line. The data gathered from a short segment placed at a particular location may not be representative of other rope segments.

iii)   There may be a considerable risk of damage to the mooring lines, risers, umbilicals or other infrastructure in the water column and on the seafloor during test insert retrieval or replacement operations, especially for operations that place test inserts several hundred feet below the water surface and adjacent to or between other mooring lines, risers, and umbilicals. Such operations require careful planning and execution in order to minimize the risk of damage to equipment and injury to personnel.

For these reasons, the potential benefits of test inserts should be carefully weighed against the potential adverse impact for each project before decisions of placing or retrieving test inserts are made.

4.2   ABS Requirement

Placement and retrieval of test inserts are not required by ABS. However, the designer should be aware of the coastal state requirements on test insert.

SECTION 14 Requirement for Witness by ABS Surveyor

This Section specifies survey, testing, inspection, and production to be witnessed by ABS Surveyor

1 Prototype and Production Testing

1.1 Yarn Testing
The ABS Surveyor should witness the following tests in Section 9:

i) Yarn Dry Breaking Strength and Elongation

ii) Yarn Dry Creep

iii) Wet Yarn-on-Yarn Abrasion

1.2 Rope Testing
The ABS Surveyor should witness the following tests in Section 8:

i) Minimum Breaking Strength

ii) Elongation and Stiffness

iii) Splice Qualification

iv) Particle Ingress Resistance

v) Torque Match with Steel Wire Rope

vi) HMPE Creep Rate Verification

vii) Aramid Axial Compression Fatigue

2 Production Tests and Inspections

i) Inspection, examination and testing during rope production (11/5.2):

ii) Inspection of completed rope product (11/5.3)

iii) Examination and inspection of terminations (11/5.4)

iv) Determination of finished rope length (11/5.5)

3 Mooring System Survey

i) Survey during Installation (13/2.1)

ii) Annual Survey (13/2.2.1)

iii) Special Periodical Survey (13/2.2.2)

iv) Special Event Survey (13/2.2.3)

v) Survey after MODU mooring failure due to tropical cyclone (Subsection 13/3)

APPENDIX 1 References

[1] ABS Rules for Building and Classing Floating Production Installations, 2014.

[2] API RP 2SK: Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd Edition, 2005.

[3] ABS Rules for Building and Classing Mobile Offshore Drilling Units, 2008.

[4] Francois, M. and P. Davies, Fiber Rope Deep Water Mooring: A Practical Model for the Analysis of Polyester Mooring Systems, Rio Oil and Gas Conference IBP24700 (2000)

[5] ABS Technical Report TR-2010-03, "Polyester Rope Stiffness modeling, Testing, and Analysis", ABS JIP Phase 1 report, June 2010.

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[22] BS ISO 18692:2007, "Fiber Ropes for Offshore Stationkeeping - Polyester", 2007.

[23]   ASTM Test Method D 885: "Tire Cords, Tire Cord Fabrics, and Industrial Filament Yarns Made From Man-Made Organic-Based Fibers", American Society for Testing and Materials, Conshohocken, PA.

[24]   BS EN ISO 2062, "Methods for Determination of Breaking Strength and Extension", 1995.

[25]   CI Standard: "Test Method for Yarn-on-Yarn Abrasion", CI 1503-00, the Cordage Institute, Hingham, MA, 2000.

[26]   ASTM D 4751 – 04: Standard Test Method for Determining Apparent Opening Size of a Geotextile, 2004

[27]   OCIMF: Guidelines for the Purchasing, Prototype testing and Production of SPM Hawsers, 2000.

[28]   API RP 2SM: Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring, 1st Edition, 2001, and the 2007 Addendum.

APPENDIX 2 Supporting Information and Examples

This Appendix provides additional information as follows:

- Stiffness values for preliminary design before more accurate data are available

- Basis for some guidance, for example results of parametric studies and guidance for dynamic stiffness test matrix

- Examples on how to apply some guidance

This Appendix is not intended to be used as part of the Guidance Notes. The purpose of this Appendix is to provide some background information and examples for better understanding and application of the Guidance Notes. The user should be aware that not all the information here is applicable to a specific project, and therefore should be cautious in using this information.

1 Stiffness values for Preliminary Design of Polyester Moorings

During preliminary design, there is a need to use approximate stiffness values since the rope manufacturer for the project may not be known. More accurate stiffness values based on rope specific testing are not available at this stage. In the absence of better information, guidance provided in the following sections can be used to determine stiffness values for preliminary design. It should be noted that these values are derived from test data of a few polyester permanent mooring projects, and all ropes have been subject to a preloading about 40% MBS to achieve initial bedding in.

1.1 Dynamic Stiffness

1.1.1 Three-Parameter Model Approach

Upper bound and lower bound dynamic model coefficients based on polyester rope test data for five recent projects are presented in Appendix 2, Table 1. The upper bound values are conservative for line tension while the lower bound values are conservative for vessel offset. The impact of dynamic stiffness on vessel offset is typically small, and quasi-static stiffness is normally the dominating factor for vessel offset. This approach requires rough estimates of mean tension, tension amplitude, and loading period.

TABLE 1
Dynamic Stiffness Coefficients for Preliminary Design

Coefficient	Upper Bound	Lower Bound
Intercept, α	26.00	20.30
Mean (%), β	0.28	0.22
Ten. Amp. (%), γ	–0.42	–0.33
Log (P), δ	–0.97	–0.76

Note: Refer to Section 3, Equation 3.3 for the definitions of these coefficients

1.1.2   Three Level Approach

In this simplified approach, the dynamic stiffness is grouped into 3 levels, as shown in Appendix 2, Table 2. The stiffness values in this table were generated for storm loads with tension amplitude reduced by 50%.

TABLE 2
Dynamic Stiffness Values for Preliminary Design

Level	Ratio of Max. Tension Amplitude over Mean Tension	Dynamic Stiffness Upper Bound (MBS)	Dynamic Stiffness Lower Bound (MBS)
1	Less than 0.2	35	29
2	About 0.5	31	26
3	Over 0.7	27	23

1.2   Quasi-Static Stiffness

Investigation of quasi-static stiffness test data for 5 recent projects indicates that variation in stiffness among post-installation and aged rope, ropes from different manufacturers is large. Appendix 2, Table 3 presents quasi-static stiffness values for preliminary design based on rope condition and stiffness class.

TABLE 3
Quasi-static Stiffness Values for Preliminary Design

Rope Condition	Rope Stiffness Class		
	Low (MBS)	Median (MBS)	High (MBS)
Post-installation	10	13	15
Aged	13	15	18

2   Examples for Determination of Polyester Rope Stiffness Based on Test Data

The following examples present procedures to develop the dynamic stiffness coefficients and quasi-static design curves based on test data for polyester ropes.

2.1   Dynamic Stiffness

Appendix 2, Table 4 presents example test data from dynamic stiffness test, which includes variation of mean tension, tension amplitude, and loading period.

The coefficients for the dynamic stiffness equation can be obtained by multiple regression analysis for the data in the left four columns. For this data set, the four coefficients, α, β, γ, δ, from multiple regression analysis are 27.5, 0.25, –0.59, –1.65 respectfully. The value of R^2 is 0.96 from the regression analysis indicating a good fit of the data to the equation (R^2 greater than 0.8 indicates a good fit, based on guidance for Excel regression analysis). Once the dynamic stiffness equation is determined, dynamic stiffness values can be calculated for various design conditions. It should be noted that γ and δ are negative in this case indicating tension amplitude and loading period tend to soften the dynamic stiffness.

TABLE 4
Example Dynamic Stiffness Test Data

Stiffness (MBS)	Mean Tension (%MBS)	Tension Amplitude (%MBS)	Log Period (sec.)	Period (sec.)
24.2	15	5	2.08	120
26.2	20	5	2.08	120
24.5	25	10	2.08	120
23.7	35	15	2.08	120
26.7	20	5	1.15	14
29.7	25	5	1.15	14
29.6	40	10	1.15	14
31.4	50	10	1.15	14

2.2   Quasi-static Stiffness

Quasi-static stiffness testing should be conducted for multiple load levels with a creep plateau at each level. Appendix 2, Figure 1 shows an example of test data for a post-installation rope. The "relative strain" assumes the strain is zero at the start of the test. The pre-tension for this project is 10% MBS, and the tension and elongation measurement for quasi-static stiffness should start from this point. There are three load levels:

i)   30% MBS with creep measurement at 1, 10, and 100 minutes

ii)   45% MBS with creep measurement at 1, 10, and 100 minutes

iii)   60% MBS with creep measurement at 1, 10, 100, and 1000 minutes

An equation for quasi-static stiffness can be derived for each load level.

FIGURE 1
Example Quasi-static Stiffness Test Data
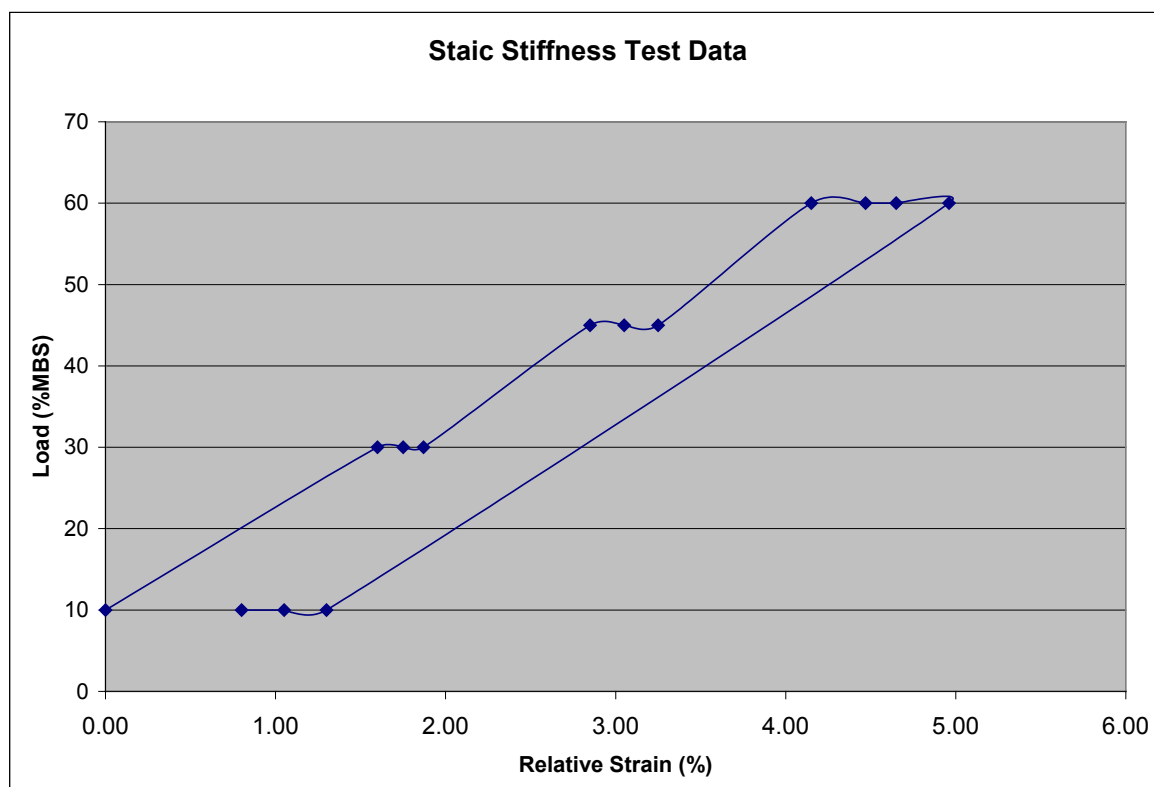
Appendix 2, Table 5 provides the creep data at 45% MBS, and Appendix 2, Figure 2 presents a plot of the creep data and a linear regression line for the data. The slope of the regression line, 0.225, is the creep coefficient C in the quasi-static stiffness equation, which is:

$$K_{rs} = (45 - 10)/[2.86 - 0 + 0.225 \log(t)]$$

$$K_{rs} = 35/[2.86 + 0.225 \log(t)] \qquad \text{(mean load = 45\% MBS)}$$

Similarly the equations for the other 2 load levels are:

$$K_{rs} = 20/[1.6 + 0.15 \log(t)] \qquad \text{(mean load = 30\% MBS)}$$

$$K_{rs} = 50/[4.22 + 0.265 \log(t)] \qquad \text{(mean load = 60\% MBS)}$$

TABLE 5
Creep Data at 45% MBS

Load Level (%MBS)	Time (Minutes)	Log Time (Minute)	Relative Strain (%)
45	1	0.00	0
45	10	1.00	0.25
45	100	2.00	0.45

FIGURE 2
Determination of Creep Coefficient for Quasi-Static Stiffness
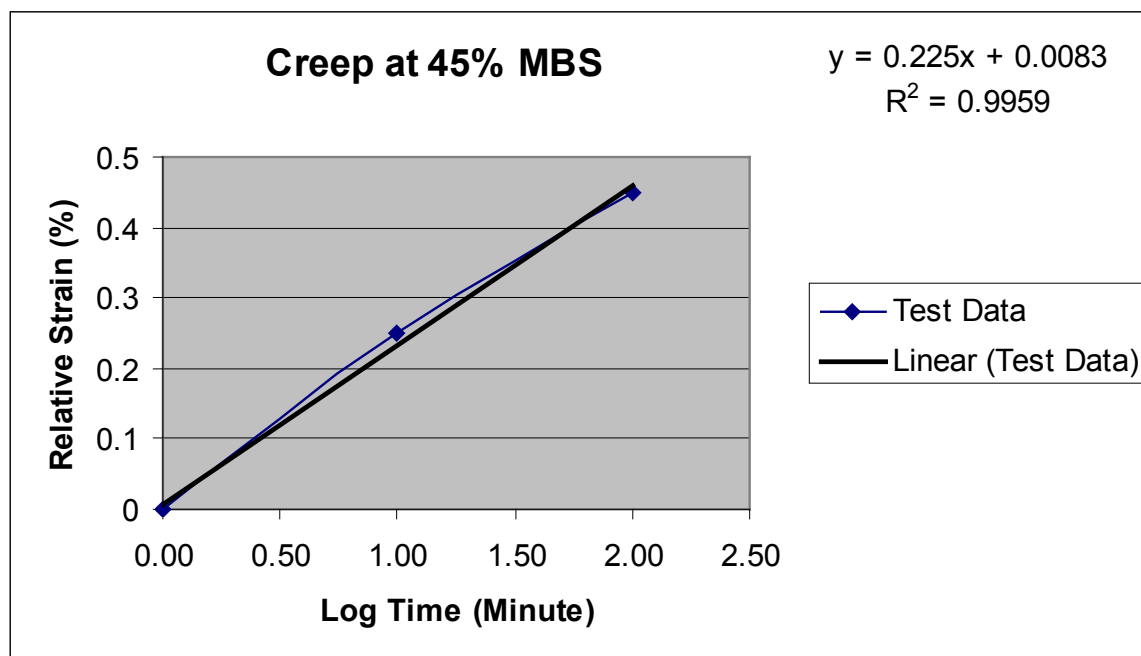
Quasi-static stiffness testing was also conducted for an aged rope, and three quasi-static stiffness equations can be obtained by the same procedure. Appendix 2, Figure 3 presents a plot of the six equations, which can be used conveniently for design. For practical purpose, the load level can be considered the mean load for the seastate, and the time can be considered the duration of the sea state.

FIGURE 3
Quasi-Static Stiffness Design Chart
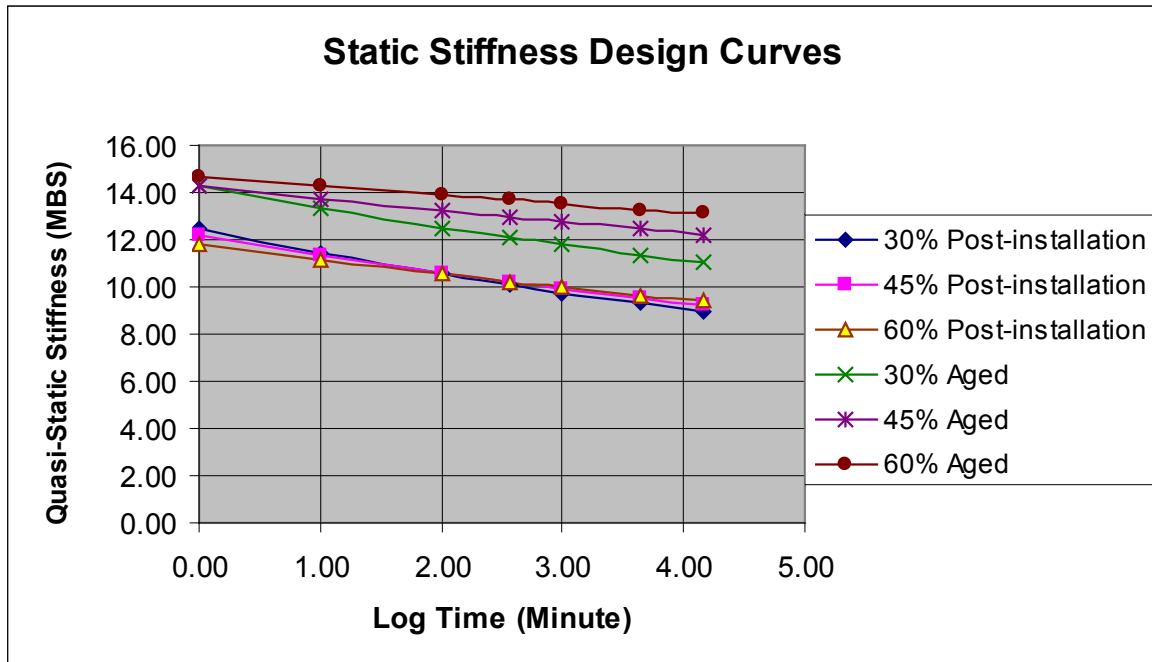
3   Major Conclusions from Parametric Studies for Polyester Mooring

Two parametric studies have been conducted in the DeepStar 6403 study [10] and in the ABS JIP [5] to investigate the influence of stiffness models and parameters on mooring analysis results under various conditions. The following parameters were studied:

- Model sensitivity: upper-lower bound model, 2-slope (static/dynamic) and 3-slope (static/LF/WF) model.

- Effect of environment: 100-year, 10-year, one-year return period and Loop current, GOM and Brazil

- Effect of water depth: 2,000 ft, 6,000 ft, and 10,000 ft

- Effect of vessel type: Spar (WF dominating) and FPSO (LF dominating)

- Same or different stiffness for all mooring lines (investigating the practice of using the stiffness for the most heavily loaded line for all mooring lines)

- Selection of stiffness for fatigue analysis

The conclusions from these studies are presented below, which can serve as guidance for practical and conservative fiber rope mooring analysis.

3.1   Stiffness Model

i)   Analysis results based on the 2-slope model are close to those based on the 3-slope model. The simpler 2 slope model is recommended.

ii)   For the 2 slope model, the dynamic stiffness can be taken as the higher of the LF and WF stiffness. In general the WF stiffness is higher than the LF stiffness.

iii)   The upper-lower bound model yields more conservative results, especially for offset

3.2   Dynamic and Quasi-static Stiffness

i)   Using the most loaded line dynamic stiffness for all mooring lines is acceptable

ii)   Dynamic stiffness values are only slightly different for various storm environments because mean load and tension amplitude offset each other. A practical and conservative approach is to calculate the dynamic stiffness for 3 environments representative of the high, median, and low seastates for the project. The highest dynamic stiffness is used for all seastates. This can significantly simplify the mooring analysis, avoiding using too many stiffness values in the analysis.

iii)   The dynamic stiffness values for FPSO are generally lower because of larger tension amplitude due to LF motions.

iv)   For a Spar under the Loop current environment, the mean tension due to current drag is dominating. Tension amplitude due to VIM is relatively small. Dynamic stiffness can be high because of high mean tension and low tension amplitude.

v)   Offset of spar under Loop current can be critical and therefore quasi-static stiffness should be carefully chosen to give conservative offset for the riser design.

3.3   Fatigue Analysis

i)   The upper bound stiffness is recommended for fatigue analysis since it predicts only slightly lower fatigue life but the analysis can be much simpler. The 2-slope or 3-slope model can be an alternative when more accurate and higher fatigue life prediction is required.

ii)   The quasi-static stiffness has low influence on fatigue life and can be taken as the average of the post-installation and aged rope stiffness. If the upper bound stiffness is used, the quasi-static stiffness is not applicable.

4   Polyester Mooring Analysis Example

4.1   Determination of Dynamic Stiffness

4.1.1   Storm Environment

A truss Spar is moored with a 9-point polyester mooring in GOM 6000 ft water depth, as shown in Appendix 2, Figure 4. Preliminary mooring analysis based on a constant stiffness of 30 MBS provides mean tensions and maximum tension amplitudes (combined LF and WF) for 3 storm environments as shown in Appendix 2, Table 6. The tensions are for the most loaded line under the inline environment. The moored system has a LF natural period of 140 sec., and the wave frequency period is assumed to be 14 sec. The dynamic stiffness equation from regression analysis of test data is (3/4.2).

$$K_{rd} = 27.5 + 0.25 L_m - 0.59 T - 1.65 \log(P)$$

Since the loading is stochastic from storm environment, the maximum tension amplitude should be reduced by a factor of 0.5 (3/4.2). The calculated dynamic stiffness values for various conditions are summarized in Appendix 2, Table 7. It can be seen that the stiffness values are not significantly different, and the highest dynamic stiffness 33 MBS can be conservatively used for all environments and all mooring lines. If the stiffness assumed in the preliminary analysis is significantly different from the calculated stiffness values, iterations may be needed. Since this is not the case for this example, iteration is not necessary.

FIGURE 4
Spar Mooring Pattern and Environmental Directions
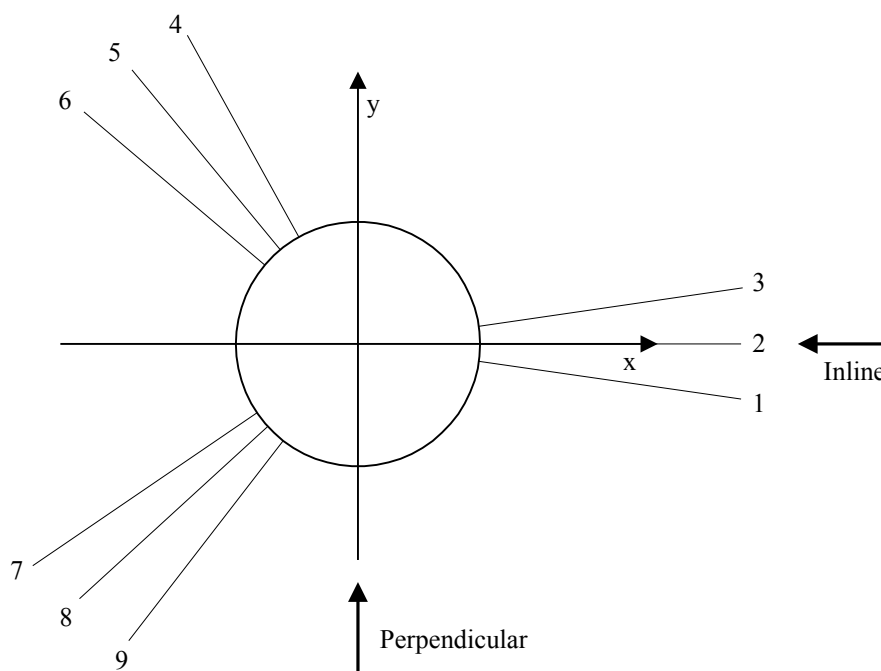
TABLE 6
Estimated Tension for Storm Environments

Environmental Load Case	Condition	Most Loaded Line Tension (% MBS)	
		Mean	Max Amplitude
100-year	Intact	32	10
	Damaged	42	11
10-year	Intact	25	6
	Damaged	34	8
1-year	Intact	20	1
	Damaged	25	1.2

TABLE 7
Dynamic Stiffness for Storm Environments

Environmental Load Case	Frequency	Dynamic Stiffness (MBS)	
		Intact	Damaged
100-year	WF	31	33
	LF	29	31
10-year	WF	30	32
	LF	28	30
1-year	WF	30	32
	LF	29	30

4.1.2   Fatigue Environment

For fatigue environment, the tension amplitude can be neglected in Equation 3.3, and only intact condition needs to be considered. The calculated stiffness values are provided in Appendix 2, Table 8, and the highest value 34 MBS can be conservatively used for all environments and all lines.

TABLE 8
Dynamic Stiffness for Fatigue Environments

Environmental Load Case	Frequency	Dynamic Stiffness (MBS)
100-year	WF	34
	LF	32
10-year	WF	32
	LF	30
1-year	WF	31
	LF	29

4.1.3   Loop Current Environment

The Spar under the 100-year Loop current is expected to experience VIM (Vortex Induced Motions) perpendicular to the current direction. The design lock-in A/D is 0.5, and two current directions, inline and perpendicular, are considered in this example. The associated waves are small and therefore only LF responses are analyzed. Preliminary mooring analysis based on a constant stiffness of 30 MBS provides the mean tensions and maximum tension amplitudes for two current directions as shown in Appendix 2, Table 9. The tensions are for the most loaded line.

Since the loading is sinusoidal under VIM lock-in condition, no reduction is needed for the maximum tension amplitude (3/4.2). The calculated dynamic stiffness values for various conditions are summarized in Appendix 2, Table 10. It can be seen the stiffness values for the inline direction are high due to high mean tension and low tension amplitude. The calculated stiffness values are significantly different, and using the highest value 38 MBS for all conditions can be very conservative. Using different stiffness for different conditions should be considered if more accurate results are desired.

TABLE 9
Estimated Mooring Line Tensions under Spar VIM

Environmental Load Direction	Condition	Most Loaded Line Tension (% MBS)	
		Mean	Max Amplitude
Inline	Intact	44	4
	Damaged	64	3
Perpendicular	Intact	47	9
	Damaged	68	12

TABLE 10
Dynamic Stiffness for Spar VIM

Environmental Load Direction	Frequency	Dynamic Stiffness(MBS)	
		Intact	Damaged
Inline	LF	33	38
Perpendicular	LF	30	34

4.2   Determination of Quasi-static Stiffness

4.2.1   Storm Environment

The quasi-static stiffness design curves generated from test data can be used to determine quasi-static stiffness values (Appendix 2, Figure 3). For example for a storm duration of 10 hours (600 minutes), the minimum quasi-static stiffness for a post-installation rope is about 10 MBS, and the maximum quasi-static stiffness for an aged rope is about 13.6 MBS, based on Appendix 2, Figure 3. These values provide an upper and lower bound for all environments. Mean vessel offsets based on both values should be provided to the riser designers to determine which value is more critical for a particular riser design. Typically the lower bound stiffness is more critical for top tension rigid risers and maximum stress of steel catenary risers. However, the upper bound stiffness may be more critical for fatigue of steel catenary risers since the smaller vessel offset may result in more concentrated fatigue damage in the touchdown area. It may be necessary to check some intermediate stiffness values, if required by riser considerations.

4.2.2   Fatigue Environment

Quasi-static stiffness has low impact on fatigue of mooring components. A conservative approach is to use the dynamic stiffness only to determine the tension range for fatigue analysis. If a more accurate 2-slope or 3-slope model is used for fatigue analysis, the quasi-static stiffness can be taken as the average of the upper and lower bound values determined in A2/4.2.1, which is 11.8 MBS.

4.2.3   Loop Current Environment

The duration of Loop currents inducing Spar VIM can be much longer than storm duration. Assuming a Loop current duration of 12 days (17280 minutes), the minimum quasi-static stiffness for a post-installation rope is about 9 MBS, and the maximum quasi-static stiffness for an aged rope is about 13.2 MBS, based on Appendix 2, Figure 3.

4.3   Determination of Upper and Lower Bound Stiffness

The upper and lower bound stiffness values for this model can be established using the dynamic and quasi-static stiffness values determined in A2/4.1 and A2/4.2.

4.3.1   Storm Environment

Upper bound: K_{rs} = 33 MBS (A2/4.1.1)

Lower bound: K_{rs} = 10 MBS (A2/4.2.1)

4.3.2   Fatigue Environment

Upper bound: K_{rs} = 34 MBS (A2/4.1.2)

Lower bound: Not applicable

4.3.3   Loop Current Environment

Upper bound: K_{rs} = 38 (A2/4.1.3)

Lower bound: K_{rs} = 9 (A2/4.2.3)

4.4   Strength Analysis Example

This example is based on the following conditions:

- A spar operating in GOM 6000 ft water depth

- 100-year in-line environment

- Static-dynamic stiffness model, K_{rs} = 12, K_{rd} = 29

4.4.1   FD Analysis

Two analyses are conducted. The first one is a static analysis for mean load only using K_{rs} = 12, and the second one is a FD dynamic analysis using K_{rd} = 29. The analysis results are summarized in Appendix 2, Table 11.

TABLE 11
FD Analysis Results

Stiffness	Offset (m)			Tension (kN)		
	Mean	Sig. LF	Sig. WF	Mean	Sig. LF	Sig. WF
K_{rs} = 12	40.92			7771		
K_{rd} = 29		2.27	3.85		616	1010

The responses are WF dominating. Assuming Rayleigh distribution for peak values for a 3-hour storm, the following maximum responses are calculated based on Equation 5.2 and 5.4 of API RP 2SK :

$$S_{max} = S_{mean} + S_{wfmax} + S_{lfsig} = 40.92 + 1.86 \times 3.85 + 2.27 = 50.35 \text{ m}$$

$$T_{max} = T_{mean} + T_{wfmax} + T_{lfsig} = 7771 + 1.86 \times 1010 + 616 = 10266 \text{ kN}$$

4.4.2   TD Analysis

Two analyses are conducted. The first one is a static analysis for mean load only using K_{rs} = 12, and the second one is a TD dynamic analysis using K_{rd} = 29. The analysis results are summarized in Appendix 2, Table 12.

TABLE 12
TD Analysis Results

Stiffness	Offset (m)		Tension (kN)	
	Mean	Max	Mean	Max
K_{rs} = 12	40.92		7771	
K_{rd} = 29	18.0	26.38	7930	9940

Based on 3/8.2, the maximum responses are calculated as follows:

$$S_{max} = 40.92 + 26.38 - 18.0 = 49.30 \text{ m}$$

$$T_{max} = 7771 + 9940 - 7930 = 9781 \text{ kN}$$

The above results represent only one realization. The design value should be the average of at least 5 realizations.

4.5   Fatigue Analysis Example

In this example, a fatigue analysis is conducted for a spread moored FPSO in 6,000 ft water depth offshore Brazil for the most loaded mooring line, assuming all environments from one direction. The fatigue analysis is based on API RP 2SK [2] fatigue analysis procedure, and the simple summation method is used to combine the LF and WF fatigue damage. The mooring is a chain-polyester-chain system, and the fatigue life is predicted for the upper studless chain, which has the shortest fatigue life among the three segments. The Brazil fatigue environment is represented by 12 sea states, and an example of fatigue calculation is presented in Appendix 2, Table 13 based on a 3-slope model. Fatigue analysis is also performed for the 2-slope and upper bound model, and comparison of analysis results based on these models are presented in Appendix 2, Table 14. Predicted fatigue lives are in a range of 116 to 157 years, which is not considered a large range for fatigue life prediction.

TABLE 13
Example Fatigue Life Prediction

Fatigue Analysis for FPSO/Brazil in 6000 ft WD

Mooring Component	Studless Chain	D (in) =	**3.5**	**Polyester Rope Stiffness**		
K =	**316**			**Static**	**LF**	**WF**
M =	**3**			15	25	28
Reference BS (kips)	1383 (MBS for ORQ Grade)					

Fatigue Bin	Hs (ft)	Tp (sec)	Tz (sec)	Tn (sec)	Nwf	Nlf	Prob. Of Occur.	T Range WF SD	T Range LF SD	Annual Dam WF	Annual Dam. LF	Annual Dam. Total
1	2.58	5.11	3.94	418	506055	4768	0.0632	0.06	3.70	3.8088E-10	1.0865E-06	1.0869E-06
2	3.94	6.05	4.66	418	849537	9481	0.1256	0.27	7.96	7.2754E-08	2.1514E-05	2.1587E-05
3	4.36	6.31	4.86	418	979040	11377	0.1507	0.40	10.10	2.8192E-07	5.2740E-05	5.3022E-05
4	4.69	6.49	5.00	418	822757	9842	0.1304	0.53	11.60	5.3873E-07	6.9120E-05	6.9659E-05
5	5.15	6.74	5.19	418	661023	8214	0.1089	0.79	14.30	1.4775E-06	1.0807E-04	1.0955E-04
6	5.53	6.94	5.34	418	267395	3417	0.0453	0.98	16.00	1.1220E-06	6.2974E-05	6.4096E-05
7	6.37	7.34	5.65	418	705197	9541	0.1264	1.68	22.20	1.5044E-05	4.6965E-04	4.8469E-04
8	6.98	7.61	5.86	418	745636	10456	0.1386	2.36	27.10	4.4096E-05	9.3626E-04	9.8035E-04
9	7.87	7.99	6.15	418	242160	3561	0.0472	3.71	35.70	5.5637E-05	7.2904E-04	7.8467E-04
10	8.86	8.37	6.45	419	271694	4186	0.0556	5.80	46.70	2.3851E-04	1.9182E-03	2.1567E-03
11	10.82	9.07	6.99	419	34760	579	0.0077	11.30	72.30	2.2566E-04	9.8533E-04	1.2110E-03
12	14.10	10.09	7.77	421	1667	31	0.0004	24.20	131.00	1.0632E-04	3.1105E-04	4.1737E-04
							1.0000		**Total**	**6.8876E-04**	**5.6651E-03**	**6.3538E-03**
									Fatigue Life (year)			**1.5739E+02**

Note: Refer to Section 3, Equation 3.5 for the definitions of *K* and *M*.

TABLE 14
Comparison of Fatigue life Prediction

Case No.	Stiffness Model	Quasi-static K_{rs}	Dynamic K_{rd}	Chain Fatigue Life (year)
A1	3 Slope	15	25 (LF), 28 (WF)	157
A2	2 Slope	15	28	137
A3	Upper bound	28	28	116

5   HMPE Mooring Analysis Example

5.1   HMPE Creep Analysis Example

A creep analysis is performed for an HMPE mooring based on the following assumptions:

i)   The analysis is performed for the most loaded line assuming all the environments coming from one direction (For more accurate analysis, the procedure in 4/2.3.1 should be used).

ii)   The annual environment can be represented by 10 weather bins as shown in Appendix 2, Table 15

iii)   The creep rate at 20°C can, for example, be represented by the following equation, which is based on curve fitting to data presented in [18]:

$$R_c = 4 \times 10^{-11} \times T_m^{4.54}$$

where

R_c =   creep rate (1/day)

T_m =   mean tension (%MBS)

The analysis results are presented in Appendix 2, Table 15, which indicates:

- The annual creep strain is 0.44%

- The total creep strain for a design service life of 20 years is 8.8%

- Three low weather bins (2, 3, and 4) contribute to about 65% of the total creep strain

TABLE 15
Creep Analysis Results

Weather Bin	Hs	Probability	No. of Days	Mean Tens.	Mean Tens.	Creep Rate	Creep/year	Weight
	(ft)	(%)	per Year	(kip)	(%MBS)	(1/day)	(%)	(%)
1	3.6	16.96	61.904	153	13.78	6.0E-06	0.037	8.37
2	8.3	36.29	132.459	162	14.59	7.7E-06	0.102	23.21
3	13.01	26.07	95.156	175.7	15.83	1.1E-05	0.106	24.11
4	17.71	13.05	47.633	192	17.30	1.7E-05	0.080	18.05
5	22.42	5.31	19.382	215.5	19.41	2.8E-05	0.055	12.41
6	27.12	1.64	5.986	242.4	21.84	4.8E-05	0.029	6.54
7	31.83	0.52	1.898	278.2	25.06	9.0E-05	0.017	3.87
8	36.53	0.13	0.475	324.8	29.26	1.8E-04	0.009	1.96
9	41.24	0.02	0.073	376.9	33.95	3.6E-04	0.003	0.59
10	45.94	0.01	0.037	480.2	43.26	1.1E-03	0.004	0.89
Total		100	365				0.44	100.00

5.2   HMPE Creep Rupture Analysis Example

A creep rupture analysis is performed for an HMPE mooring based on the following assumptions:

i)   The analysis is performed for the most loaded line assuming all the environments coming from one direction (For more accurate analysis, the procedure in 4/2.4.1 should be used).

ii)   The annual environment can be represented by 10 weather bins as shown in Appendix 2, Table 16

iii)   The creep rupture time at 25°C can, for example, be represented by the following equation, which is based on curve fitting to data presented in [18]:

$$T_r = 2 \times 10^{12} \times T_m^{-6.25}$$

where

T_r =   creep rupture time (day)

T_m =   mean tension (%MBS)

The analysis results are presented in Appendix 2, Table 16, which indicates:

- The annual creep rupture damage is 0.0076

- The predicted creep rupture life is 1/0.0076 = 132 years

- Four low weather bins (2, 3, 4 and 5) contribute to about 68% of the creep rupture damage

TABLE 16
Creep Rupture Analysis Results

Weather Bin	Hs	Probability	No. of Days	Mean Tens.	Mean Tens.	Rupt. Time	Creep Dam.	Weight
	(ft)	(%)	per Year	(kip)	(%MBS)	(Days)	per year	(%)
1	3.6	16.96	61.904	153	13.78	151189.4	0.0004	5.41
2	8.3	36.29	132.459	162	14.59	105770.4	0.0013	16.55
3	13.01	26.07	95.156	175.7	15.83	63678.9	0.0015	19.75
4	17.71	13.05	47.633	192	17.30	36573.9	0.0013	17.21
5	22.42	5.31	19.382	215.5	19.41	17772.1	0.0011	14.41
6	27.12	1.64	5.986	242.4	21.84	8519.9	0.0007	9.28
7	31.83	0.52	1.898	278.2	25.06	3601.7	0.0005	6.96
8	36.53	0.13	0.475	324.8	29.26	1368.1	0.0003	4.58
9	41.24	0.02	0.073	376.9	33.95	539.8	0.0001	1.79
10	45.94	0.01	0.037	480.2	43.26	118.8	0.0003	4.06
Total		100	365				0.0076	100.00

5.3   Example of HMPE Quasi-Static Stiffness

An HMPE rope has a static stiffness of 45 MBS, and a creep rate of 0.0117% per hour at a load of 54% MBS at 20°C, the quasi-static stiffness as a function of storm duration is presented in Appendix 2, Figure 5. It can be seen that the quasi-static stiffness decreases rapidly with increasing storm duration at this load level and temperature.

FIGURE 5
Example Quasi-Static Stiffness for HMPE
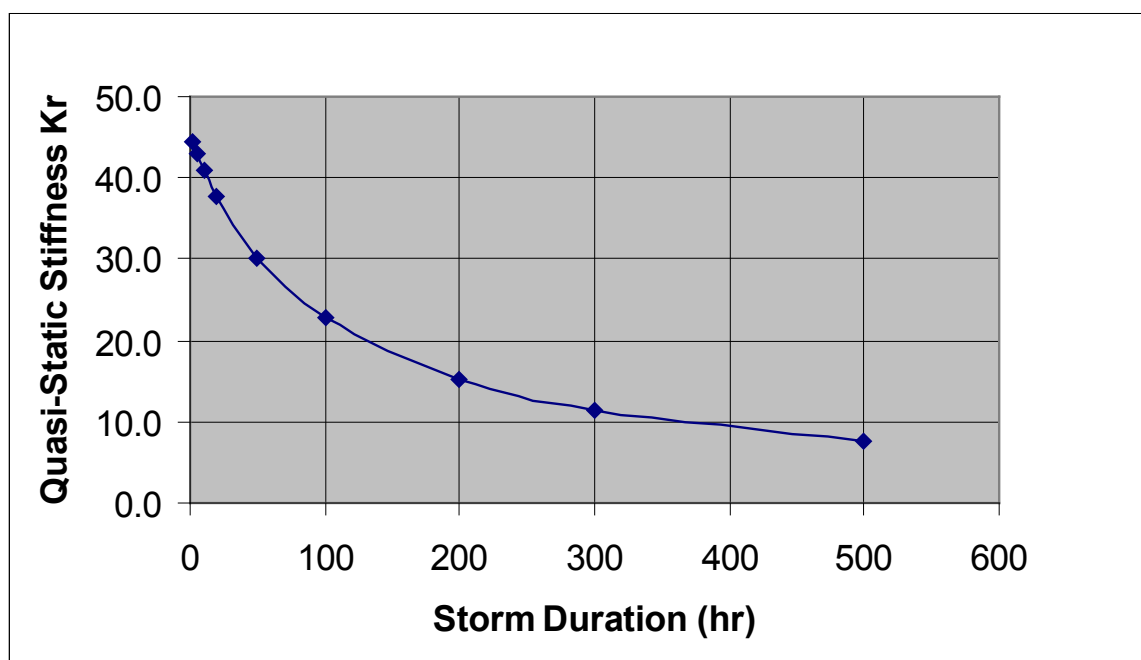
6   Guidance for Dynamic Stiffness Test Matrix

A dynamic stiffness test matrix for general application is provided in 8/5.4. If a project specific dynamic stiffness testing program is desired, the following guidance can be used.

i)   The test matrix should include variation in loading period, mean tension, and tension range.

ii)   The wave frequency period should be in the range of 12 to 35 seconds.

iii)   The low frequency period should be close to the natural period of the moored floating unit.

iv)   Several levels of mean tension and associated tension amplitude should be selected to represent a reasonable range of storm environments. The tension amplitude in the test is the maximum tension amplitude in the analysis, and tension range can be taken as tension amplitude times 2.

v)   If VIM (vortex induced motion) under high current may occur, the matrix should include cases representing VIM loadings. VIM may occur for Spar and deep draft semisubmersible hull forms and may have different amplitude to mean tension ratio from storm conditions. For example VIM loading for Spar typically has high mean tension and low tension amplitude.

vi)   The number of data should be sufficient for multiple regression analysis to obtain dynamic stiffness coefficients.

vii)   The maximum tension in the test should be less than 75% MBS.

viii) The ratio T_{amp}/T_{mean} should have significant variation to yield good results from regression analysis.

APPENDIX 3   Alternative Procedure to Determine MBS

1   General

For ropes of parallel construction with MBS greater than 2000 MT, a procedure for a combination of subrope and full rope tests can be considered, as illustrated in the following examples. This procedure should be used only when serious limitations such as unavailability of large test machine are encountered. ABS has not developed detailed test specification and specific acceptance criteria for this procedure, and only general guidance is provided in this Appendix. Should situation dictate that this procedure must be used, detailed testing specifications should be developed based on the principles provided here or other valid principles. Also documentation supporting the reliability of the testing and data analysis procedures should be submitted in a timely manner to allow review well in advance of their implementation.

2   Example 1 – Fixed Number of Subropes

The rope is made up of a fixed number of subropes, and the subrope size changes as the full rope size changes (Method A in 8/2.4).

Assumption:

A rope has an MBS of 2600 MT and the test machine can only test ropes to 2000 MT. The rope has N subropes.

Procedure:

1. Conduct subrope and full rope break tests for ropes of the same design. The minimum number of tests is shown in Appendix 3, Table 1. Let:

    L_f =   break load of full rope

    L_s =   average break load of the subropes (minimum 4 tests)

    N =   number of subropes in full rope

    Conversion factor $F = L_f/(NL_s)$ .... (A3.1)

TABLE 1
Alternative Method A to Determine MBS

Rope No.	MBS (MT)	No. of Full Rope Test	No. of Subrope Test	Conversion Factor F	Method for F
1	1,300	2	4	$F_1(2)$	Tested
2	1,700	3	4	$F_2(3)$	Tested
3	2,000	4	4	$F_3(4)$	Tested
4 (Target)	2,600	0	4	F_4	Estimated
Total		9	16		

Note that MBS for rope No. 1 and No. 3 should be greater than 50% and 75% of the target MBS, respectively. MBS for rope No. 2 should be close to the average MBS of rope No. 1 and No. 3.

2.   Conduct regression analysis for the conversion factors F_1, F_2 and F_3 (total 9) and determine F_4 based on evaluation of test data and the statistical values (mean, mean minus *SD*, mean minus 2*SD*) from the regression analysis for all rope samples.

3.   The estimated break load for the target rope is:

$$L_f = F_4 \times N \times L_s \dotfill \text{(A3.2)}$$

The MBS will be accepted if the estimated break load is greater than the MBS.

4.   This method applies only to ropes with same design parameters:

- Number of subropes
- Sub-rope construction
- Yarn type
- Number of layers in eye configuration
- D/d ratio for hardware
- Shape of hardware bearing surface
- Splice lengths (Number of strand tucks and tapered tucks)
- Chafe protection material and application in the eye

3   Example 2 – Fixed Size of Subrope

The rope is made up with subropes of the same size, and the number of subrope changes as the full rope size changes (Method B in 8/2.4).

Assumption:

A rope has an MBS of 2600 MT and the test machine can only test ropes to 2000 MT. The rope has 26 subropes ($N = 26$).

Procedure:

1.   Conduct subrope and full rope break tests for ropes of the same design. The minimum number of tests is shown in Appendix 3, Table 2 (refer to Equation A3.1).

TABLE 2
Alternative Method B to Determine MBS

Rope No.	MBS (MT)	N	No. of Full Rope Test	No. of Subrope Test	Conversion Factor F	Method for F
1		13	2		$F_1(2)$	Tested
2		17	3		$F_2(3)$	Tested
3		20	4		$F_3(4)$	Tested
4 (Target)	2,600	26	0	4	F_4	Estimated
Total			9	4		

Note that number of subropes for rope No. 1 and No. 3 should be greater than 50% and 75% of that for the target rope, respectively. Number of subropes for rope No. 2 should be close to the average number of subropes of rope No. 1 and No. 3.

2.   Conduct regression analysis for the conversion factors F_1, F_2 and F_3 (total 9) and determine F_4 based on evaluation of test data and the statistical values (mean, mean minus *SD*, mean minus 2*SD*) from the regression analysis for all rope samples.

3.   The estimated break load for the target rope is:

$$L_f = F_4 \times 26 \times L_s \quad\text{..}\quad (A3.3)$$

The MBS will be accepted if the estimated break load is greater than the MBS.

4.   This method applies only to ropes with same subrope and full rope design parameters as indicated below:

Subrope parameters

- MBS

- Subrope construction

- Yarn type

Full rope parameters

- *D/d* ratio for hardware

- Shape of hardware bearing surface

- Splice length (Number of strand tucks and tapered tucks)

- Chafe protection material and application in the eye