

Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring

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Foreword

API 2SM is under the jurisdiction of the API Subcommittee on Offshore Structures. The main purpose of this document is to provide guidelines on the use of synthetic fiber ropes for offshore mooring applications. The secondary purpose of this document is to highlight differences between synthetic rope and traditional steel mooring systems, and to provide practical guidance on how to handle these differences during system design and installation.

The contents of this document should be used in conjunction with the most recent editions of API 2SK and API 2I, and other recommended practices and standards, as appropriate. Where the mooring design, construction and installation details are similar or equivalent to steel mooring systems, no further comments are included in this document.

This document reflects the latest learning from research, design, installation, and operation of synthetic fiber mooring components. The technology in synthetic fiber rope moorings continues to evolve. Designers are advised to take appropriate measures to ensure that their practices incorporate all research advances available to them.

The verbal forms used to express the provisions in this specification are as follows:

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Suggested revisions are invited and should be submitted to the Standards Department, API, 200 Massachusetts Avenue, NW, Suite 1100, Washington, DC 20001, standards@api.org.

Contents

	Page
1 Scope	1
2 Normative References	1
3 Terms, Definitions, Symbols, and Abbreviations	2
3.1 Terms and Definitions	2
3.2 Symbols and Abbreviations	8
4 Basic Considerations	9
4.1 General	9
4.2 Synthetic Fiber Ropes for Offshore Mooring	9
4.3 Main Characteristics of Synthetic Fiber Ropes	10
5 Rope Design and Properties	11
5.1 General	11
5.2 Rope Material	11
5.3 Rope Construction	13
5.4 Rope Filter Barrier and Jacket	13
5.5 Rope Termination	14
5.6 Rope Properties	15
6 Mooring Design and Analysis	21
6.1 General	21
6.2 Mooring Configuration and Design	21
6.3 Design Criteria	22
6.4 Mooring Analysis	23
6.5 Model Testing	31
7 Rope Specification and Testing	31
7.1 General	31
7.2 Rope Specification and Documentation	31
7.3 Rope Testing	37
8 Rope Manufacture, Inspection, and Quality Assurance	40
8.1 General	40
8.2 Rope Fiber Material	40
8.3 Rope Manufacturing	42
8.4 Termination	42
8.5 Assembly	42
8.6 Inspection	43
8.7 Quality Control and Assurance	44
9 Rope Storage, Handling and Installation	45
9.1 General	45
9.2 Storage, Handling, and Installation Specifications	45
9.3 Storage, Handling, and Installation Considerations	46
9.4 Installation Design Considerations	49
9.5 Installation/Recovery Procedures	54
10 In-service Inspection and Maintenance	56
10.1 General	56
10.2 Destructive Inspection of Inserts	56
10.3 Operations	56

Contents

Page

Annex A (normative) Filter Barrier Particle Ingress Test	57
Annex B (normative) Testing of Rope Load-elongation Properties	59
Annex C (normative) Torque and Rotation Tests	86
Annex D (normative) Testing of Rope Tension-tension Fatigue Qualification	88
Annex E (normative) Testing of Rope Strength	90
Annex F (normative) Testing of Rope Axial Compression Performance	92
Annex G (informative) Polyester Mooring Analysis Example	94

Figures

1 Polyester Durability JIP, OTC 5720 and Fiber Tethers 2000 Fatigue Test Data, Compared with Wire Rope and Chain TN Curves from API 2SK	19
2 Polyester Rope Load-Elongation: Load-vs.-Extensometer	24
3 Idealized Polyester Behavior	26
4 Diagram of Eye Splice Showing Features	35
5 Typical Reel and Lifting Arrangement	47
6 Surface Buoys Tensioned Together to Maintain Fiber Rope in Tension	53
A.1 Grading of Sand for Particle Ingress Resistance Test	58
B.1 Idealized Synthetic Rope Elongation Behavior	61
B.2 Quasi-static Stiffness	73
B.3 Strain Component for DES/DER/Creep Test	85
G.1 Mooring Pattern for Identical Eight Line Equally Spaced Mooring System	95
G.2 Linear and Nonlinear Polyester Load-elongation Models	96
G.3 Maximum Vessel Offset, Nonlinear and Linear Load-elongation Curves	99
G.4 Maximum Tensions, Nonlinear and Linear Load-elongation Curves	100
G.5 Polyester Rope Delayed and Recoverable Elastic Stretch	101
G.6 Maximum Vessel Offsets for Three Nonlinear Moorings—Cases 1, 2-a, and 2-b	104
G.7 Maximum Tensions for Three Nonlinear Moorings—Cases 1, 2-a, and 2-b	104

Tables

1 Fiber Properties	11
2 Typical Rope Weights and Sizes for 10,000 kN Break Strength (including Jacket)	16
3 Typical Stiffness Values in EA/CBS	17
4 Fiber Rope Fatigue Curve Qualification Test Cycles	39
5 Resistance to Chemical and UV Radiation Damage	47
G.1 Mooring Line Properties, Eight Identical Lines	95
G.2 Anchor Distances and Grounded Lengths for Pretensions of 250 kips	96
G.3 Hurricane Metocean Conditions and Mean Loads for Return Periods between 5 and 40 Years	97
G.4 Maximum Vessel Offsets and Tensions—Nonlinear Load-Elongation Curves	98
G.5 Vessel Offsets for Four Linear Load-Elongation Curves	99
G.6 Un-stretched Total Polyester Rope Lengths, Outboard Wire Rope Lengths, and Pretensions for Three Moorings	102
G.7 Quiescent Equilibrium Vessel Offsets for Three Moorings	103
G.8 Maximum Vessel Offsets and Tensions for Three Moorings	103

Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring

1 Scope

1.1 This document applies to synthetic fiber ropes used in the form of taut leg or catenary moorings for both permanent and temporary offshore installations such as:

- a) monohull-based floating production, storage, and offloading units (FPSOs);
- b) monohull-based floating storage units (FSOs, FSUs);
- c) monohull or semi-submersible based floating production units (FPU, FPSs);
- d) mobile offshore drilling units (MODUs);
- e) spar platforms;
- f) catenary anchor leg mooring (CALM) buoys (spread mooring only);
- g) mobile offshore units (MOUs, e.g., construction, pipelay, floating accommodation vessels).

1.2 This document covers the following aspects of synthetic fiber ropes:

- a) design and analysis considerations of mooring system;
- b) design criteria for mooring components;
- c) rope design;
- d) rope specification and testing;
- e) rope manufacture and quality assurance;
- f) rope handling and installation;
- g) in-service inspection and maintenance.

1.3 Application of this document to other offshore mooring applications is at the discretion of the designer and operator. This document is not intended to cover other marine applications of synthetic fiber ropes such as tanker mooring at piers and harbors, towing hawsers, mooring hawsers at single-point moorings (SPMs), and tension leg platform (TLP) tethers. Additionally, very little test data are available for large synthetic fiber ropes permanently deployed around fairleads and thus this document is limited to fiber ropes which span freely between end terminations.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document applies (including any addenda/errata).

API RP 2I, *In-Service Inspection of Mooring Hardware for Floating Drilling Units*

API RP 2SK, *Design and Analysis of Stationkeeping Systems for Floating Structures*

CI 1503¹, *Test Method, Yarn-on-Yarn Abrasion, Wet and Dry*

ISO 18692², *Fibre ropes for offshore stationkeeping – Polyester*

3 Terms, Definitions, Symbols, and Abbreviations

For purposes of this recommended practice, the following terms, definitions, symbols, and abbreviations apply.

3.1 Terms and Definitions

3.1.1

as-installed length

After installation, the total length of the synthetic mooring line (at zero load) is the as-purchased length plus the installation stretch.

3.1.2

as-purchased length

The length of the rope (at specified minimal load) when it leaves the factory.

3.1.3

basic yarn

The smallest yarn-like component of the rope, generally as received from the yarn producer; however, the producer may carry out some of the intermediate yarn assembly steps.

3.1.4

bend restrictor

A device placed on the rope adjacent to a termination to prevent abrupt bending at the termination.

3.1.5

catalog break strength

CBS

The manufacturer's design or target break strength for the rope assembly, including terminations.

3.1.6

catenary mooring

Chain or steel wire at the seabed to provide a catenary that provides both compliance and weight to prevent or reduce vertical loading at the anchor.

3.1.7

certified verification agent

CVA

An independent third-party who verifies that applicable technical specifications and drawings are adhered to during the rope design, manufacturing process, and deployment.

NOTE The CVA acts on behalf of, and is certified by, the owner and/or pertinent regulatory agency.

3.1.8

construction stretch

The permanent elongation caused by the maximum historical load that the rope has experienced during the lifetime of the rope, primarily due to bedding-in of the rope and fibers.

¹ Cordage Institute, 994 Old Eagle School Road, Suite 1019, Wayne, PA 19087, www.ropecorde.com.

² International Organization for Standardization, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, www.iso.org.

3.1.9**creep**

The permanent increase in length under sustained tension or cyclic loading.

3.1.10**creep failure****creep rupture**

Rope failure due to cumulative, irrecoverable elongation of a fiber rope under load over time.

3.1.11**creep-log time plot**

A graph of creep (ordinate) against the log of time under tension (abscissa).

3.1.12**delayed elastic recovery**

Rope reduction in length as a function of time after the rope is unloaded from a previously higher load, excluding elastic stretch and permanent elongation.

3.1.13**delayed elastic stretch**

Rope increase in length as a function of time after the rope is loaded from a previously lower load, excluding elastic stretch and permanent elongation.

3.1.14**fiber producer****yarn producer**

The entity which produces the fiber and/or yarn and applies special processes to that yarn before it is received by the rope manufacturer.

3.1.15**fiber finish**

A designation of the process and finish used on a fiber for a particular purpose.

EXAMPLE Marine finish.

3.1.16**fiber grade**

A designation of the quality of a particular fiber, indicating the adherence of tolerances on properties.

3.1.17**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 oils.

3.1.18**installation stretch**

The permanent increase in length introduced after application of the installation loads. Installation stretch is the construction stretch due to the installation tension.

3.1.19**insert**

A short length of rope which can be installed in the mooring line for the purpose of extraction for testing and/or monitoring.

3.1.20**jacket**

A braided or plastic covering which is placed over the rope (or over individual strands) for protection and to hold the rope structure together.

3.1.21**lay length**

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

3.1.22**manufacturing specification**

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

3.1.23**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.

3.1.24**material certificate**

A document prepared by the manufacturer and the fiber producer certifying the type and grade of fiber material, the properties of the yarn, and that the material used in rope production is that which is specified in the rope design specification.

3.1.25**material chemical composition**

The generic designation of a specific chemical composition and process of material used in the fiber.

EXAMPLE Nylon, polyester, aramid, or high modulus polyethylene.

3.1.26**minimum bending radius****MBR**

Minimum radius to which the synthetic fiber rope construction can be bent to without damage to any part of the rope construction (including the jacket and filter).

3.1.27**minimum break strength****MBS**

The minimum single value from a series of five prototype rope assembly break tests, including terminations.

3.1.28**potted socket**

A termination generally consisting of a tapered socket into which the rope is inserted with separated strands and broomed out yarns and then secured by pouring of a liquid, setting resin or similar compound.

3.1.29**production rope**

The rope produced for the offshore mooring system order.

NOTE Also, a rope sample removed from production or selected after production for the purpose of testing.

3.1.30**prototype rope**

A rope 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.

3.1.31**quality assurance manual**

A document which completely describes the manufacturer's quality control and assurance program.

3.1.32**quality assurance supervisor**

An employee of the manufacturer who is responsible for ensuring the manufacturer adheres to quality assurance procedures.

3.1.33**quality control checklist**

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.

3.1.34**quality control report**

A document prepared at the completion of a designated step of the rope making and assembly process, which includes the completed quality control checklists, material certificates, and inspection reports.

3.1.35**recognized classification society****RCS**

A classification society being a member of the International Association of Classification Societies (IACS), with recognized and relevant competence and experience from the synthetic fiber rope activities, and established rules/guidelines for design, manufacturing and testing of synthetic fiber ropes for use in the classification/certification activities.

3.1.36**reference break strength****RBS**

The reference break strength for sample under test.

NOTE 1 For a full rope assembly, RBS is the catalog break strength of the rope.

NOTE 2 For a subrope, RBS is the break strength of the subrope estimated by the manufacturer.

NOTE 3 For a scaled rope, RBS is the break strength of the scaled rope assembly estimated by the manufacturer.

3.1.37**rope assembly**

The rope, its terminations, and any other accessory gear, as described in the purchaser's specification or order.

3.1.38**rope assembly length**

The distance between the assembly interface points (as defined in the specification or purchase order) as measured at a defined tension and by a method agreed to by the purchaser and the manufacturer.

3.1.39**rope assembly interface**

The physical connection which is part of the end of the rope assembly and is used to interconnect rope assemblies or to connect a rope assembly to another tension member (e.g. a wire rope or chain) or to hardware (e.g. an anchor, a buoy, or a platform).

3.1.40**rope construction**

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

3.1.41**rope design specification**

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

3.1.42**rope production report**

A document which completely describes the rope product, including rope design, termination design, and assembly length, and which includes the material certificates, material test results, and the various checklists.

3.1.43**rope stiffness**

rope modulus

The ratio of rope stress to strain/the ratio of rope tension to elongation.

NOTE Stiffness is often preferred as it is difficult to determine the area for a synthetic rope. Often the terms dynamic modulus/stiffness and static modulus/stiffness are used. Dynamic refers to modulus/stiffness values obtained when the rope is loaded quickly (seconds to minutes) where static refers to modulus/stiffness values obtained when the rope is loaded slowly (hours to days).

3.1.44**rope strength factor**

The ratio of rope break strength to aggregate yarn strength.

3.1.45**rope termination**

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

3.1.46**rope yarn**

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

3.1.47**splice**

A termination is normally formed by looping the rope around a spool or similar attachment means, separating the rope into strands or groups of strands, and then tucking these strands back into the rope structure.

3.1.48**strain**

The ratio of elongation to the gauge length over which the elongation takes place.

3.1.49**strand**

The largest component of the rope, which is twisted, braided, or otherwise assembled together to form the finished rope, and which is formed by twisting or otherwise assembling rope yarns together, generally with an opposite twist direction to that of the yarns.

3.1.50**strand assembly checklist**

A document completed during the strand assembly process which states the nominal values and records the actual values for each set-up of each step of the process of assembling strands.

3.1.51**subrope-to-rope efficiency**

The percentage of the full rope strength compared to the aggregate subrope strength of the assembly.

3.1.52**taut leg mooring**

A system that relies principally for its compliance on the axial extensibility of the mooring line rather than the catenary profile. Such moorings provide a significant upward load on the seabed connection.

3.1.53**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.

3.1.54**torque**

The product of applied force and moment arm required to prevent rotation of a rope when tension is applied.

3.1.55**wedged socket**

A termination generally consisting of a tapered socket into which the rope is inserted with separated strands and broomed out yarns and then secured by a tapered wedge-like device set and driven into the center of the yarns.

3.1.56**yarn**

A generic term for a bundle of untwisted or twisted fibers.

3.1.57**yarn assembly checklist**

A document completed during the yarn assembly process which states the nominal values and records the actual values for each set-up of each step of the process of the yarn.

3.1.58**yarn break strength**

The average breaking load from several yarn break tests.

3.1.59**yarn creep**

The characteristics of the yarn that undergo a time related non-recoverable increase in length when subjected to sustained load.

3.1.60**yarn elongation**

The average elongation at break from several yarn break tests.

3.1.61**yarn-on-yarn abrasion property**

The average cycles to failure at a designated applied load which the yarn exhibits when tested by the yarn-on-yarn abrasion test method.

3.2 Symbols and Abbreviations

A	rope fiber cross sectional area
C	constant
CALM	catenary anchor leg mooring
CBS	catalogue break strength
c_i	creep rate per year within the tension interval i , unit of time
C_i	creep failure life (resistance) for the tension interval i , as determined by rope creep test, unit of time
CI	Cordage Institute
CVA	Certified Verification Agent
D/d	bearing diameter of the hardware D over Rope diameter d
E	Young's modulus (of elasticity)
EA	static rope stiffness of the synthetic rope
EIPS	extra improved plow steel
E_t	annual cumulative creep damage ratio
F	load period coefficient
FPS	floating production and storage unit
FPSO	floating production, storage, and offloading unit
FPU	floating production unit
FSO	floating storage unit
HMPE	high modulus polyethylene
i	unit of time
IACS	International Association of Classification Societies
ISO	International Organization for Standardization
IWRC	independent wire rope core
JIP	joint industry project
JONSWAP	Joint North Sea Wave Project
L_0	new rope length
L_a	load amplitude
L_c	creep rupture life
LCP	liquid crystal polymer
$L_{\max}$	breaking strength
L_{μ}	mean load
M	mean load coefficient
MBR	minimum bend radius
MBS	minimum break strength

MODU	mobile offshore drilling unit
MOU	mobile offshore unit
OCIMF	Oil Companies International Marine Forum
PEN	polyethylene naphthalate
QA	quality assurance
RBS	reference break strength
RCS	recognized classification society
ROV	remotely operated vehicle
SM	specific modulus
SPM	single point mooring
T	loading period ³
T	rope tension
tex	linear mass density of fibers defined as the mass in grams per 1000 meters
TLP	tension leg platform
TN	tension — number of cycles to failure
UV	ultraviolet
VIM	vortex-induced motion
WD	water depth
WRC	wire rope construction
ϵ	permanent strain in the rope

4 Basic Considerations

4.1 General

This section provides a brief overview of mooring systems incorporating synthetic fiber ropes. Requirements as specified in API 2SK and API 2I are applicable unless otherwise modified herein. Key design considerations in using synthetic fiber materials are discussed.

Since synthetic fiber rope properties influence the mooring system performance, mooring design and analysis; rope design, testing, and manufacturing; rope handling and installation; and rope inspection and maintenance should be integrated to provide a consistent mooring system design methodology.

The fiber materials covered in this document include polyester, aramid, high modulus polyethylene (HMPE), and nylon; and the rope structures include “wire rope-construction” and “parallel-subrope” types. Other fiber materials and rope structures may be used, but the recommendations given shall be re-evaluated with considerations of the properties and performance of these materials and constructions. Furthermore, the document has been primarily developed based on the test data and knowledge on polyester ropes. Designers should consult rope manufacturers when other types of ropes are considered.

³ See Annex B for further definition

4.2 Synthetic Fiber Ropes for Offshore Mooring

With increasing exploration and production in deeper waters, it can be advantageous to utilize synthetic ropes that have higher strength to weight ratios than traditional steel wires and chains; however, unlike steel, synthetic fiber ropes exhibit axial load-elongation characteristics that are non-linear and vary with time and loading history.

Advantages of using synthetic fiber moorings include a reduction in vessel offset and associated riser costs, reduction in vertical loads and associated structural costs, reduction in the extreme line dynamic tension due to lower axial stiffness, and a possible reduction in handling and installation costs. One difficulty associated with the use of large diameter fiber ropes is the availability of facilities suitable for testing large diameter ropes.

Fiber ropes can be used as segments in steel catenary systems, or in taut leg mooring systems. These applications are discussed further in 6.2. The differences between synthetic mooring systems and steel mooring systems include the non-linear load-elongation properties, permanent elongation, recoverable stretch, creep phenomenon, minimum tension requirements for some fibers, location of fiber rope segment between the sea surface and seafloor, and different handling procedures.

4.3 Main Characteristics of Synthetic Fiber Ropes

4.3.1 Fiber Materials

The fibers currently being considered for use in permanent or temporary moorings are polyester (polyethylene terephthalate), aramid (aromatic polyamide), HMPE (high modulus polyethylene), and nylon (polyamide). This document does not preclude the use of other synthetic fibers in the design of mooring systems, provided that good engineering practice is followed.

Currently, polyester is the most commonly used synthetic fiber for offshore mooring applications due to its relatively low axial stiffness, good fatigue properties, good strength to weight ratio, and good creep resistance. Other fibers such as HMPes and aramids can be more suitable for applications where a smaller rope diameter or other properties are desired.

4.3.2 Rope Construction

There are many different rope construction types. Based on test data currently available, three types of rope construction are considered in this document: wire rope construction (WRC), braided, and parallel strand.

4.3.3 Rope Elongation and Stiffness

Fiber ropes are constructed from fiber materials that display visco-elastic properties. The rope exhibits a non-linear load-elongation behavior that is dependent on mean load, load range, temperature, rate of loading, and load history. As the rope is loaded beyond its previous maximum load, it undergoes a permanent increase in length, which results in larger mean offsets, if the mooring line length is not adjusted in the field.

The mooring installation tension is typically much lower than the maximum design tension. When the mooring line is loaded beyond its installation tension, there are two effects that change the performance of the fiber rope mooring system. First, the synthetic rope permanently lengthens due to additional bedding-in and fiber elongation. Second, the stiffness of the rope increases. The overall effect of the increase in line length combined with an increase in rope stiffness can result in an increase in vessel mean offsets and higher stiffness at the mean position.

Vessel offsets are a primary concern for risers. Proper evaluation of offsets requires detailed information on the permanent elongation (bedding-in) and load-elongation properties of the synthetic rope over a

range of tensions. Furthermore, the permanent elongation and load-elongation properties used for mooring performance evaluation need to be representative of the planned mooring operation, including installation tension, pretension and mooring line length management.

Additional consideration should be given to other potential influences on global mooring system performance. These influences include: base fiber properties, marine finish, manufacturing process, rope construction, rope usage, and history.

Permanent elongation, whether due to creep or construction stretch or other mechanisms, can lead to the need to adjust the length of the mooring lines in the field.

4.3.4 Durability and Fatigue

Factors which limit the life of synthetic fiber ropes for moorings and should be evaluated during design include hydrolysis, heating and internal abrasion, and tension-tension fatigue; axial compression fatigue can be a problem for aramid ropes.

4.3.5 External Abrasion and Cut Resistance

Jacketing is often used on fiber ropes to guard against damage from external abrasion that can occur while in service and during installation and recovery. Certain rope constructions, such as parallel strand, need a jacket to hold the subropes together. If a jacket is used, the interaction between the jacket and the rope core should be considered when evaluating rope properties, service life and installation/recovery procedures. Braided ropes that are constructed from fibers with high wear resistance may be used without jacketing if it is demonstrated that the wear resistance is adequate for the intended application.

5 Rope Design and Properties

5.1 General

This section provides an overview of typical rope materials, rope constructions, rope termination types, and indications of their effect on final rope assembly properties. The principal components of synthetic fiber ropes are yarns supplied by fiber manufacturers, which are used in the main load bearing core of the rope. The fibers in the rope core may also contain marine finishes, which serve as lubricants.

5.2 Rope Material

5.2.1 Fiber Types and Properties

The choice of a particular fiber material depends on the nature of the application, experience with the material, durability, density, elasticity, abrasion resistance, strength, and cost. The industry has experience with polyester, aramid, HMPE, and nylon. Properties of these fibers are listed in Table 1. Other fibers, such as LCP and PEN, are also being considered.

Table 1—Fiber Properties

Property	Fiber			
	Polyester	Aramid	HMPE	Nylon
Strength to weight ratio	medium	high	high	low
Stiffness	medium	high	high	low
Tension-tension fatigue damage resistance	high	high	high	low ^a
Axial compression fatigue damage resistance	high	low ^a	high	high
Abrasion resistance	high	medium	high	low
Creep resistance	high	high	low	medium
^a The effects of this property depend on construction and application.				

5.2.2 Basic Yarn Quality

Quality control procedures stated in Section 8 of this document should be used to ensure that the basic yarn quality is maintained.

5.2.3 Marine Finish

Typically, synthetic fiber manufacturers apply a non-water-soluble marine finish coating to fibers in marine ropes to enhance performance. Purposes of the marine finish include:

- providing lubrication to assist bedding-in of the rope during initial tensioning; and
- increasing the rope's service life by reducing yarn-on-yarn abrasion.

The characteristics, use, and specification of marine finishes for moorings are complicated by a number of factors as follows.

- While the effectiveness and durability of marine finishes for short-term use is established, the long-term (greater than several years) durability has not been confirmed by test data.
- Marine finish technology is considered highly proprietary and has historically been subject to refinement without notification to the end-user.
- For permanent moorings (e.g. floating production systems), the marine finish is thought to minimize fiber-to fiber abrasion during the one-time initial bedding-in period, but its importance in increasing the long-term service life has not been proven.
- For temporary moorings (e.g. MODUs) the long-term effectiveness of the marine finish is considered to be more important due to frequent recoveries and redeployments.

Marine finish may not be required for all fibers, depending on the application. However, sufficient testing, in accordance with industry standards, for fatigue of the rope and the spliced terminations should be performed for the rope type, to ensure that yarn-on-yarn abrasion does not adversely affect the rope's integrity.

HMPE fiber possesses good inherent yarn-on-yarn abrasion properties in both wet and dry conditions. In addition, the tension-tension fatigue performance for HMPE fiber ropes without marine finish also confirms that marine finish is not necessary for this fiber (see CI 1503).

5.2.4 Quality of Marine Finish

The following shall apply due to the potential importance of marine finishes on mooring ropes.

- a) Fiber, yarn, and rope test data used for design of mooring ropes shall explicitly denote whether the yarn used in making the specimens has a marine finish, and shall state the yarn producer's descriptive designation of the marine finish.
- b) As part of the rope fatigue testing, post-test analysis of the fibers shall be performed to determine if the finish remains effective during wet cyclic fatigue for the duration of the testing.
- c) As part of mooring rope procurement quality control, fiber finish quality shall be determined by yarn-on-yarn abrasion testing to confirm that the finish used in the production ropes has comparable performance to the finish used in the prototype rope.

The yarn producer or rope manufacturer should conduct a test to demonstrate that the yarn marine finish remains effective after exposure to sea water.

5.3 Rope Construction

Most fiber ropes are comprised of a core to withstand tensile loads and an outer jacket, which has little tensile load bearing capability. Additional protective coatings or wrappings may be applied during or after rope manufacture.

Typical rope construction types suitable for fiber ropes are wire rope constructions, braided and parallel strand types. The main structural levels in a fiber rope, although not all are present in every construction, are:

- textile yarns, as made by the fiber producer and typically consist of hundreds of individual filaments;
- rope yarns, assembled from a number of textile yarns;
- strands made up from many rope yarns;
- sub-ropes of several strands;
- sub-rope filter barriers;
- sub-rope jackets;
- rope core assembly;
- filter barrier;
- rope jacket.

In general, the closer that the bearing yarns are aligned with the rope axis, the higher the rope break strength to weight ratio and stiffness to weight ratio. However, a small amount of twist is desirable to give structure to the yarns and strands and to enhance load sharing among the components which make up the rope.

Section 7 provides general guidelines for specification and testing of ropes.

5.4 Rope Filter Barrier and Jacket

5.4.1 Jacket Design

An important function of the jacket is to protect the rope from external abrasion, which can occur during transportation, installation or operation phases. Design of the protective jacket depends on the application and installation method. In general, risk of damage to the load bearing cores due to external abrasion, friction and wear can be reduced by the appropriate selection of a jacket design. Typical jackets can be braided, extruded, tape-wound, or otherwise applied.

Rope jackets shall be tightly fixed to the termination area to prevent slippage of the jacket away from the termination and resultant exposure of rope core.

A clearly visible marking on the jacket or visible portion of the rope should be provided to allow monitoring of twisting of the rope.

5.4.2 Particle Ingress (Internal Abrasion)

Strength loss in fiber ropes has been attributed to internal abrasion due to water-borne particles such as sand or grit. Fiber rope mooring lines shall not be used in areas of high turbidity unless protected by suitable jackets or filter barriers that minimize particle penetration while allowing water ingress.

To qualify as particle ingress resistant, the jacket or filter barrier shall be tested in accordance with Annex A or ISO 18692. The test condition of the rope should reflect the condition of the rope when exposed to particles.

5.4.3 Free Flooding

The rope jacket and filter should be designed such that water is allowed to completely fill the rope structure. Water serves to transmit heat and alleviate heat buildup during cyclic loading. Air pockets can prevent heat dissipation during cyclic loading. If the rope is designed with a jacket and filter that do not flood, the implications for jacket and filter integrity, submerged weight and cooling of the fibers should be considered.

5.4.4 Jacket Bending Stiffness

The jacket shall be sufficiently flexible to permit the fiber rope assembly to be safely deployed over rollers or sheaves under the design deployment loads. The limiting bend radius based on jacket or rope bending stiffness shall be established for short periods under loads occurring during installation and for prolonged periods of storage or transportation.

5.5 Rope Termination

5.5.1 End Termination and Construction Types

Three main types of end terminations are used for synthetic fiber ropes as follows:

- a) spliced eye;
- b) resin socket, or resin potted socket, or conventional socket;
- c) barrel-and-spike, or socket and cone, or wedged socket.

Presently, only the spliced eye has demonstrated strength, fatigue performance, and resistance to hysteresis heating for large rope sizes. The other terminations are used on small ropes and test ropes, but have not been used on large fiber ropes.

Splicing procedures for a particular rope design shall be developed by the rope manufacturer, taking into account the rope construction, material, and termination connecting hardware geometry. Consideration shall also be given to the continuity of soil ingress protection (e.g. jackets or filter barriers) around the spliced eye.

5.5.2 Termination Design Consideration

Termination design should involve careful consideration of the termination weight, bending limitations and heat build-up.

Termination connecting hardware can be of steel construction, and therefore considerations should be given to the added weight, bending moments, and abrasion at these in-line joints, particularly during installation. Terminations and fittings using materials other than steel may be used if their performance has been proven to be satisfactory.

Limitation on the minimum bending radius near terminations shall be established for both storage and installation conditions. The spliced eye termination has the advantage over its socket counterparts in that the splice itself usually provides a gradual change in rope flexural stiffness, which can reduce stress from rope bending at the terminations.

5.5.3 Protection for Spliced Eyes

For spliced eye terminations, a means shall be provided to minimize friction and maximize wear resistance between the spliced eye and the termination connecting hardware. Fiber cloth, elastomeric materials, low friction coatings, etc. may be used for this purpose.

5.5.4 Spliced Eye Hardware

Spliced eyes require hardware in the form of a pin, bushing, or thimble fitted into the eye to make a connection between a fiber rope and other components in the mooring system. The width and the shape of the termination hardware shall accommodate the rope size and structure so as not to compress the rope, and in the case of multiple layers of subrope, not allow nesting of outer layers into inner layers.

The selection of D/d ratio, (bearing diameter of the hardware D over rope diameter d) is critical to provide adequate strength and fatigue performance of the rope's spliced eye. The hardware utilized shall provide a D/d ratio in accordance with the manufacturer's recommended value for the particular rope design, and the design of the termination hardware shall provide sufficient strength and fatigue life to meet the mooring system requirements.

5.5.5 Subrope Splicing

Subrope splicing is defined here as the replacement of one subrope for another by any means, such as overlapping, tucking, intertwining, or interbraiding. Subrope splicing should only be done to repair damage during assembly of the rope. If subrope splices are allowed in the rope, then such subrope splices shall be included in the prototype or production ropes prepared for break and cyclic tests in accordance with Section 7. The subrope-to-subrope splice connection shall be subjected to splice integrity testing.

The end user shall approve the manufacturer's specifications covering preparation of subropes for splicing, the process of splicing, the process of finishing the splice, and all critical dimensions for the particular rope design. The minimum spacing of such subrope splices along the axial length of the finished rope and the maximum number of such splices shall be specified. The locations of subrope splices shall be marked on the cover of the finished rope with a contrasting color strand or similar permanent marking.

5.6 Rope Properties

5.6.1 Introduction

The key technical characteristics for synthetic fiber ropes including terminations are described in this section.

5.6.2 Sizes and Break Strength

In this document, the catalog breaking strength (CBS) is defined as the manufacturer's design or target break strength for the rope assembly, including terminations. The minimum break strength (MBS) is defined as the minimum single value from a series of five prototype rope assembly, including terminations, break tests. The MBS shall not be less than the CBS.

For rope tests performed on subropes or scaled ropes (e.g., load elongation, fatigue, creep, etc. tests) the reference break strength (RBS) is used to normalize the subrope or scaled rope test results. See Annex B for additional information on RBS.

Testing on the full rope assembly shall be conducted with terminations of the same type as used on the production ropes. Testing details for break strength definition are described in Section 7.

Typical values of weight in water and rope diameter (with jacket) for fiber rope assemblies of 10,000 kN CBS are set out in Table 2. For preliminary design, rope break strength may be scaled with weight in air or diameter squared. For final design, data from the rope manufacturer shall be used.

For polyester ropes, the minimum rope core tenacity (breaking strength divided by mass per unit length) of 0.47 N/tex (Newtons per g/km) should be in accordance with ISO 18692 since this has shown to result in ropes of high tensile efficiency in terms of overall fiber-to-rope efficiency, subrope-to-rope efficiency and adequate tension-tension endurance.

NOTE When requesting information from manufacturers, the mooring designer should request information based on the rope break strength, not the rope diameter, as diameter versus break strength varies with rope construction, jacketing, manufacturer, etc.

Table 2—Typical Rope Weights and Sizes for 10,000 kN Break Strength (including Jacket)

Rope Type	Total Weight in Air kgf/m	Total Weight in Sea Water kgf/m	Typical Overall Diameter mm
Synthetic			
Polyester	22.2	5.6	176 to 189
Aramid	13.8	3.8	149
HMPE	11.0	Buoyant	132
Steel			
6-Strand IWRC, EIPS	74.4	62.5	134
Jacketed spiral strand	52.2	44.0	101

5.6.3 Creep and Creep Rupture

Some polymer-based fiber ropes are subject to creep, potentially leading to creep rupture. The creep behavior of different rope fibers differ in many significant ways. For example, the rate of creep for polyester fiber decreases logarithmically over time, while the rate of creep for HMPE fiber over time is linear until shortly before failure, at which point it accelerates.

Although HMPE fibers exhibit higher creep, the rate and extent of the creep is predictable. The rate of creep depends on the particular HMPE yarn, temperature, mean load versus rope break strength, and load duration. HMPE ropes are subject to failure due to creep rupture. Therefore, the risk of creep rupture should be evaluated in consultation with the yarn supplier and rope manufacturer, taking into account the expected loading history, rope construction, and other conditions.

Polyester and aramid 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.

5.6.4 Rope Load-Elongation Characteristics

Compared to steel wire rope, the change-in-length properties of fiber rope mooring lines are more complex. These properties are not the same for all fiber ropes, even for the same material, but vary with the material grade and the rope construction. Stiffness is non-linear and dependent on mean load, load amplitude, and frequency. Permanent construction stretch due to maximum historical load affects installation, operation of the system, and long term mooring line length management.

The rope load-elongation properties of interest, not all of which are exhibited by a particular rope type, include:

- permanent non-recoverable elongation (construction stretch) due mainly to maximum historical load;
- recoverable elongation due to sustained or low frequency loads (recovered when loading ceases);
- permanent creep elongation due to sustained or low frequency loads (not recovered when loading ceases);
- load-elongation behavior under near-static loading;
- load-elongation behavior under low frequency dynamic loads; and
- load-elongation behavior under wave frequency dynamic loads.

The design and installation engineers should work with the rope manufacturer to determine the amount of elongation due to permanent non-recoverable elongation and creep to be expected during installation and design life of the project based on expected loads. Permanent non-recoverable elongation and creep elongation estimates shall be based on rope test data. The designer shall calculate the effect of increase of line length on mooring performance during service and determine retensioning requirements as applicable.

The values provided in Table 3 are indicative only and are not to be used for design. Tests shall be conducted to establish these rope properties. The fiber rope properties and the methods used when measuring and expressing them are discussed in detail in Annex B.

Table 3—Typical Stiffness Values in EA/CBS

Rope Type	Static Stiffness	Low Frequency Dynamic	Wave Frequency Dynamic
	0 % to 70 % CBS	0 % to 70 % CBS, 10 % CBS Amplitude	0 % to 70 % CBS, 10 % CBS Amplitude
Polyester	5 to 35	15 to 40	15 to 40
Aramid	33	33 - 60	60
HMPE	35	35 - 70	70

5.6.5 Hysteresis Heating

High internal temperatures can develop in tension-tension fatigue testing of ropes at high strain amplitudes or high frequencies. The maximum temperature rise depends on cycling frequency, diameter, internal pressure, constructional type, sheath type and thickness, lubricant, presence of water or fillers, and many other factors.

Temperature limits should be provided by the fiber producer or rope manufacturer. The designer should consider alternate constructions and materials if prototype tests indicate that equilibrium temperatures exceed the recommended values.

Hysteresis heating is usually not a problem for mooring ropes continuously submerged in water and subject to wave frequency loading. Joint industry studies indicate that heating effects can be small in large polyester ropes for strain amplitudes less than 0.25 % [5]. Additional lubricants and fillers may also be used to improve heat transfer and reduce the formation of hotspots within the rope [6], provided they are compatible with the yarn finishes.

5.6.6 Fatigue

5.6.6.1 General

The effect of fatigue on the mooring system shall be considered as specified by API 2SK.

5.6.6.2 Fatigue Damage Modes

The fiber ropes covered by this document are typically connected to chain or wire rope at both ends, i.e., used in the free span of the mooring line. Consequently, bending-tension fatigue damage due to deployment over rollers and sheaves is limited to that which occurs during installation or retrieval. Therefore, bending-tension fatigue damage is not covered in this document.

Tension and free-bending fatigue loading on taut mooring lines near terminations should be addressed by design that minimizes bending moments.

5.6.6.3 Tension-Tension Fatigue

Fatigue test results for polyester rope performed by the Polyester Durability JIP [7] are compared in Figure 1 with the wire rope and chain TN curves from API 2SK. The earlier polyester rope fatigue data from OTC 5720 [8] and the Fiber Tethers 2000 [9] are also shown in the figure.

The Polyester Durability JIP tension fatigue tests showed essentially no degradation when ropes were cycled with mean loads and load ranges typical of mooring applications, even after millions of cycles. Moderate tension serves to lock the strands together by friction, and a small cyclic tension range is not sufficient to overcome this friction and cause relative movement between strands.

Evidence of internal strand-upon-strand abrasion was found when ropes were cycled over high tension ranges about low mean tension for millions of cycles. Note that these conditions were not typical of those in mooring applications. The internal friction at the very low trough tension in those tests was not sufficient to restrain against relative movement between strands, and the high tension range then induces internal abrasion. Tests like these, in which the trough tension is almost zero, is more severe than a test over the same range with higher mean and maximum tensions.

The fatigue life of polyester rope exceeds that of steel wire or chain by a considerable margin, as shown in Figure 1. In typical mooring applications, polyester rope is used in series with steel components, e.g. chain at the anchor, polyester in the free span, and chain at the fairlead. Consequently, fatigue analyses for polyester mooring systems should focus on the fatigue life of the steel components in the mooring lines. The fatigue life of the steel components is sensitive to the load-elongation properties of the

polyester rope and the method of modeling the polyester rope that is used in the mooring system fatigue analysis.

For other types of fiber ropes or untested constructions, the designer should acquire fatigue data either through testing or from the manufacturer to qualify the fatigue life of the system.

5.6.6.4 Axial Compression Fatigue

Axial compression fatigue is not a concern with polyester and HMPE fiber ropes.

Axial compression fatigue damage can occur in an aramid rope when it is subject to sustained cyclic loading with a low trough tension. Strength loss due to axial compression fatigue damage can be avoided with proper rope design and use [10]. Precautions should be taken to keep sufficient tension on aramid rope mooring lines, especially on leeward lines during storm conditions.

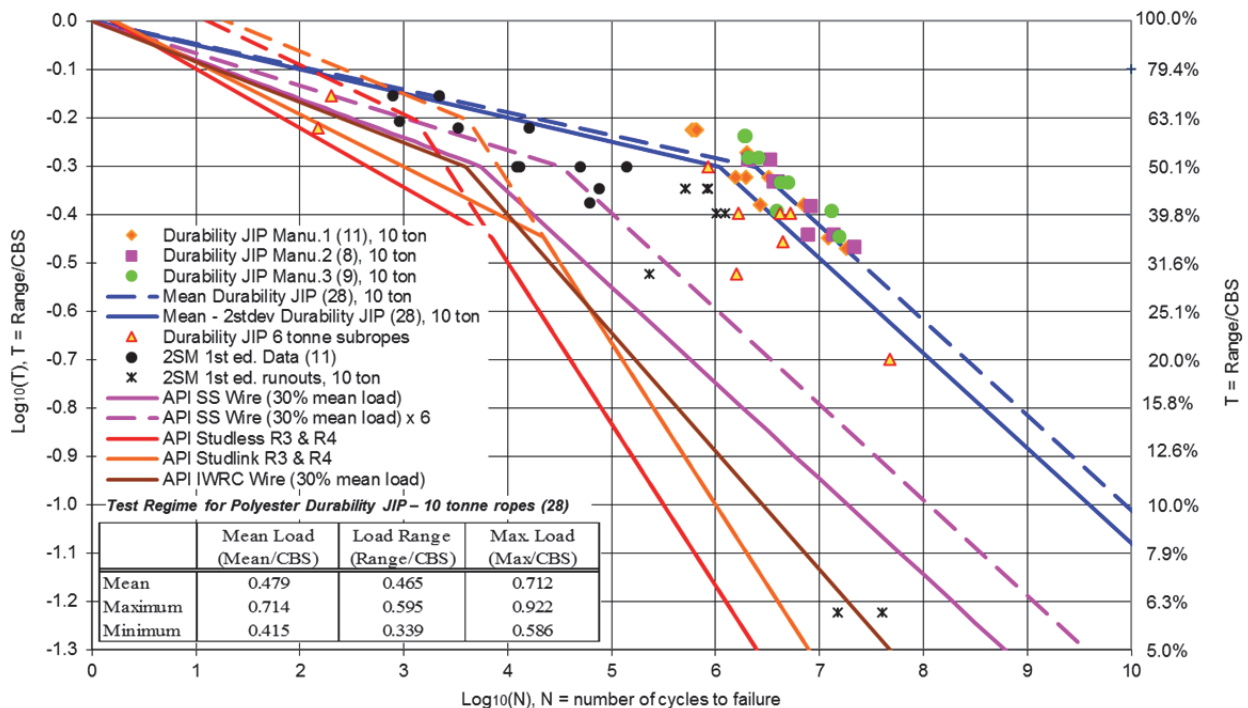


Figure 1—Polyester Durability JIP, OTC 5720 and Fiber Tethers 2000 Fatigue Test Data, Compared with Wire Rope and Chain TN Curves from API 2SK

5.6.7 Torque and Twist Effects

Synthetic ropes may be manufactured with either torque matched or torque neutral construction. Torque compatibility should be considered among different mooring components consisting of synthetic fiber rope, chain, and wire. In general, the effect of torque mismatch in a mixed component mooring line is more detrimental to the steel component. Additional information can be found in API 2SK.

Torque and twist effects do not generally affect synthetic ropes with typical parallel or wire rope subrope constructions. However, for braided fiber rope constructions, torque and twist effects can lead to unequal load sharing among the subropes causing an effective loss in capacity of the overall rope.

Excessive twisting from unbalanced torque should be avoided during handling, installation, operation, and recovery.

Two categories of torsional imbalance problems should be considered:

- a) twist introduced into components and transferred between them during installation or recovery operations, which can result in operational problems;
- b) incompatibility between installed components in operation.

Care should be taken when developing installation procedures or selecting installation equipment to ensure an acceptable level of twist is not exceeded. Models of component behavior should be used to predict problems during installation. Information on the response of the installed components due to imposed twist, for both static and cyclic (fatigue) loads, should be considered in the design.

A permanent marking stripe should be placed on the outside of the rope so that twist can be monitored externally. The rope manufacturer shall verify the maximum allowable twist for any particular rope design and application.

The testing of fiber rope torque and rotation properties as described in Section 7 and Annex C shall be used to determine the torsional characteristics of the rope.

5.6.8 Other Environmental Effects

5.6.8.1 General

Most fiber ropes are generally resistant to ultraviolet (UV) radiation and chemicals encountered in typical marine environments even when unjacketed ^[11]. The risk of damage from other external causes, such as external wear and mechanical damage during deployment or by work boats or wires can be reduced by proper jacketing, installation methods, and work boat exclusion zones.

Loss of strength due to hydrolysis in aramid and polyester ropes is not expected to occur to any appreciable extent unless the temperature is greater than 30 °C for long periods of time. Aramid yarns are more affected by hydrolysis and the possible loss of strength shall be evaluated in consultation with the yarn supplier. HMPE is not subject to strength loss due to hydrolysis.

Another environmental aspect is the formation of salt crystals following wetting and drying. Once salt crystals form, internal rope abrasion has been shown by the dry testing of yarns which were first immersed in salt water ^[12]. Therefore, this document recommends that fiber rope designated for offshore moorings should only be used where fiber ropes remain totally immersed in seawater during use. Ropes previously used in sea water should not be used in dry applications.

Additional comments on salt crystallization are contained in 9.3.11.

5.6.8.2 UV Resistance

Polyester fibers have excellent resistance to UV radiation, consequently degradation due to UV radiation for rope jackets made of polyester is not a concern.

Uncovered aramid or HMPE ropes can suffer degradation of surface yarns if exposed to UV radiation for a prolonged period of time while awaiting installation or if permanently deployed without a jacket or cover in the upper few meters of water. In such cases an opaque jacket or cover is recommended. Concerns on UV radiation damage should be discussed with the manufacturer.

5.6.8.3 Marine Growth

Minor strength loss in synthetic fiber ropes caused by marine growth has been reported. For operations where harmful marine growth is a concern, the fiber ropes should be placed outside of this marine growth zone. Marine growth can influence the weight in water and drag loading on the line and hence loadings

on the whole mooring system. Use of particle filters has been shown to be effective at preventing harmful marine growth within the load bearing members of the rope.

Marine organisms with hard shells can grow between the rope jacket and the load bearing core and cause abrasion damage to core yarns. Soft marine growth can cover the rope and hence affect the ability of ROV inspection of the rope. If marine growth is to be removed mechanically this operation should be done in such a way that damage to the rope itself is avoided.

5.6.9 Snap Back at Failure

Considerable energy is stored elastically in tensioned lines and the safety implications for the crews and equipment, especially during handling and installation if one of the lines breaks, shall be considered in the development of installation procedures.

Snap back can induce significant fiber compression damage in fibers which are subject to axial compression damage, such as aramid. Additional information on return-to-service of ropes which have been subjected to snap back is in API 2I.

5.6.10 Effect of Water Depth

In water depths of present and projected offshore mooring projects, the hydrostatic pressure is substantially less than the strength of the synthetic fibers. This pressure has a negligible effect on yarn mechanical properties, and is only responsible for a small transverse strain and the accompanying axial strain on a rope.

6 Mooring Design and Analysis

6.1 General

Mooring design and analysis shall follow the methods provided in API 2SK; however, there are issues unique to fiber rope moorings that are not covered by API 2SK.

Fiber rope and steel mooring systems differ in the way individual mooring line and total mooring system energy is stored; the energy is illustrated by the area under the line's or system's restoring force versus offset curve. For steel catenary mooring systems, system energy is stored mainly as the change in potential energy of the mooring lines in the gravitational field, due to the small axial compliance (L/EA) and large weight in water of the lines. For taut-leg fiber rope systems, system energy is stored mainly as the change in strain energy of the mooring lines, due to the large axial compliance and small weight in water of the lines. Consequently, stress-strain or load-elongation properties are more important for fiber rope mooring systems while the weight in water is more significant for steel catenary systems.

Supplemental information for the design and analysis of synthetic fiber rope moorings is provided below.

6.2 Mooring Configuration and Design

In general, a mooring system with synthetic fiber ropes can be configured as a taut-leg or a catenary-leg system. The choice depends on many considerations which are beyond the scope of this document. These types of moorings differ in the way the mooring lines provide restoring force and the resulting total mooring system load-offset performance. They also differ in low-frequency line damping, fatigue performance, and anchor loading. These differences shall be considered in the design and analysis of synthetic fiber rope mooring systems.

For synthetic moorings, a suitable length of steel wire or chain should be provided at the top and bottom ends of the synthetic rope mooring leg. The upper steel mooring component segment can be used for adjustments of the mooring leg tension needed to allow for rope elongation throughout the installation life and other repositioning operations. Therefore, suitable equipment for adjusting the length of the upper

steel mooring component segment should be provided for each mooring leg. Further, the length of the upper steel mooring component segment should be adequate to ensure that the upper end of the fiber rope remains, during the platform's service life, at a depth where it is clear of mechanical damage from surface vessels and surface marine activities, harmful sunlight penetration, and salt encrustation.

Where temporary moorings require regular handling of fiber ropes due to repeated deployment and recovery, the use of fiber ropes that have high resistance to external abrasion should be considered.

The level of post-installation stiffness required for the fiber rope should be verified by the mooring system designer based on the maximum allowable vessel excursions during operating and survival conditions, and be consistent with the rope testing.

Anchor test load requirements for permanent and temporary moorings are in API 2SK.

6.3 Design Criteria

6.3.1 Strength and Fatigue Safety Factors

The minimum safety factors for strength and fatigue for fiber rope shall be the same as for steel (see API 2SK).

For fatigue assessment the RBS, specified in API 2SK, is equal to the CBS. For polyester and HMPE ropes that are of similar construction and fiber type to those for which fatigue test data exist [6], the fatigue life may be assumed to be six times that given in API 2SK for a spiral strand wire rope at a mean load of 30 % of the CBS, for tension ranges not exceeding 50 % CBS.

For rope types for which no fatigue data exist, qualification testing shall be performed. That is, for a new prototype rope construction or splice (termination), at least one tension-tension fatigue test as described in Annex D shall be conducted to demonstrate that the rope, including terminations, possesses a minimum level of fatigue endurance.

6.3.2 Minimum Tension and Maximum Allowable Low Tension Cycles

The requirement to maintain a minimum tension and remain below a maximum number of low-tension cycles is applicable to aramid and similar fiber types. It is not applicable to polyester, nylon, or HMPE fiber ropes as they are not susceptible to axial compression fatigue.

The provisional guideline is to limit aramid fiber rope mooring lines to experience less than 500 cycles below a trough tension of 10 % CBS over the life of the mooring line. In the context of evaluating axial compressive fatigue damage, if the tension in the line is below the 10 % CBS threshold at any time in the cycle, then that cycle is counted toward the axial compression fatigue design limit. Aramid fiber ropes can be designed to sustain more cycles or lower tensions than indicated above before significant strength loss occurs. However, test data shall be provided for justification of relaxing this general guideline.

6.3.3 Creep Failure

Creep failure is a concern in HMPE ropes. Creep failure (or creep rupture) is a result of cumulative, irrecoverable elongation of a fiber rope under load over time. Cumulative creep is dependent on mean load, temperature, and load duration. Unlike fatigue damage that is mainly caused by cyclic loading from waves, creep damage results from the mean tension from environmental components, including wind, waves, and current. Special attention should be given to high current events such as a loop current event in the Gulf of Mexico, which can impose high steady loads of long duration on the floating structure. If applicable, such an event shall be included in the design conditions for creep rupture analysis.

The factor of safety for creep failure is defined as the predicted creep failure life divided by service life of the mooring rope. The recommended factor of safety for creep failure is ten times the service life of the

rope for the intact mooring condition. It is prudent to assess the creep failure life for various environments for the damaged mooring condition for contingency plans to be developed, if required, e.g. if the damaged mooring creep failure life is extremely short then contingency plans for spares and installation should be in place.

For fiber ropes that require creep failure analysis (see 6.4.4), such as HMPE, estimates of rope creep failure resistance shall be based on the rope extension test similar to that described in Annex B, but with modified tensions and duration (until the rope fails) to yield data for creep failure analysis.

For polyester, nylon, and aramid mooring systems designed to API 2SK safety factors, creep failure is not typically a design issue in the intact mooring condition. However, for conditions which result in high fiber loads (greater than 70 % of the fiber break strength) for a long duration, creep failure can be a concern.

In addition to the above analysis, the designer should check to ensure that the cumulative rope strain during the service life does not exceed the maximum allowable value.

6.4 Mooring Analysis

6.4.1 Fiber Rope Load-elongation Properties

6.4.1.1 General

This edition of API 2SM does not recommend a single method of representing fiber rope load-elongation properties in mooring analysis software to account for the non-linear or frequency-dependent load-elongation properties of fiber ropes. The upper and lower bound constant stiffness (linear load-elongation) method may be used, and the test procedure described in Annex B allows those stiffness values to be derived. However, the mooring analyst is encouraged to use a more realistic model of fiber rope load-elongation properties. Ideally the rope load-elongation model uses the load-elongation test results (stress-strain) in the mooring analysis software in such a way that the laws of physics, in particular conservation of energy, are not violated. However, this is not always possible with computer programs. Consequently the mooring analyst should develop a method that is compatible with the available mooring analysis software and best represents the non-linear load-elongation (varying stiffness) behavior of the fiber rope while predicting accurate line tension and vessel offset responses.

Presently, software used for mooring analysis represents mooring line segments, steel or fiber rope, as a perfectly elastic material; the elastic model is linear or nonlinear. The segment length is completely defined by its initial unloaded length and the tension; the length of the segment is unaffected by previous load history. Consequently, for fiber ropes, the analyst should determine the range of permanent elongation, and if required, the recoverable stretch of the fiber rope segments to be used when analyzing a particular load case (i.e., each combination of wind, wave and current conditions, together with vessel draft and associated line pretensions). The unloaded length should be determined such that the length at pretension accounts for the delayed elastic stretch. The unloaded length used for each fiber rope segment depends on the method of analysis employed by the designer. The increase in length due to delayed elastic stretch may be directly included in the unloaded length of the segment by increasing the rope length in the analytical model. Alternately, the increase in the unloaded length of the fiber rope is accounted for, at least in part, by the use of a low value of fiber rope stiffness.

As shown in Figure 2, the load-elongation properties of fiber ropes are non-linear and load rate dependent. The unloaded length and stiffness properties of the rope depend on the load time history. Therefore, a proper representation of the complete mooring line requires a non-linear load-elongation, time-dependent model and the definition of the unloaded length of the fiber rope, together with any line length adjustments of the fairlead chain or wire segments that are planned to manage the increase in the length of fiber rope during the life of the mooring system.

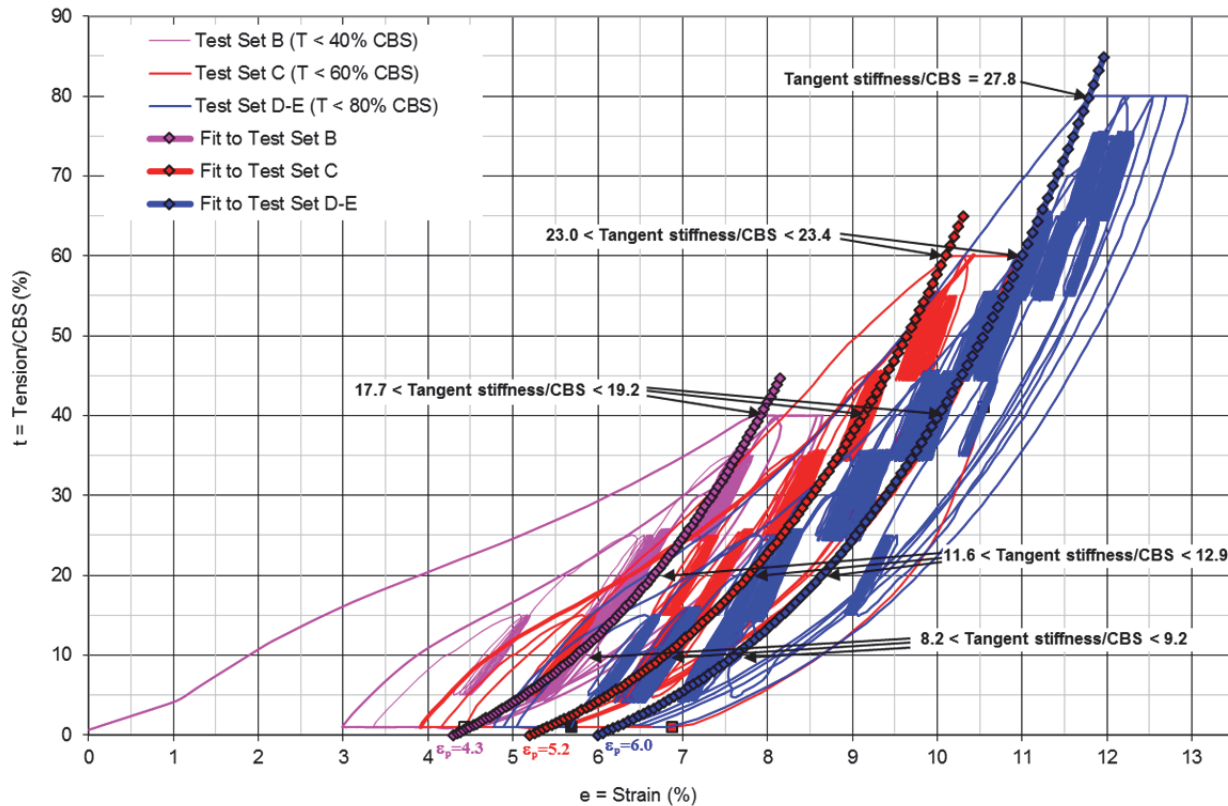


Figure 2—Polyester Rope Load-Elongation: Load-vs.-Extensometer

6.4.1.2 Simplified Method, Lower and Upper Bound Constant Stiffness Method

In the simplified linearized approach, each load case is analyzed twice; once using the lower bound stiffness to estimate maximum vessel offsets and once using the upper bound stiffness to estimate maximum mooring line tensions. The same stiffness values may be used for each line; alternately, the value may be different for each line depending on mean load.

It is not possible to keep the unloaded line length (i.e., the unstretched length under zero tension), pretensions at the fairlead, and anchor locations all constant in the lower and upper bound stiffness mooring models. One of the following approaches may be used in the simplified method.

- Pretension and anchor locations constant. The lower and upper bound stiffness mooring models have the same pretensions and anchor locations, the fiber rope segment lengths are greater in the upper bound stiffness model than in the lower bound model.
- Pretensions and fiber rope segment lengths constant. The lower and upper bound stiffness mooring models have the same pretensions and fiber rope segment lengths, the fairlead to anchor distances are greater in the lower bound stiffness model than in the upper bound model.
- Anchor locations and fiber rope segment lengths constant. The lower and upper bound stiffness mooring models have the same anchor locations and fiber rope segment lengths, the pretensions are greater in the upper bound stiffness model than in the lower bound model.

The simplified method may be implemented in either the frequency or time domain, as within each mooring analysis the same set of load-elongation properties is used for calculating the mean, low, and wave frequency vessel and line responses.

A sensitivity study should be conducted to investigate whether these stiffness values are adequate to identify the maximum and minimum line tensions and vessel offsets. The actual stiffness values used in the mooring analysis shall be derived from rope testing.

6.4.1.3 Separate Decoupled Mean, Low Frequency, and High Frequency Responses

The decoupled method of performing mooring analyses uses three different, but constant stiffness, models for calculating mean, low frequency, and wave frequency responses, as follows.

- a) Mean response. The vessel's static equilibrium position and mean line tensions under the mean environmental load are calculated using the static stiffness, the lowest of the three stiffness values.
- b) Low frequency response. The vessel's low frequency surge, sway, and yaw motions are calculated based on a mooring model that uses the low frequency stiffness, generally an intermediate value of the fiber rope stiffness, with excitation provided by the slowly varying wind, wave, and current loads. Care shall be taken to ensure that the mean tensions in the low frequency analysis are consistent with those calculated for the mean response.
- c) High frequency response. The wave frequency components of the mooring line tensions are calculated based on a mooring model that uses the wave frequency stiffness, generally the highest of the three fiber rope stiffness values, combined with the vessel's wave motion response amplitude operators and the spectra of wind-waves and swell-waves.

The selection of the vessel offsets that correspond to API 2SK's two cases for calculating maximum tensions and offsets (mean plus low frequency maximum plus wave frequency significant, and mean plus low frequency significant plus wave frequency maximum) require special attention.

As this method uses different mooring models for mean, low, and high frequency responses, it can only be performed as a decoupled analysis. Although each of the three distinct analyses may be performed in either the frequency or time domain, within each part of the analysis the load-elongation properties do not change.

6.4.1.4 Nonlinear Load-elongation Method

In this method, the fiber rope's load-elongation properties are modeled as nonlinear elastic, either by expressing the load-elongation (stress-strain) relationship analytically or by using lookup tables.

The Del Vecchio equation is one way of representing the nonlinear dynamic fiber stiffness. For polyester fibers, Del Vecchio ^[13] expressed the stiffness (specific modulus) of fiber as follows.

$$SM = C + M \left(\frac{L_{\mu}}{L_{\max}} \right) + \alpha \left(\frac{L_a}{L_{\max}} \right) + \phi \log_{10} (T_{\text{cyc}}) \quad (1)$$

where

SM is the specific modulus (N/tex);

C is the constant (N/tex);

L_{μ} is the mean load (N);

M is the mean load coefficient (N/tex);

L_a is the load amplitude (N);

α is the load amplitude coefficient (N/tex);

$L_{\max}$ is the breaking strength (N);

T_{cyc} is the loading period (sec);

ϕ is the load period coefficient (N/tex).

NOTE A tex is a metric unit used in the textile industry to measure the density of a single fiber of yarn. One tex equals a density of one gram per kilometer of length, or 1 mg/m. One tex equals 10 drex or 9 denier.

The dynamic stiffness of the fiber depends on the mean load, L_{μ} , the load amplitude, L_a , and the load period, T_{cyc} . For a fiber rope, this equation should be modified to account for the particular type of fiber and the rope construction used, resulting in a modified version of the Del Vecchio stiffness model.

Delayed elastic stretch and delayed elastic recovery (DES and DER) should be accounted for in long duration events. That is, the mooring model should be adjusted by lengthening lines resisting the environmental loads (DES) and shortening lines on the slack side (DER).

For fully coupled time domain programs, each fiber rope line segment is represented by a single nonlinear load-elongation model that is used for solving for mean, low frequency, and wave frequency responses, as shown in Figure 3; however a different representation may be used for each line segment. Coupled frequency domain programs use different load-elongation properties for the wave frequency response than those used for the mean and low frequency response, if the software supports this differentiation.

6.4.2 Recommendations on Application of Analysis Methodology

For MODU or temporary moorings where line lengths are easily adjusted to manage mean vessel offsets, it is sufficient to use the simplified linear load-elongation approach, with the lower bound stiffness used for calculating offsets and the upper-bound stiffness for calculating line tensions, as described in Section 6.4.1.2.

For permanent moorings, it may be necessary to use more accurate information on static and dynamic stiffnesses to better estimate vessel offsets, line tensions, and fatigue damage. Simplified stiffness models (see 6.4.1.2) can lead to nonconservative results if parameters are not properly selected. Use of bounding stiffness values for all aspects of design may result in overly conservative estimates of vessel offsets and mooring line tensions. However, it is possible the mooring line and riser fatigue is not conservatively predicted using the simplified bounded stiffness methods. Thus, this simplified approach can lead to increased mooring line size, capital cost and installation cost.

The designer should be cognizant of the impact of permanent rope elongation when working with non-adjustable mooring systems (as discussed in 4.3.3).

6.4.3 Fiber Rope Length

6.4.3.1 General

The line length shall be managed such that the fiber rope stays in the appropriate position within the system. The appropriate position depends on the application; for example, fiber ropes may be used as hawsers near the water surface or in the water column of temporary or permanent mooring systems.

Required rope clearances from the fairlead and seabed shall be maintained. The permanent elongation due to construction stretch during installation and additional bedding-in and recoverable or creep elongation during the mooring's service life shall be accounted for in the design.

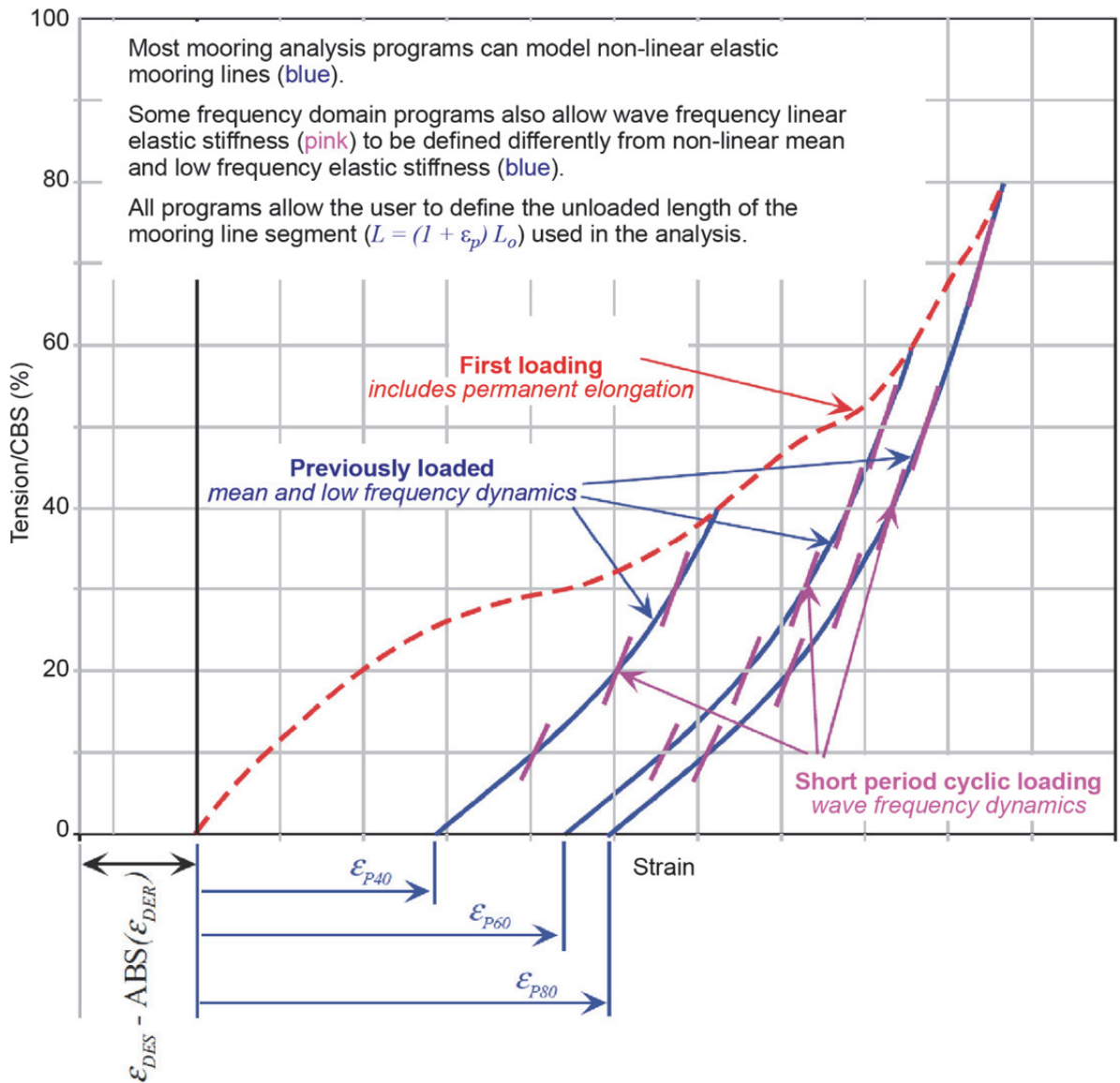


Figure 3—Idealized Polyester Behavior

6.4.3.2 Length Management Issues

6.4.3.2.1 General

For MODU moorings, line length adjustments are frequently made and ropes are reused at different locations. Consequently length management issues for MODUs differ greatly than those for permanent mooring systems. This section focuses on length management issues for permanent systems although some of the discussion is applicable to MODUs.

Construction stretch is the permanent elongation caused by the maximum historical load that the rope has experienced during its life. There are primarily two maximum loads of interest: installation load and maximum design load. The permanent elongation caused by these loads is herein called installation stretch and maximum design stretch, respectively.

The as-purchased length is the length of the rope (at specified minimal load) when it leaves the factory. This is also referred to as the rope assembly length, which includes the rope assembly interfaces.

The installation load is applied to the synthetic rope at the time the mooring is hooked up to the vessel. The installation load may be applied to a preset portion of the synthetic mooring line with workboats, anchor handling tugs, or other installation vessels prior to actual hook-up to the vessel. Alternately, the installation load may be applied to the synthetic mooring line via the vessel's on-board tensioning equipment after hook up.

The mooring designer and installation planner draft a set of installation procedures and estimate the mooring installation load. The increase in length in the synthetic rope due to the application of the installation load is defined as the installation stretch. After installation, the total length of the synthetic mooring line (at zero load) is the as-purchased length plus the installation stretch. This length is called the as-installed length.

If the synthetic rope is loaded beyond the installation load, for example to the maximum design load, the rope elongates permanently under this maximum load. Generally, a single extreme environmental event does not load all lines equally. For example, windward lines withstand much higher environmental loads than leeward lines. Thus, the synthetic ropes in only a few lines undergo additional permanent stretch. The mooring designer needs to address the impact of this permanent stretch on the mooring system performance.

For permanent moorings, the synthetic rope vendor calculates the as-purchased length of rope required to meet the as-installed length under the installation load. The vessel operator needs to develop a suitable length management plan. A few options for length management are discussed below.

6.4.3.2.2 No Length Adjustment

The length of the mooring line cannot be adjusted. For example, this situation would exist for a vessel with fixed padeyes in place of fairleads. The mooring designer needs to address the impact of the rope elongation due to the maximum design loads on the global mooring performance over the life of the mooring system.

6.4.3.2.3 Length Adjustment through Shortening of Fairlead Segments

The length of the mooring line is adjusted by hauling in the fairlead segment. The mooring designer needs to address the impact of the additional fiber rope length combined with the resultant shorter fairlead segment on the global mooring performance. The chain lockers or wire storage drums should be sized to accommodate the additional chain or wire that might be hauled in and permanently stored on the vessel. Alternately, the additional chain may be removed from the vessel.

6.4.3.2.4 Length Adjustment through Shortening the Fiber Rope

The length of the mooring line is adjusted by removing a length adjustment insert in the fiber rope. The mooring designer, in conjunction with the rope vendor, needs to estimate the length of these adjustment inserts and address the impact of changes in the fiber rope properties on the global mooring performance. The onboard equipment (length of fairlead segment and winch capability) required to remove fiber rope inserts needs to be specified during the design phase.

6.4.3.3 Impact of Fiber Rope Length Changes

Change in fiber rope length and other properties are unlikely to cause problems for the mooring system itself. However, these changes can, without line length adjustment, impact the stationkeeping performance of the mooring system, and thus impact the performance of other critical systems, such as import and export risers. It is not possible to predict the sequence of environmental events over the life of an offshore installation. It is possible to develop a number of "what if" cases that bound the impact of fiber rope length changes on mooring system performance. Suggestions for developing these cases are as follows.

- a) Determine the conditions that result in changes in line length that have a significant impact on mooring system performance as follows.
 - For polyester systems, determine the metocean conditions that result in maximum loads equal to the installation load. Anything lower than these conditions does not permanently lengthen the synthetic mooring lines.
 - For HMPE systems, determine how long it takes for cumulative creep strain to significantly impact mooring system performance, based on the long-term metocean conditions, i.e., annualized statistical metocean data, at the location (see 6.4.4 for creep analysis calculations).
- b) Evaluate the impact of the worst environmental conditions (e.g., the 100 year extreme event from the worst direction) on the fiber mooring line load and determine the maximum design stretch and resultant permanent elongation.
- c) Reanalyze the mooring system performance based on the new fiber rope length and properties.
- d) Analyze the impact on the variation in mooring system performance on critical systems, such as riser fatigue life. Consider the effect of the timing of the worst event (e.g., in the first year, in the tenth year, etc.).

It may be necessary to maintain a mooring model that is updated as required throughout the design life to analyze the impact of changes to the fiber mooring line length and its properties.

6.4.4 Creep Failure Analysis

Generally, rope creep behavior is based on a creep model for the rope construction and yarn creep test data. Alternatively, creep failure calculations may be based on rope creep test data. The analysis should be performed based on creep data suitable for the temperature at which the rope will be deployed.

Creep failure life predictions are made by comparing the long-term loading in a mooring component with the resistance of that component to creep failure. Similar to the Miner's rule for fatigue analysis, the annual cumulative creep damage ratio E_t is calculated by the following equation:

$$E_t = \sum \frac{c_i}{C_i} \quad (2)$$

where

c_i is the creep rate per year within the tension interval i , unit of time;

C_i is the creep failure life (resistance) for the tension interval i , as determined by rope creep test, unit of time consistent with c_i .

The predicted creep life to failure for the mooring component, which is $1/E_t$, shall be greater than the field service life multiplied by a factor of safety defined in 6.3.3. For used mooring components, creep (failure or rupture) damage from previous operations shall be taken into account.

A method of evaluating creep damage is described as follows.

- 1) The long-term environmental events may be represented by a number of discrete design conditions (e.g., weather bins). Each design condition consists of a reference direction and a reference sea state, characterized by significant wave height, wave spectrum, current velocity, and wind velocity. The probability of occurrence of each design condition shall be specified.