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

API RECOMMENDED PRACTICE 2SM
SECOND EDITION, JULY 2014

energy API

AMERICAN PETROLEUM INSTITUTE

## Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Users of this Recommended Practice should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

## 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:

— the term "shall" denotes a minimum requirement to conform to the specification;

— the term "should" denotes a recommendation or that which is advised but not required to conform to the specification;

— the term "may" is used to express permission or a provision that is optional;

— the term "can" is used to express possibility or capability.

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually by API, 1220 L Street, NW, Washington, DC 20005.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, DC 20005, 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 (FPUs, 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 1503 [1], *Test Method, Yarn-on-Yarn Abrasion, Wet and Dry*

ISO 18692[2], *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 |
| $L_\mu$ | 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 |
| $\varepsilon$ | 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<br>kgf/m | Total Weight in Sea Water<br>kgf/m | Typical Overall Diameter<br>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.

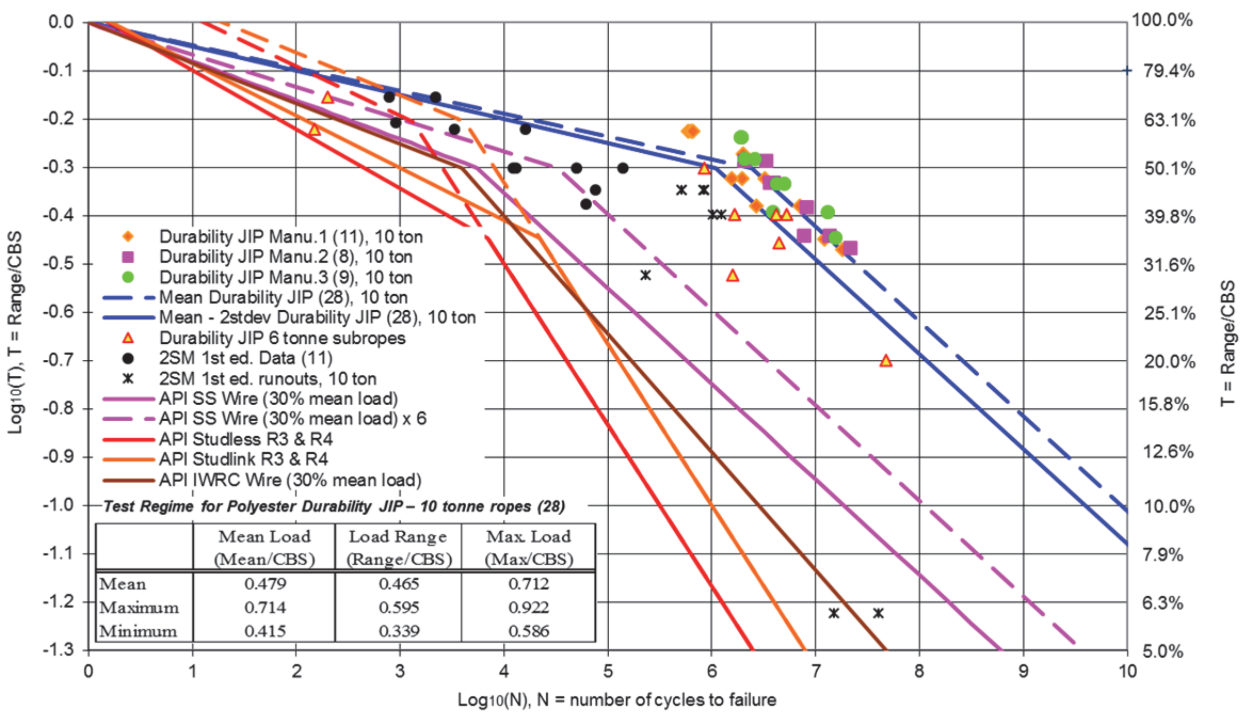


**Figure 1—Polyester Durability JIP, OTC 5720 and Fiber Tethers 2000 Fatigue Test Data, Compared with Wire Rope and Chain TN Curves from API 2SK**

### 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 ºC 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.

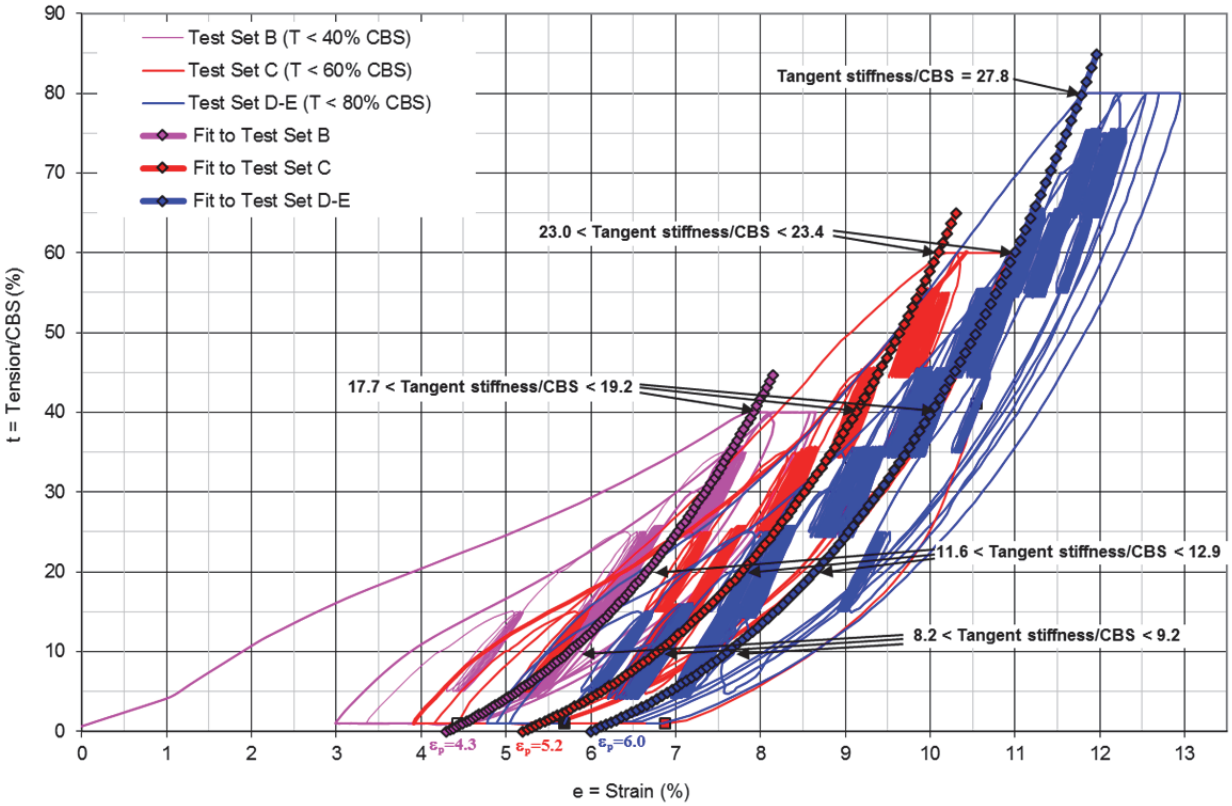


**Figure 2—Polyester Rope Load-Elongation: Load-vs.-Extensometer**

### 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.

a) 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.

b) 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.

c) 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.

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

where

$SM$ is the specific modulus (N/tex);

$C$ is the constant (N/tex);

$L_\mu$ is the mean load (N);

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

$L_\text{a}$ is the load amplitude (N);

$\alpha$ is the load amplitude coefficient (N/tex);

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

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

$\phi$ 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, $L_{\mu}$, 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.

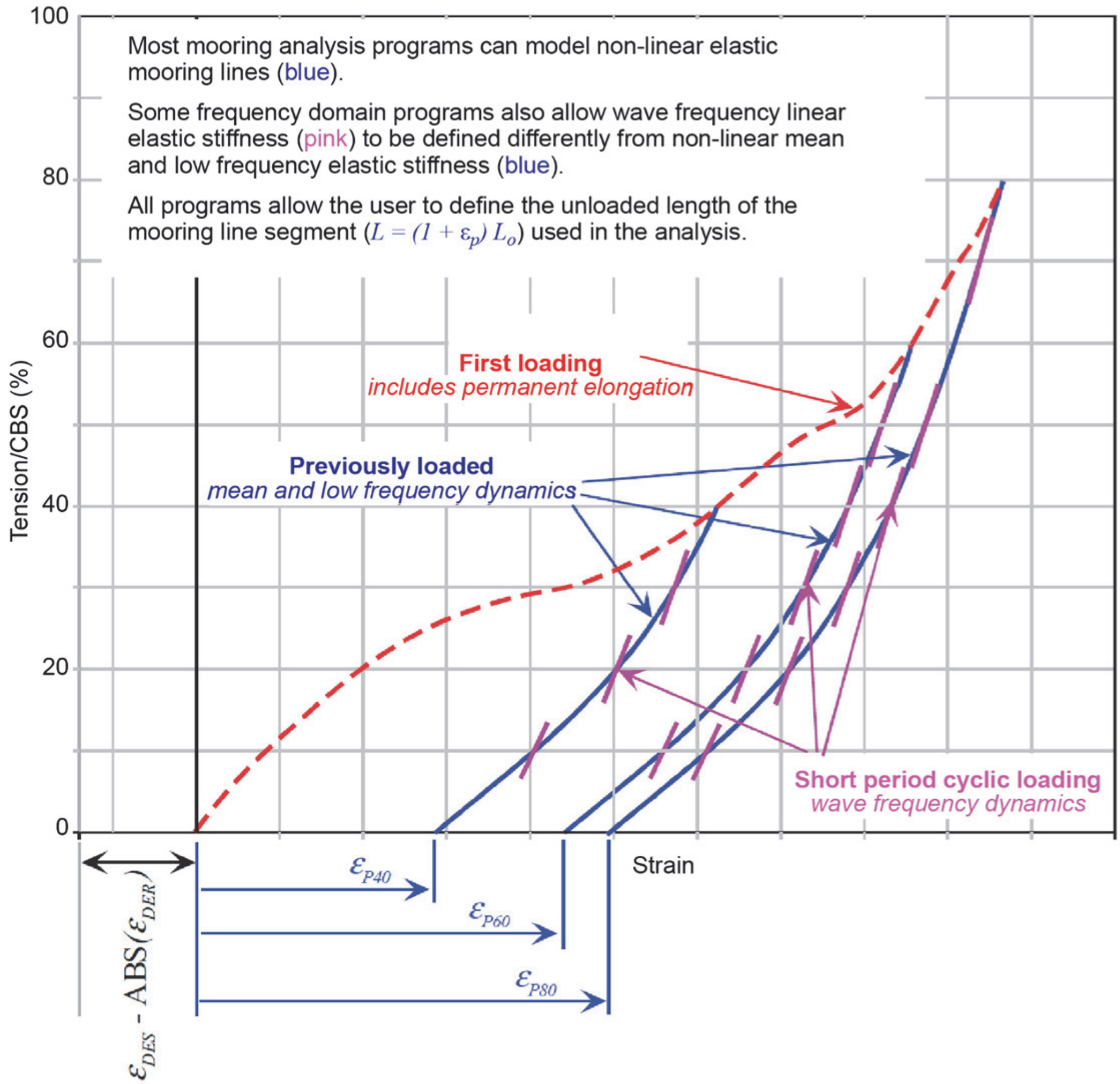


**Figure 3—Idealized Polyester Behavior**

### 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:

$$E_t = \sum \frac{c_i}{C_i} \tag{2}$$

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.

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

3) Compute the annual creep damage, $c_i/C_i$, from each design condition (sea state and direction) using Equation 2. Since line tensions are of random nature, different intervals of tension for each design condition should be defined and the associated duration for each interval should be determined. Summation of creep damage from all tension intervals is the creep damage for the design condition. Alternatively, a conservative constant line tension (greater than the average tension under mean environmental load for the bin), instead of the random tension history, may be used to simplify the calculation.

4) Repeat Step 3 for all sea states and directions and compute the total annual creep rupture damage $E_t$, which is the sum of creep rupture damage from all sea states and directions.

The predicted creep rupture life of the mooring line is:

$$L_c = 1/E_t \quad \text{(years)} \tag{3}$$

Unlike fatigue damage that is mainly caused by cyclic loading from waves, significant contributions to creep rupture damage are caused by wind, waves, and current. Special attention should be given to high current events, such as the loop current event in the Gulf of Mexico, which impose high steady loads of long duration on the floating structure.

In addition to the above analysis, the designer should check to ensure that the cumulative rope strain from the service life does not exceed the maximum allowable value, if such a value is available from the rope manufacturer or other reliable sources.

### 6.4.5 Tension-Tension Fatigue Analysis

The fatigue analysis methodology as described in API 2SK shall be used for fiber rope mooring systems. Note that the fatigue analysis is typically performed to assess the fatigue life of the steel components rather than the fiber components; however, the properties of fiber ropes can have a significant impact on the fatigue life of the steel components.

It is possible that the simplified upper and lower bound fiber rope stiffness models do not provide conservative results for all lines in the same weather bin since:

— low frequency natural periods decrease with increasing fiber rope stiffness, resulting in an increase in the number of low frequency cycles;

— low frequency tension ranges increase or decrease depending on the effect of fiber rope stiffness on low frequency damping and motion amplitudes;

— wave frequency tension ranges increase or decrease with changes in rope stiffness depending on the line tangent at the fairlead and the wave frequency motions of the vessel at the fairlead in the tangential direction.

In addition, the VIM of spars and other FPSs are sensitive to the sway natural period, so it is possible that the use of the simplified upper and lower bound fiber rope stiffness models does not provide conservative results. The current speeds at which lock-in occurs and the resulting mean loads and VIM amplitude will not necessarily provide conservative combinations of tension ranges and their probability of occurrence.

### 6.4.6 Axial Compression Fatigue Analysis

This analysis is only necessary for fiber ropes constructed from fibers known to be sensitive to axial compression fatigue damage, such as aramid. It is not required for polyester and HMPE.

Minimum axial tensions shall be derived by analysis. Where lower and upper bound stiffness models are used, different but appropriate stiffnesses shall be chosen for all lines. The number of cycles of low tension may be computed by consideration of the long-term distribution of the environment, associated wind, wave, and current conditions. For criteria on allowable number of cycles refer to 6.3.2.

The minimum tension may be predicted using either the frequency or the time domain method. The analysis method should reflect the effect of the various parameters used to approximate the nonlinearities. Wind, wave, and, where appropriate, current induced dynamic motions shall be included, since they all contribute to the number and magnitude of low-tension cycles.

### 6.5 Model Testing

Recommendations for undertaking model tests are provided in API 2SK.

For systems with synthetic fiber rope moorings, the model tests can account for the non-linear load-elongation behavior of the lines.

## 7 Rope Specification and Testing

### 7.1 General

This section provides guidelines on rope specification and testing methods.

All synthetic fiber rope provided for use in deepwater moorings should be certified by a recognized classification society (RCS). A third-party certified verification agent (CVA) may also be used provided that it is acceptable to the authority having jurisdiction over the area of operation.

Test results and other rope information shall be provided in the rope production report.

### 7.2 Rope Specification and Documentation

#### 7.2.1 General

The rope specification should completely and accurately describe the design of the rope in sufficient detail to permit evaluation of its suitability for purpose and to distinguish it from other similar ropes. The rope specification should include at least the following:

- CBS and required MBS;
- the elongation, modulus and torque (if applicable) properties;
- the generic fiber material type and grade;
- rope structure;
- termination type;
- overall length (as-purchased, as-installed);
- length tolerance;
- jacketing and particle ingress protection, as required.

The following documentation should be included in the rope specification:

— rope design specification;

— fiber and yarn specification;

— rope assembly specification;

— rope component identification specification;

— rope testing specification;

— packaging, shipping, and handling specification (see Section 9).

### 7.2.2 Rope Design Specification

#### 7.2.2.1 Break Strength

The rope specification should include test procedures, number of test samples and reporting methods in determining the MBS. The minimum break strength and catalog break strength are defined in Section 3 and Section 5. A break strength test procedure is provided in Annex E.

The purchaser may request that a number of subropes be break tested to show the conversion from subrope MBS to full rope MBS.

#### 7.2.2.2 Load-Elongation Properties

The elongation and creep properties are defined in accordance with Section 4. These properties should be included in the rope specification. The test procedures should be developed to establish the load-elongation properties of the rope. The test procedures should be consistent with how the system is installed, operated, and analyzed. A test procedure for load-elongation properties is described in Annex B and includes at a minimum the following properties:

— static load-elongation;

— low frequency load-elongation;

— wave frequency load-elongation;

— permanent elongations at selected loading sequences and over the rope service life;

— creep properties and creep rupture resistance, as required.

Estimated load-elongation properties should be provided by the rope manufacturer for initial mooring design calculations.

#### 7.2.2.3 Rotation and Torque Properties

If rope rotation and torque properties are of importance, these properties should be included in the specification, indicating the range of tolerances and testing methods by which the properties are to be determined. Additional guidance is provided in Annex C.

#### 7.2.2.4 Fatigue Performance

The specification should include the most appropriate rope fatigue data to be used in the fatigue design calculations. The fatigue performance properties are discussed in 5.6.6.

For a new prototype rope construction or splice (termination), at least one tension-tension fatigue test as described in Annex C shall be conducted to demonstrate that the rope, including terminations, possesses a minimum level of fatigue endurance. For proven rope constructions and terminations tension-tension fatigue tests are not required.

Axial compression fatigue is not a concern with polyester and HMPE fiber ropes. Provisional axial compression fatigue criteria for aramids are given in 5.6.6.4.

### 7.2.3 Fiber and Yarn Specification

The fiber specification shall include at a minimum the base fiber material type and grade, minimum fiber strength requirements, and testing requirements.

The yarn specification shall include principal yarn properties such as yarn break strength, yarn elongation, creep, marine finish, and yarn-on-yarn abrasion performance.

Fiber and yarn properties are further described in 5.2.

### 7.2.4 Rope Assembly Specification

#### 7.2.4.1 General

The rope specification should cover details that describe the completed rope assembly for each segment of each mooring leg, including, but not limited to items discussed in the following sub-sections.

#### 7.2.4.2 Rope Construction

Typically mooring ropes are assembled by combining a number of subropes. The construction and assembly of the subropes can be of the following types:

- parallel lay;
- wire rope type;
- braided;
- other.

The rope can either develop torque under tension or remain torque neutral. Parallel lay construction is torque neutral if the number of left hand lay subropes is balanced with the number of right hand lay subropes. Wire rope type constructions are typically not torque balanced. Generally, braided rope constructions are torque neutral.

#### 7.2.4.3 Overall Rope Length

The specification shall include the overall installed lengths, e.g. pin-to-pin length, at the corresponding installation tension or the length of rope required before installation, as measured at an agreed reference tension. The purchaser and manufacturer should agree on a method for rope length calculation for delivery. The tolerance on the overall length shall be established in collaboration with the rope manufacturer, taking into account its effect on the mooring system installation and performance.

The reference tension is a small tension used to straighten out the rope to measure its length. The reference tension used for mooring ropes may be higher than 1 % of CBS or RBS [3]. The same reference tension shall be used for all length measurements on the entire production order.

A secondary method of verifying the rope length based on unit rope weight in accordance with ISO 2307 or CI 1500 may be used. The humidity in the air can have a significant effect on weight resulting in an inaccurate length for large scale mooring ropes.

#### 7.2.4.4 Rope Termination and Termination Hardware

##### 7.2.4.4.1 General

The rope termination and termination hardware comprise the elements that serve to connect the fiber rope segments to adjacent fiber rope, chain, wire rope, anchor, or other mooring hardware. These elements can include spliced eyes, thimbles, shackles, connectors, H-links, chains, or other components.

Full details of the termination should be specified, including the following, as appropriate:

- rope termination documentation including subrope markings and splice mapping;
- strength, fatigue, torque performance of the termination, if these are different from that of the rope;
- any critical dimensions of the termination, including tolerances if appropriate;
- material for the termination hardware;
- description of processes, finish, coatings, cathodic protection, and other forms of protection for the termination hardware that are essential to the performance of the mooring;
- termination hardware identification as further described in 7.2.5.

The types of rope terminations, e.g. splice, potted socket, wedged socket, etc., which are used to secure the rope to the connecting hardware should be specified. The purchaser may also request the rope manufacturer to provide an estimated ratio of the strength of the rope body (excluding termination) to the minimum terminated rope breaking strength.

The termination shall be designed to have strength greater than the CBS of the fiber rope so that the hardware can be disconnected, removed, and replaced without unreasonable application of force up to the CBS of the rope.

Detailed termination procedures which match the procedures used for the prototype testing should be specified, although the prototype work may be carried out on dummy terminations with the same geometry as production fittings.

Termination design and material selection shall address factors such as fatigue and corrosion to ensure that the termination is adequate for the service life of the mooring system.

A discussion of the specification for different termination types is presented in 7.2.4.4.2 .and 7.2.4.4.3.

##### 7.2.4.4.2 Spliced Eyes

The typical termination for mooring ropes is the spliced eye. The spliced eye specification shall include the splicing procedures. Unless otherwise specified, the eye size shall be determined as the dimension from the inside back of the eye to the crotch of the eye with the two legs of the eye close together as shown in Figure 4. The tolerance should be agreed upon between the rope manufacturer and the purchaser.

The purchaser may request that the manufacturer demonstrate the splice, when loaded and cycled, is adequate.

Hardware to support the spliced eye can take the form of one piece fittings or of separate bushes and shrouds. In the latter case the bush acts as the interface between the rope eye and the connecting shackle pin. The shroud, which fits over the bush, retains the eye in position preventing asymmetric loading and protecting against abrasion. The bush shall be a neat fit on the shackle pin and the root diameter shall be specified. The crush resistance of the bush material shall be such that it withstands the CBS of the rope assembly. This shall be demonstrated through prototype testing.

Hardware shall be free of sharp edges and rough surfaces which might cut or abrade the rope or chafe the jacket or cover. The mouth of a thimble should be flared and rounded to reduce chafing. When the thimble is shackled to a chain, the thimble design should have provision to prevent the shackle from moving forward and contacting the rope. All hardware shall be designed so that the rope eye remains securely in position during deployment, in-service and recovery operations.

Unless otherwise specified, the load at which the thimble deforms or fails, with appropriate safety factors, shall be greater than the CBS of the rope. The strength of the thimble shall be demonstrated through testing of a prototype of a representative size of the rope.

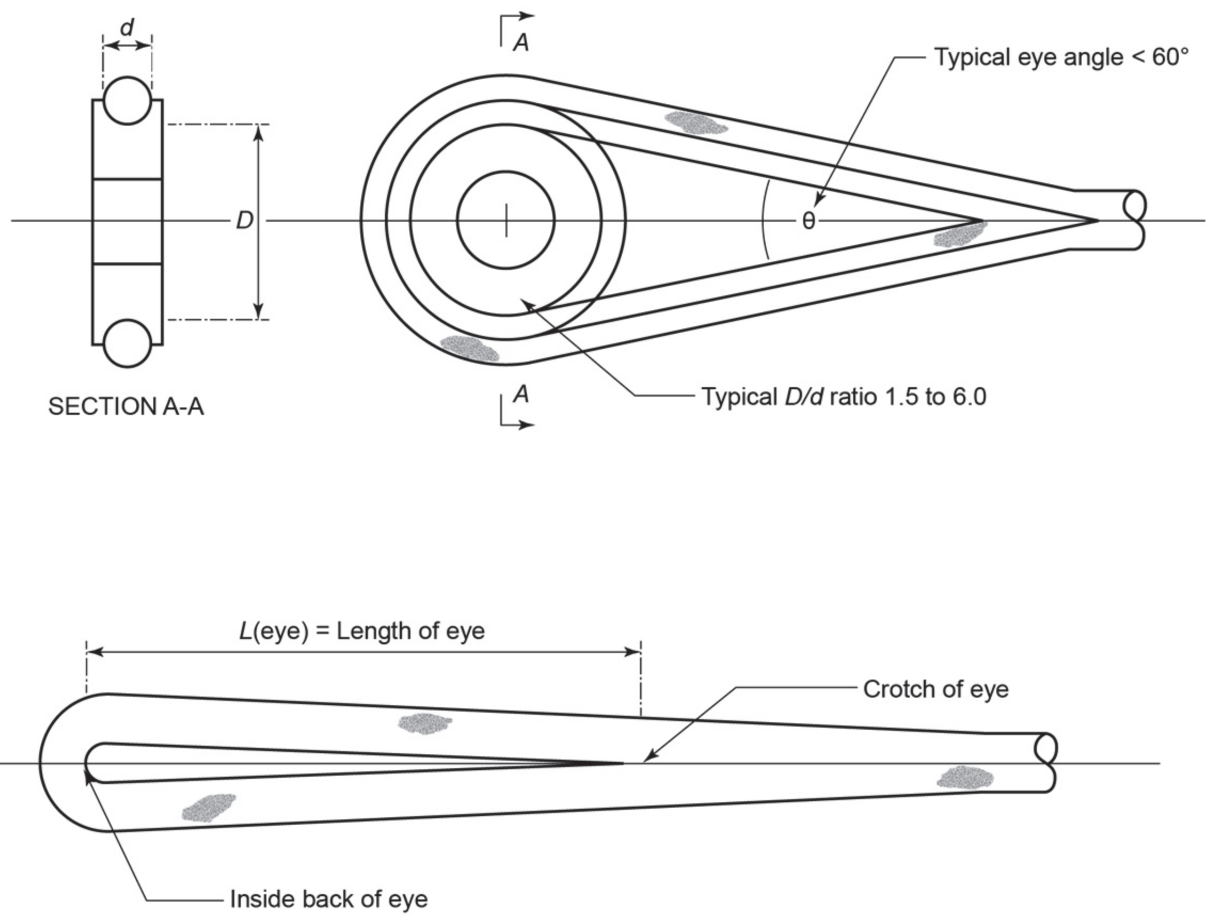


**Figure 4—Diagram of Eye Splice Showing Features**

#### 7.2.4.4.3 Other Terminations

Terminations other than the spliced eye generally have not been used for large fiber ropes. Terminations other than eye splices may be used if appropriately qualified and suitable for its application.

Socket terminations may be applied using cast resin cones, barrel-and-spike, or a combination of these techniques. The choice of termination shall be suitable for the particular rope construction. The effectiveness of the termination shall be demonstrated through prototype testing.

Resin systems shall be chosen with care to ensure chemical compatibility with the rope materials and suitability for prolonged sea water immersion.

#### 7.2.4.5 Rope Jacketing

The form of jacketing or protection to be placed on the rope, e.g. braided jacket, elastomeric cover, etc. shall be specified. Although not required, jacketing may also be used for subropes and subrope strands comprising the rope.

The specification shall include the type and quality of rope jacket, in particular requirements for exclusion of particulate matter, and for free flooding of the rope structure if required.

Details concerning the jacket design are in 5.4.

#### 7.2.4.6 Particle Ingress Protection

If the rope is designed for seabed contact or high turbidity environments then a proven filter barrier shall be required. Filter barriers are typically achieved by either a combination of strand and rope jacketing or by implementation of a filter membrane underneath the rope jacket. The user should analyze the need to qualify the filter performance for the given rope construction including the splice and define additional testing based on installation procedures and intended use. See Annex A for a test procedure to qualify the filter.

Depending on the intended use of the rope, the minimum particle size for filtration shall be specified (see 5.4.2).

#### 7.2.4.7 Rope Marking

Appropriate permanent markings should be placed on each rope assembly. Such markings may be used to monitor twist and length during installation and operation. The specification shall include the type, location(s), and means of applying these markings.

This specification includes the following:

— color and additional description of the markings;

— axial stripe along the length of the assembly;

— markings along the length of the assembly to indicate length from a termination to facilitate installation and inspection;

— marker tape.

#### 7.2.4.8 Specialized Hardware and Features

Some other components and features which may be included in the specification include bend restrictors at terminations, fire protection or resistance, abrasion protection at terminations, special abrasion or silt protection in dip section, and flotation on part or all of the rope.

### 7.2.5 Rope Component Identification and Tracking

Rope component identification and tracking are required to facilitate inspection, maintenance, and repair throughout the life of the component. See API 2I for additional information.

Appropriate permanent markings or other identification shall be placed on each rope component, including the main rope, splice, termination hardware, H-links, etc. The specification shall include the type, location(s), and means of applying these markings.

This specification includes the following:

- — a serial number and/or a leg designation to uniquely identify the specific rope component;
- — assembly markings and diagrams;
- — a manufacturing or inspection date;
- — the name of the manufacturer;
- — the material and other characteristics of the rope or component.

## 7.3 Rope Testing

### 7.3.1 General

The following rope tests shall be conducted as appropriate to determine or demonstrate rope properties:

- — break test;
- — static load-elongation test;
- — dynamic (low frequency and wave frequency) load-elongation test;
- — tension-tension fatigue qualification test.

The following rope tests shall be conducted to demonstrate rope properties when this information is required for the rope design:

- — torque and rotation test;
- — axial compression fatigue test;
- — creep and delayed elastic stretch and recovery test.

For large fiber mooring ropes made from a number of parallel subropes, testing may be performed on multiple subropes, instead of testing the full rope, for the following properties:

- — static load-elongation test;
- — dynamic (low frequency and wave frequency) load-elongation test;

— creep and delayed elastic stretch and recovery test.

The duration of the creep and delayed elastic stretch and recovery tests is long. This test shall be performed for new rope fibers or constructions. The manufacturer shall provide the test results to purchasers of that rope type.

### 7.3.2 General Testing Practice

#### 7.3.2.1 General

Rope testing shall be conducted according to Annex A through Annex F or equivalent rope testing practices, for example as specified by an RCS or ISO. Typically prototype rope tests are performed prior to production. Portions of the testing may be conducted during production for quality assurance purposes.

#### 7.3.2.2 Test Sample Length

The test sample for all tests should have sufficient free-span between the rope terminations to ensure that the test sample is representative of the actual installed rope.

NOTE There are limitations to existing test facilities that can dictate the maximum test sample length. The present available test machines have useable bed length limitations; consequently, for large diameter ropes, subrope testing may be a preferred method for some properties.

When ropes are recovered from service for testing, it is permissible to shorten the rope for testing by making one new splice termination to achieve the proper test specimen length, providing that one termination is original.

#### 7.3.2.3 Wet or Dry Testing

Where rope properties differ depending on whether the rope is wet or dry, the rope shall be tested wet. The properties of nylon rope are known to be affected by wetting. Some marine finishes, splices, friction in the splices, and friction in the rope can also be affected by wetting. Wetting can be used to prevent the rope from overheating during cyclic testing.

Wetting the rope may involve submergence of the rope in water during testing, or the wetting of the rope, with sprinkler or soaker hoses during testing. Soaking of the rope overnight prior to testing may be adequate provided that, during testing, the rope does not dry out and its internal temperature does not increase to unacceptable levels.

#### 7.3.2.4 Reference Tension

A uniform reference tension shall be applied in accordance with 7.2.4.3 as part of the tests involving length measurements.

#### 7.3.2.5 Bedding-in

A few load cycles shall be applied before conducting break tests to bed-in the rope structure and stabilize the splices.

#### 7.3.2.6 Machine Accuracy

The test machine should be calibrated to provide at least ±1 % accuracy of the estimated break strength of the sample. The gauge length should be of adequate length after consideration is made of the elongation measurement accuracy. A minimum of ±10 % accuracy on the elongation measurement should be used in accordance with CI 1500.

### 7.3.3 Break Strength Test

All tests shall be carried out using the same loading procedures to maintain consistency. This includes any cycling procedures and load ranges. It has been observed that average break strength generally increases while statistical scatter decreases due to the application of load cycles. This is due to the setting-in of splices, and the fibers becoming more orientated into the direction of load [14].

Test sample preparation and procedures shall be in accordance with Annex E, or equivalent.

### 7.3.4 Load-elongation Test

These tests shall be performed to determine the permanent elongation, static and dynamic load-elongation properties, and any other related properties of the fiber rope that are required by the mooring designer (e.g. for operational purposes). The mean loads and cycling amplitudes should be representative of the actual loads anticipated in situ. The number of cycles and frequency over which the dynamic modulus is measured shall also be documented. Sample preparation and test procedures shall be in accordance with Annex B, or equivalent.

Creep tests shall be performed for ropes made from fibers that are susceptible to creep rupture to determine the likely creep elongation during the lifetime of the unit and the creep rupture resistance of the rope. Sample preparation and test procedures shall be in accordance with Annex B, or equivalent.

### 7.3.5 Tension-tension Fatigue Qualification Test

As indicated in 5.6.6.3 and 7.2.2.4, for rope types for which no fatigue data exist, qualification testing shall be performed. When fatigue qualification testing is required, at least one fatigue qualification test shall be carried out to demonstrate that the fiber rope has at least equivalent fatigue resistance represented by the selected design curve. Specifications for the qualification test are listed in Table 4. However, regardless of the tension range used in the qualification test, the test shall continue for a minimum of 5500 cycles. As an example, if the sample is tested with a tension range of 50 % of RBS for 5500 cycles, then the spiral strand fatigue curve given in API 2SK for mean load of 30 % of RBS should be used in the fatigue analysis, as indicated in Table 4.

The test sample shall have the same rope construction, fiber material, splice design and thimble as the production rope and have a minimum RBS scale of 50 %. Sample preparation and test procedures shall be in accordance with Annex D, or equivalent.

**Table 4—Fiber Rope Fatigue Curve Qualification Test Cycles**

| Tension-Tension Fatigue Loading | | | | Cycles for API 2SK TN Curves | | | | Six-times Spiral | Polyester Durability JIP 10-tonne Failures (28) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Range $R$ | Mean | Min. | Max. | Studless | Studlink | IWRC Wire | SS Wire | 6 × SS Wire | Mean - 2σ | Mean |
| Load Range/RBS | | | | $N = K/R^m$ | | | | $N = K/R^m$ | | |
| 0.30 | 0.20 | 0.05 | 0.35 | 11,712 | 37,037 | 31,738 | 72,701 | 436,203 | 14,594,960 | 32,202,782 |
| 0.40 | 0.25 | 0.05 | 0.45 | 4941 | 15,625 | 9785 | 17,006 | 102,035 | 3,377,144 | 7,451,438 |
| 0.50 | 0.30 | 0.05 | 0.55 | 2530 | 8000 | 3928 | 5511 | 33,064 | 1,085,172 | 2,394,358 |

#### 7.3.6 Torque and Rotation Tests

Where torque and rotation properties are of concern, rope torque tests shall be conducted in accordance with Annex C, or equivalent.

Rope/Splice torque compatibility shall be established for ropes where torque and rotation characteristics of the splice are different from those of the rope itself, and in applications where such differences can have an impact on the performance of the rope or splice.

NOTE The fatigue tests will provide insight on the performance of the splice integrity under cyclic loading.

#### 7.3.7 Axial Compression Fatigue Test

Where axial compression fatigue damage is of concern, axial compression fatigue testing shall be performed to demonstrate that the synthetic rope does not lose significant strength when allowed to relax in service, and may be used as evidence that the rope can tolerate axial compression fatigue criteria less strict than those indicated in 6.3.2. Test sample preparation and test procedures shall be performed in accordance with Annex F, or equivalent.

The test shall be performed for aramid mooring lines.

#### 7.3.8 Scaling of Rope Test Data

Break strength tests shall be performed on full scale ropes and terminations. For other rope tests, full scale, scaled rope, or subrope testing may be used.

For scaled rope testing, the test results may be interpolated or extrapolated from ropes made of the same material, construction and termination. Due to differences in rope construction, the manufacturer should provide guidance for details of the scaled rope used in testing. In no case shall the RBS of a scaled rope be less than half or more than twice that of the production rope’s CBS.

Subropes for testing shall be of the same size, material, and construction as the production subropes. When subrope testing is used rather than full rope testing, the rope manufacturer should demonstrate, by test, the scaling from subrope loads to full rope loads. Depending on subrope splicing and the fitting of those splices into the full rope splice, the full rope CBS could be approximately 10 % less than the sum of the subrope RBSs.

## 8 Rope Manufacture, Inspection, and Quality Assurance

### 8.1 General

A rope product shall meet the requirements of the rope specification as called for in 7.2. A quality assurance (QA) plan, as described in 8.7, shall be written prior to manufacturing prototype ropes. This QA program shall be followed when manufacturing both prototype and production ropes.

Information on the rope manufacturing, inspection and quality assurance will be included in the rope production report. This can include; yarn assembly checklist, strand assembly checklist and termination specification.

### 8.2 Rope Fiber Material

#### 8.2.1 General

The following procedures shall be followed to ensure that the fiber material used in making the mooring rope is within stated tolerances of the fiber material used in making the prototype test ropes.

### 8.2.2 Material Certification

The fiber producer shall certify and document the following properties of the yarn:

- fiber type and grade;
- finish designation;
- merge number and other pertinent identifying information;
- yarn size (linear density);
- dry break strength;
- dry elongation to break;
- wet break strength (nylon only);
- wet elongation to break (nylon only);
- dry creep;
- wet creep (nylon only);
- finish level;
- wet yarn-on-yarn abrasion property.

The fiber producer shall conduct suitable tests to verify these properties for the particular grade, type, and designation of fiber and finish.

### 8.2.3 Material Quality Testing

#### 8.2.3.1 General

Either the fiber producer or the rope manufacturer shall conduct the following tests to demonstrate the associated yarn properties:

- yarn size (linear density);
- dry break strength;
- dry elongation to break;
- wet yarn-on-yarn abrasion property;
- twist level.

#### 8.2.3.2 Responsibility for Material Quality Testing

If the fiber producer is ISO 9000 qualified, these tests may be conducted by that fiber producer, either as the yarn is produced, or as it is prepared for shipment to the rope manufacturer. Otherwise the rope manufacturer shall conduct these tests on representative samples removed at random from yarn shipments as received from the fiber producer.

#### 8.2.3.3 Frequency of Material Quality Testing

At least one yarn package of each twist shall be taken at random from each 20,000 kg (45,000 lb) of yarn twisted or container delivered. A minimum of five samples of each twist shall be tested for dry break strength, and dry elongation at break.

At least four yarn samples shall be taken from each package used for the break tests and tested for linear density, twist level, and wet yarn-on-yarn abrasion as described below.

Wet yarn-on-yarn abrasion testing shall be done in accordance with CI 1503 except that only four samples need to be tested and at only one applied tension. The applied tension should be chosen such that the average duration of each test is approximately 5000 cycles. ISO 18692 provides additional guidance on load levels for polyester yarns.

### 8.2.4 Material Storage and Handling

All materials to be used in manufacturing the rope shall be identified and controlled while in storage, transit, and during the manufacturing process.

Each fiber material package and each container of fiber material packages shall be distinctly labeled with the identity of the fiber material.

Once the fiber material enters the rope manufacturing process, each material container or major package shall be tracked whenever it moves to another manufacturing step.

## 8.3 Rope Manufacturing

The rope manufacturer shall prepare a manufacturing specification that completely describes the rope construction and parameters and the steps and processes used in making the rope.

This manufacturing specification should be at least as complete as that described in the OCIMF Hawser Guidelines [15], including quality control checklists.

This manufacturing specification should be reviewed and approved by an RCS at the time prototype ropes are manufactured or prior to the beginning of manufacturing ropes to a production order.

During manufacturing of both prototype ropes and production ropes to an order, the manufacturer shall completely follow the manufacturing specification for the particular rope design. Any deviations from the manufacturing specification shall be brought to the attention of the purchaser, the inspector and, if applicable, the classification society and the regulatory authority.

## 8.4 Termination

The rope manufacturer shall prepare a termination specification which completely describes the rope construction and parameters and the steps and processes used in making the rope termination.

This termination specification should be at least as complete as that described in the OCIMF Hawser Guidelines [15], including quality control checklists.

This termination specification should be reviewed and approved by an RCS at the time prototype ropes are manufactured or prior to the beginning of manufacturing ropes to a production order.

During termination of both prototype ropes and production ropes to an order, the manufacturer shall completely follow the termination specification for the particular type of termination. Any deviations from the termination specification shall be brought to the attention of the purchaser, the inspector, and, if applicable, the classification society and the regulatory authority.

## 8.5 Assembly

The rope manufacturer shall assemble the rope in accordance with the purchaser's specifications and instruction, and provide the details as called for in 7.2.

## 8.6 Inspection

### 8.6.1 Introduction

An inspector who is knowledgeable of rope design, manufacturing processes and termination procedures shall be employed to conduct the rope inspection. This inspector may be a representative from the RCS or the purchaser.

The rope manufacturer shall prepare appropriate inspection checklists and report forms. These items should be at least as comprehensive as those given in the OCIMF Hawser Guidelines [15].

### 8.6.2 Review of Rope Documentation

The inspector shall have access to all relevant rope documentation.

### 8.6.3 Inspection During Production

The inspector shall have access to the rope making and assembling facilities at any time while rope production and assembly are in process. This includes access to operations of assembling yarns, assembling strands, making ropes, terminating ropes, and testing materials.

The inspector shall endorse the inspection checklist for each rope inspected. This document shall be made a part of the quality control report and maintained by the rope manufacturer.

### 8.6.4 Selection of Sample Rope Section

One sample rope section with an approximate length of 2 m (6.6 ft) shall be taken from each continuous length of rope, or from one of the cut points if that continuous length is to be cut into shorter lengths before splicing. The rope section should be cut squarely at the ends and secured with adhesive tape to prevent unraveling.

### 8.6.5 Inspection of Sample Rope Section

The two-meter sample rope section should be measured and weighed to an accuracy of ±0.1 % and the weight divided by the length to determine the weight per unit length.

The non-load bearing outer jacket and particle barrier of the sample should be carefully removed and the weighing operation repeated to determine the weight per unit length of the load-bearing core.

The total number of strands in the load-bearing core shall be verified by counting and recorded. The numbers and dispositions of the strands shall be the same as given in the manufacturing specification. Extra colored marker strands are not counted.

The inspector shall examine the material and construction of the rope, and assure that the numbers and arrangements of yarns and strands comply with the manufacturing specification.

The rope manufacturer, in the presence of the inspector, shall conduct testing to confirm the fiber material used in producing the rope. The Fiber Material Identification Tests given in the OCIMF Hawser Guidelines [15] or other suitable test methods should be used.

The inspector shall examine all identification marks to ensure they comply with 7.2.4.7.

### 8.6.6 Determination of Rope Strength

During prototype rope manufacturing and testing, the rope strength factor (the ratio of rope break strength to aggregate yarn strength) should be determined using the procedures given in the OCIMF Hawser Guidelines [15]. These tests and calculations shall be witnessed and certified by the inspector.

During rope manufacturing, the inspector shall witness removal of samples of fiber material from the sample rope sections, subropes, or the full scale production ropes for strength testing using the same procedures as were used with the prototype rope. These samples shall be tested in the presence of the inspector. The calculated production rope strength shall be documented using the same procedures as used for the prototype rope and using the rope strength factor that was determined for the prototype rope.

### 8.6.7 Inspection of Rope Termination

The selection of terminations for inspection shall be at the discretion of the inspector. At least one termination assembly or application shall be witnessed by the inspector for each rope design and termination type.

The inspector shall examine the selected termination in detail, making reference to the termination procedure given in the termination specification and to the completed quality control checklists, to assure that it is in compliance.

### 8.6.8 Inspection of Finished Rope Assembly

The inspector shall thoroughly inspect the assembled rope, after application of terminations and as appropriate before or after the application of any other appliances and accessories.

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

## 8.7 Quality Control and Assurance

### 8.7.1 Introduction

Appropriate quality assurance procedures are necessary to demonstrate that fiber rope assemblies manufactured for a specific order have the same qualities as the prototypes and have the same properties without requiring further prototype testing.

### 8.7.2 Quality Assurance Plan

The rope manufacturer shall prepare a quality assurance plan which completely and accurately describes the quality control and assurance program used in manufacturing the rope.

### 8.7.3 Quality Assurance Supervisor

The rope manufacturer shall designate a quality assurance supervisor. The quality assurance supervisor and any deputies should not be under the authority or control of the manufacturing, purchasing, or sales branches of the rope manufacturer’s company organization. The quality assurance supervisor and any deputies shall have the authority to stop rope production when quality assurance is less stringent than the documented procedures or when quality deviates from the specified values or tolerances.

### 8.7.4 Quality Control Checklists

The rope manufacturer shall prepare quality control checklists for the processes of yarn assembly, strand assembly, rope making, rope jacketing, splicing, potted socket application, wedge socket application, bend restrictor application, and other processes as applicable. Copies of the checklists should be posted at each location where the work is to be performed. The checklists shall be followed and completed by each assembler during the respective step of the assembly process for each rope segment.

#### 8.7.5 Quality Control Report

The rope manufacturer shall prepare a quality control report that includes the required quality control checklists for the production and assembly of that rope. This report shall also include the material certificates, material and yarn test results, and rope inspection and test reports, as applicable.

The quality control report should be maintained for a minimum period of five years or longer, as appropriate.

# 9 Rope Storage, Handling and Installation

## 9.1 General

This section provides guidance for the development of specifications and procedures for handling, installation and recovery (if applicable) of synthetic fiber ropes. General requirements are given regarding the contents of specifications, procedures, and general considerations are given concerning handling of fiber ropes, emplacement of anchors, installation of mooring lines, hook-up of mooring lines to the floating platform, and tensioning and testing of the lines of the mooring system.

## 9.2 Storage, Handling, and Installation Specifications

Care should be taken in selection of packing, shipping, and storage systems for synthetic fiber ropes. The designer of such systems should be mindful of the manufacturing process, onshore and offshore transportation and handling, yard storage and staging, installation, and recovery (if applicable). A detailed specification shall be developed, which includes the following items as a minimum:

— lifting requirements;

— spooling requirements;

— transportation requirements;

— installation requirements;

— storage requirements.

The requirements shall be in accordance with the manufacturer's recommendations, the rope design, installation and vessel contractor's procedures, and properties as outlined in Section 5. In conjunction with the requirements in this section, additional considerations are given in 9.3.

Particular packing, shipping, and handling procedures shall be included in the specification.

Details concerning limitations on handling procedures (e.g. limiting local and global pressures on rope), minimum bending radii (e.g. for spooling, etc.), shall be specified. For extremely long lengths of rope with large diameters, it may be necessary to utilize cable laying techniques and for the rope to be laid into special storage tanks on a dedicated vessel.

In most situations, the rope assemblies are supplied on reels. Logistics, installation techniques, or economics may determine the specification of installation and/or transportation reels.

## 9.3 Storage, Handling, and Installation Considerations

### 9.3.1 Reels

The basic functions of fiber rope reels include storage, transportation, and installation. The designer should consider which functions the reels serve. Reels may be designed to perform any or all of these functions.

Transportation reels are typically used only for storage and transportation, the rope subsequently being rewound onto a more substantial reel for installation. In this case, consideration should be given to the reel dimensions to suit the rewinding operation.

Installation reels may be taken directly from the production facility to the installation vessel and used for deployment. In this case, dimensions of the reel and its strength and the winding tensions should be carefully designed to ensure a trouble free installation.

Each reel shall be clearly labeled to identify the contents and provide traceability.

If the rope is shipped or stored on a reel, the finished package should be securely wrapped with weather proof material.

Reels shall be designed for the expected service, including as applicable but not limited to the following:

- weight and volume of rope;
- minimum bending radius requirements;
- end terminations;
- lifting, both onshore and offshore;
- ground and marine transportation limitations (size, weight, etc.);
- accelerations due to ground transportation;
- accelerations due to vessel motions, both coastal and offshore;
- seafastening arrangements, both coastal and offshore;
- spooling loads;
- spooling equipment compatibility;
- installation loads;
- installation equipment.

Reels may be constructed with two compartments; the larger compartment to hold the major component of the rope length, the smaller one to hold the two ends of the rope complete with terminations. The reel shall be large enough to accommodate the complete assembly without any portion protruding above a flange.

Suitable means for lifting shall be provided, which prevents damage to the rope and reel during handling. Figure 5 shows an example of a suitable lifting arrangement using lifting lugs and a spreader bar.

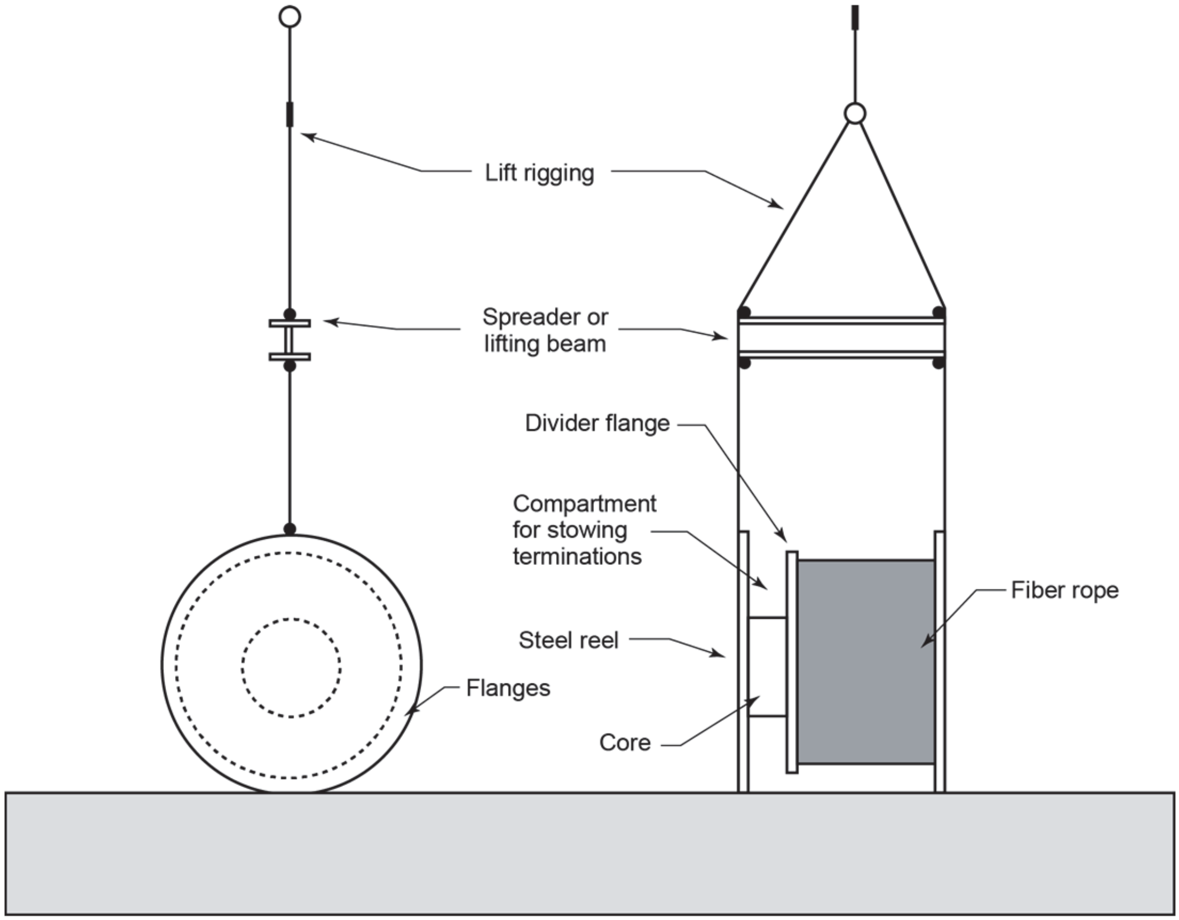


**Figure 5—Typical Reel and Lifting Arrangement**

### 9.3.2 Chemical and UV Radiation Damage

Fiber ropes should be protected from the effects of chemical and UV radiation damage during storage, transportation, and installation.

Table 5 provides generic information regarding typical resistance levels of rope materials to chemical and UV radiation damage (see CI 2003). The designer should obtain detailed information from the rope manufacturer as required for the planned application.

**Table 5—Resistance to Chemical and UV Radiation Damage**

| Damage Type | Polyester | Aramid | HMPE | Nylon | Steel (for comparison) |
|---|---|---|---|---|---|
| Chemicals | Good[a] | Good[a] | Excellent | Good[a] | Varies[b] |
| UV radiation[c] | Good | Fair | Fair | Good | Excellent |

[a] Attacked by strong alkalis and acids.

[b] Corroded by water, acids, etc.

[c] Protective coatings and jackets can reduce the harmful effects of UV radiation on ropes manufactured with synthetic fibers (CI 2003).

### 9.3.3 End Fittings

Connecting hardware that has sharp and/or protruding edges should be avoided when ropes are stored and/or wrapped onto a reel. If this is not possible, adequate protection shall be provided to prevent chafing of the ropes on the reels. Metal end fittings shall be individually wrapped or otherwise kept separate (packaged separately) to prevent chafing of any underlying fiber rope.

Terminations complicate the storage and handling of the terminated ends of the line. Care should be taken to ensure that excessive bending is not applied to the fiber rope or termination during installation, which might cause damage to fibers or disturb the splice.

### 9.3.4 Rope Twisting

The maximum twist in-place shall not exceed the manufacturer’s limits based on torque tests as described in 7.3.6. Markings along the rope may be used to assist in monitoring the twist of the line.

Twisting of fiber rope can be induced by:

— spooling between reels;

— deployment;

— recovery of pre-laid mooring lines from the seabed;

— connection of preset moorings to a surface buoy; and

— mismatch of torque characteristics between work lines and the fiber rope.

Twist can be induced into components and then transferred between them during installation procedures. This twist can cause operational problems and should be avoided. Work lines of a non-torque balanced type (e.g. six strand wires) should not be used with torque neutral fiber rope, unless consideration has been made for the effect of any twist induced into the installed mooring components.

### 9.3.5 Bending Radius

The minimum bending radius (MBR) is a function of the tension in the rope. The minimum bending radius quoted for installation or maximum design conditions are generally not the same as that for storage conditions, since these bending radii are associated with different mean and dynamic tensions. The rope manufacturer shall establish the limits of drum diameter to rope diameter ratios for installation and handling, taking into account the associated working tensions of the mooring line, as indicated in 5.4.4.

In general, fiber ropes for permanent or temporary moorings should not be installed around bollards or fairleads unless their performance has been proven to be satisfactory. This is due to the limited knowledge of their long term behavior under fatigue tension and bending and the potential for significant wear and internal fiber damage that can occur in the length of rope in contact with the bollard or fairlead.

During deployment, rope assemblies need to be stored and reeled around drums, fairleads, and rollers. Failure of the external rope sheath (particularly the extruded polymer type) can result in a local bending stiffness discontinuity. Adequate steps should be taken in the design and installation to avoid this type of damage.

### 9.3.6 Cutting and Abrasion

Handling equipment should be designed to not induce excessive bending, chaffing, wear, cutting, etc. Any restrictions concerning the use of clamping devices or other stopping devices in the deployment of fiber ropes should be established.

Care should be taken when applying shearing forces to fiber ropes. Shear can be induced by friction as the rope runs over a bollard, or when gripping the rope to apply tension. Shearing loads can result in damage to the rope jacket or core.

#### 9.3.7 Heat Damage

The fiber maximum working temperature should not be exceeded, as indicated in 5.6.5. In this respect, ropes should not be located near heat sources caused by welding, steam pipes, engine exhausts, heaters, etc. Heat build-up from frictional effects during deployment and re-spooling should be monitored and cooling methods such as water spray should be considered. Heat build-up can also be more severe if fiber ropes are running over surfaces which naturally provide insulation.

#### 9.3.8 Foreign Particles

Foreign particles such as blasting grit, sand, etc. should be prevented from coming into contact with the ropes, as noted in 5.4.2. When the installation work is excessively delayed due to weather or other reasons, protective covers should be provided to protect the rope from foreign matter and potential UV radiation damage.

See 9.4.3 for special requirements for ropes deployed on the seabed.

#### 9.3.9 Wire Rope/Synthetic Rope Mix on Drums

During spooling and re-spooling, mixing wire rope and synthetic rope on the same drum can result in damage due to jacket snagging, puncture through the jacket and filter barrier, or cutting. Segregation, such as dividers, or assurance, such as inspecting work wires, should be provided to prevent damage. This issue can be avoided through the use of synthetic work lines.

#### 9.3.10 Fiber Rope Weight and Volume

Fiber ropes have significantly lighter weights than steel wire rope or chain lines of equivalent strength and this feature can facilitate installation, especially in deep water. However, diameters of fiber ropes (particularly for polyester) are likely to be greater than steel wire rope of equivalent strength, which can define the maximum segment length and number of required reels. This combination can have a significant effect on transportation and installation logistics.

#### 9.3.11 Salt Crystallization

Fibers that are alternately wetted with salt water and allowed to dry out can suffer from abrasion damage from the internal formation of salt crystals. When fiber ropes are reused (e.g. temporary moorings), efforts should be made to minimize exposure to repeated handling cycles or high tension fluctuations before the rope is submerged during re-deployment and before the salt crystals dissolve. For permanent mooring systems, this damage is not a problem as the fiber rope is completely submerged throughout its life.

### 9.4 Installation Design Considerations

#### 9.4.1 Deployment

Deployment techniques for polyester rope from installation vessels may include the use of rotary, traction, capstan, or caterpillar winches or hand-over-hand methods using special grips. Interference-type stoppers (e.g. shark jaws) designed for use with steel wire rope or chain should not be used for handling fiber rope. If necessary, several links of chain or shackles may be added to the rope termination hardware and the clamp may be used on those steel components. Other handling equipment usually used for conventional steel wire or chain moorings should not be used for fiber rope unless it is shown that the equipment does not adversely affect the rope and jacket integrity.

Only a small proportion of the strength capacity of a rope can be transferred in shear by means of gripping the rope with linear winch grips or rope stoppers. Means for gripping of synthetic rope should be suitable for the stopper loads required and should be approved by the rope manufacturer. Grips, stoppers, or Chinese fingers type stoppers should only be used within the load limits established by the rope manufacturer. Grips or clamps should be free of sharp edges and exert their gripping force over a sufficient length and area of rope in accordance with the rope manufacturer's recommendations.

During deployment, consideration should be given to separating the fiber rope from the termination hardware by means of split reels or special wrapping of the hardware, as required.

Damage can occur if fiber ropes are unreeled from loosely tensioned drums with the result that the line becomes buried in the lower wraps of rope. It is possible to avoid this damage by using a proper spooling tension when loading the rope onto the deployment reel, with due consideration to the planned tension applied during deployment.

To prevent rope damage, care should be taken to minimize the time that the rope is stationary on a stern roller, deployment sheave, or overboarding fairlead, while the rope is under significant load. In case unexpected events cause rope deployment stoppage, procedures should be developed to mitigate the potential damage due to localized abrasion, bending fatigue, and heat build-up.

### 9.4.2 Minimum Tension and Maximum Allowable Low Tension Cycles

This requirement only applies to fiber ropes constructed from fibers known to be sensitive to axial compression fatigue damage, such as aramid. It is not required for polyester and HMPE.

During the installation, a minimum line tension in the synthetic fiber rope should be maintained to prevent lines from possible axial compression fatigue damage. If the installation method results in excessive number of load cycles in which the line tension goes from the installation tension to below the guideline limit provided in 6.3.2, then analysis is required to demonstrate acceptability. Activities that result in such loading include deployment of anchors and anchor proof loading. An analysis should be performed to demonstrate that the total number of load cycles below the guideline tension for both the installation phase and the remaining life time of the installation does not exceed the limiting value provided in 6.3.2 of this document.

For pre-deployed lines suspended in the water column awaiting the arrival of the platform, the environmental loads can induce small tension variations in the synthetic fiber rope. As general guidance, the minimum tension is not allowed to fall below 2 % CBS for this condition; it is recommended that the rope manufacturer be consulted to determine design criteria for axial compression fatigue damage.

### 9.4.3 Contact with Seabed During Deployment

Fiber rope may be pre-deployed prior to hook-up with the moored unit. Any installation plan involving the pre-deployment of fiber lines on the seabed shall include the following:

- site survey, including rock outcroppings and soil properties such as abrasiveness and softness;
- suitable justification through testing or otherwise that the jacket provides adequate resistance to the ingress of soil particles;
- foreign particle ingress protection at rope terminations;
- on bottom stability;
- environmental loading such as waves and current;
- rope compression fatigue, where applicable;
- rope buoyancy considerations (e.g. flooding or non-flooding rope);
- buoy (if used) structural integrity and size.

Other considerations such as the site-specific nature of marine operations and particular fiber properties should also be included.

The ingress of foreign particles such as sand has been found to affect the rope's yarn-on-yarn abrasion resistance and, hence, adversely affect the rope's strength over time. Unless it has been demonstrated through testing that the rope jacket and filter barrier (if applicable) are impermeable to damaging ingress of the silt and other particles present on and near the seabed, a rope that is dropped to the seabed should not be used until it is demonstrated that the rope has retained 90 % of the required design strength of the mooring line as detailed in API 2I.

### 9.4.4 Anchor Installation and Connection

Connection of the mooring line to the anchor may be made either on the surface or after the anchor has been installed. The ability to make a subsea connection of the line to the anchor depends on the type of connection hardware specified and the power and capability of the remotely operated vehicle (ROV).

In case the mooring line and its fiber rope segments are connected to the anchor prior to anchor deployment, care should be taken to avoid damage to the fiber rope as a result of twist or contact with adjacent equipment, other installation lines, or the seabed. Potential damage that should be avoided includes the following:

- — abrasion or fouling of the mooring line with the anchor system, anchor chain, separate anchor lowering lines and bridles, connectors, etc.;
- — twisting of the fiber rope or adjacent wire ropes due to torque mismatch between mooring line fiber rope and steel rope segments;
- — twisting of anchor due to lack of torque balance in anchor lowering lines, while simultaneously lowering the mooring line;
- — risk of the contact between fiber ropes and seabed, if the mooring line is used for the embedment of anchors and this embedment requires a low mooring line angle at the seabed.

For anchors connected to the synthetic fiber mooring lines, a length of chain or wire rope may be used to keep the fiber rope clear of the seabed and to avoid damage to the fiber rope during anchor handling on board the installation vessel. The length of this steel line segment may also depend on the selected preset or designed configuration of each mooring leg.

Fiber ropes with proven filter barriers and jackets are allowed to come into contact with the seabed. If fiber ropes are used in applications with seabed contact, they shall be specifically designed for such use. The mooring and rope designer shall address, as a minimum, the following items:

- — site survey, including rock outcroppings and soil properties such as abrasiveness and softness;
- — damage to jacket and filter barrier during installation due to abrasion with hard soils;
- — impact of cyclic motion on soil particle migration through the filter barrier;
- — on-bottom stability for ropes abandoned on the seabed prior to installation;
- — inspection issues (see API 2I).

Anchor test load requirements for permanent and temporary moorings are in API 2SK. The mooring test load for fiber ropes in mooring systems should also satisfy the need to achieve an acceptable post-installation stiffness value for the fiber ropes.

Since 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.

For temporary moorings, breaking-out of anchors such as drag embedment anchors should be monitored carefully (if fiber ropes remain attached), since there is a possibility of undesirable fiber rope loading and damage.

### 9.4.5 Snap-back Behavior

If lines fail under tension during the installation stage, there is significant potential for injury to personnel and damage to equipment as a result of rope snap-back energy. The installation phases should be planned to minimize the risk of such an incident. As a general health and safety requirement, personnel should be kept clear of lines under tension whether they be steel or synthetic.

Methods of designing against or minimizing snap-back damage include the minimizing of line tension during operations when personnel are working close to the rope, and reducing opportunities for the taut line to be abraded or touched by other items of equipment during installation particularly when under tension.

### 9.4.6 Possible Pre-deployment Techniques

#### 9.4.6.1 General

For mooring systems in which the project scheduling and/or the mooring design require the fiber ropes to be pre-deployed to await arrival of the surface vessel or platform, the installation schedule and procedures should be established to prevent the fiber ropes from being damaged or minimize the amount of time the ropes are left unattended to reduce the likelihood of damage that can occur while awaiting hook-up to the vessel or platform. The same applies to temporary moorings if the surface vessel has been disconnected and the fiber ropes are left at the location.

#### 9.4.6.2 Surface Buoyed Lines

Pre-deployed aramid mooring lines should not be left buoyed at the surface awaiting connection to a platform unless the minimum tension requirements of 6.3.2 are met. Design issues associated with the possibility of independently buoyed lines being allowed to rotate should also be considered. These requirements are intended to avoid the aramid fibers in the line undergoing compression with the possibility of axial compression fatigue damage.

Pre-deployed, surface buoyed lines that are tensioned together in groups while awaiting platform arrival may be used to keep lines in tension and avoid multi-turn twisting of mooring lines as shown in Figure 6.

Failure of the buoy or connecting hardware can result in the fiber rope being dropped in an uncontrolled fashion to the seabed, resulting in possible damage.

A bottom length of chain or wire should be provided to avoid seabed thrashing damage.

#### 9.4.6.3 Bottom Laid Lines

Fiber ropes that lie on the seabed (temporarily or permanently) require a jacket to protect them against external abrasion from the seabed and to prevent ingress of particles that can result in accelerated internal abrasion (see seabed contact criteria in 9.4.3). Particular care should be paid to the design of the jacket at the termination to prevent soil ingress at the end of the rope; if the jacket does not flood, the implications for jacket and filter integrity, submerged weight, and cooling of the fibers should be considered.

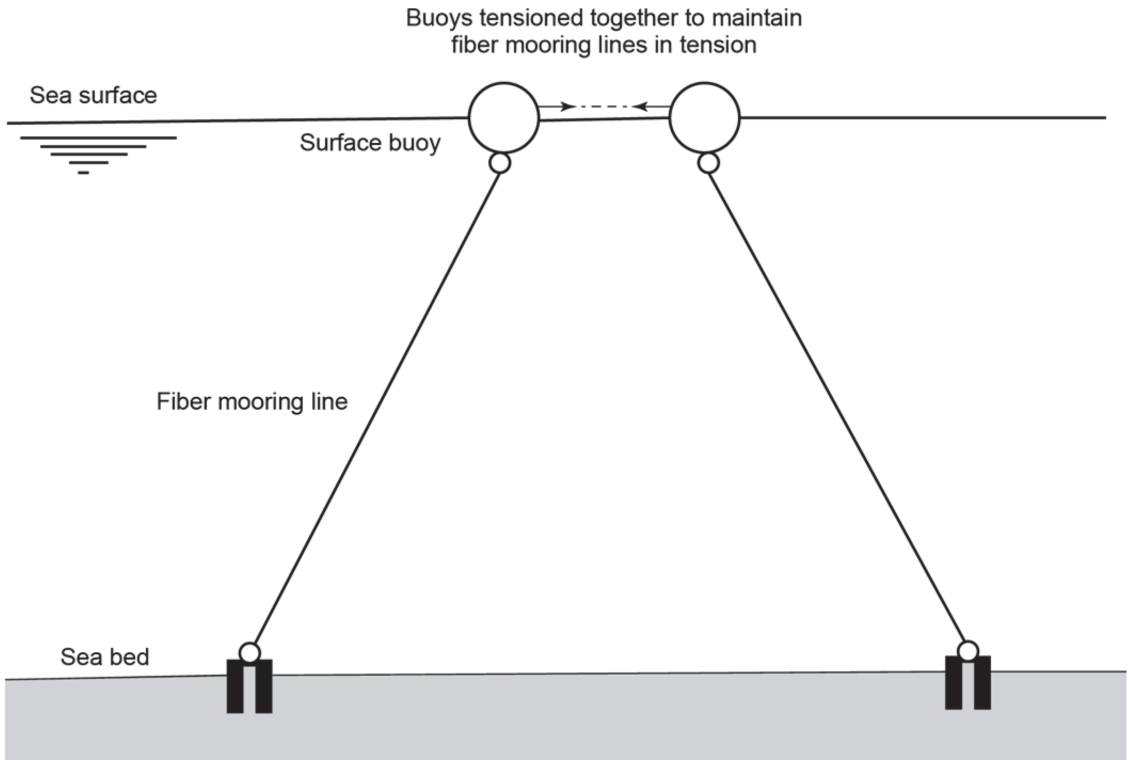


**Figure 6—Surface Buoys Tensioned Together to Maintain Fiber Rope in Tension**

Following careful study, lines may be laid on the seabed to await arrival of the platform. The ends of the line should be weighted to keep them firmly on the seabed and the actual weight of the fiber rope in water should be carefully considered in evaluating the on-bottom stability of ropes under the effects of seabed currents. HMPE fibers, which are positively buoyant, may be suitable for this form of deployment if fitted with a suitably heavy jacket. Alternatively, the buoyancy of such lines may allow them to be pre-deployed as a reverse catenary, but in this case the design of the rope should consider abrasion damage at the touch down locations.

The recovery line required at the top end of the laid down mooring should be suitably designed to prevent it from dragging over and damaging the fiber rope. This may require additional clump weights on the pre-deployed line. Alternately, a buoyant sling may be used in place of a recovery line.

#### 9.4.6.4 Mid Span Suspended Lines

Lines may be pre-deployed so that they are suspended along their length clear of the seabed but below wave action. In this arrangement the suspended line shall be capable of surviving movement due to current. For aramid mooring ropes, the suspension buoy shall be large enough to maintain sufficient tension in the line to prevent fiber axial compression fatigue damage (see minimum tension requirements of 6.3.2). The suspension buoy should also hold the end terminations clear of the seabed. For fiber ropes that are positively buoyant, a mid-length buoy may not be required.

For most synthetic ropes, this method requires a mid-length buoy designed to withstand significant hydrostatic pressure. Installation of this buoy is an added complication during deployment. Failure of the buoy or connecting hardware could result in the fiber rope being dropped in an uncontrolled fashion to the seabed with attendant concerns about what, if any, damage it would sustain.

## 9.5 Installation/Recovery Procedures

### 9.5.1 General

Complete and detailed procedures shall be developed for the installation and recovery (where applicable) of moorings incorporating synthetic rope segments. These procedures shall define in adequate detail the vessels and equipment to be used for the work and the methods for handling rope segments to prevent rope damage and maintain control of the rope. The procedures shall be in compliance with the rope manufacturer's requirements for handling and loading of the synthetic ropes, and the manufacturer's stated limitations for rope handling shall be defined in the procedures. If special rope jacketing or soil filter is used, conditions for allowable seabed contact shall be provided in the mooring system specifications and installation procedures.

### 9.5.2 Installation Planning

During the installation planning, procedures to cover the shipping and handling activities shall be developed as follows.

a) Details of rope shipping, shipping reels, rope protection, shipping reel handling, lifting, storage, etc. shall be included. If the shipping reels are to be used during installation and/or recovery, their design shall be adequate for the intended offshore operation. Standard shipping reels can be inadequate for some operations and thus require reinforcement or modification. Any modification to the reels shall be performed prior to spooling rope onto the reel.

b) If synthetic ropes are to be re-spooled from shipping reels to installation machinery, either at a port facility or on board an installation vessel, the procedures for re-spooling shall be developed to ensure that these operations are safe, and that the equipment used for re-spooling is adequate and properly tested.

### 9.5.3 Installation Operations

Installation operations depend upon the mooring system being installed, the available installation equipment, prevailing weather and site conditions. Detailed offshore installation or recovery procedures shall include the following elements.

a) Arrangement of installation machinery/equipment on board the vessel(s) in the installation spread.

b) Stability assessment of the vessel(s) and recommended loading conditions to maintain vessel stability and minimize motions (if applicable).

c) Sea-fastenings/tie-downs of installation machinery and equipment, including synthetic rope reels. If this equipment is not part of the normal vessel's equipment, and is installed specifically for the operations, special attention should be paid to the design and fabrication of equipment tie-downs, and equipment power supply and control systems. Equipment tie-downs shall be adequate for design storm conditions offshore in standby mode. The design limits of the installation machinery, equipment, and tie-downs on board the vessel(s) shall be specified, and procedures developed for timely transit to safe haven, if limiting metocean conditions are predicted.

d) Procedures for the deployment of anchors. These procedures are intended to prevent damage to any mooring leg components and minimize the risk of entanglement between synthetic rope segments and steel mooring line components or any separate anchor deployment lines. If the anchor is lowered on a separate deployment line, there should be adequate separation between this deployment line and the mooring leg being deployed, to prevent such entanglement and prevent spinning of the anchor during deployment/recovery.

e) Procedures for the deployment of the mooring leg components, whether steel or synthetic, including details of the equipment to be used for the deployment/recovery of all components, and details of vessel position, heading, movement, etc.

The procedures should ensure that the synthetic rope sections can be safely deployed/recovered by the proposed equipment, without damage to the rope and its terminations. Testing of the synthetic rope handling/installation equipment may be used to demonstrate the safety of the operations.

Typically, mooring lines with synthetic rope segments do not lend themselves well for deployment from the MODU or FPS vessel. Therefore these systems are expected to be pre-deployed or deployed via separate installation vessel(s). The pre-installed configuration of the mooring system should be carefully considered, and fully detailed, to minimize damage to the system while left unattended. To minimize axial compression fatigue damage on aramid ropes, special arrangements may be used either to ensure the minimum tension applicable for the type of synthetic rope or to limit or minimize load cycling at low tensions.

If surface buoys are used to support the preset mooring legs, they shall be suitably marked to minimize the risk that such buoys are damaged by vessel traffic, which can result in synthetic line segments dropping on the seabed. If this is considered a serious risk, the manner in which the mooring legs are left at location may have to be modified, or a vessel may have to be stationed in the field to warn oncoming traffic.

Detailed procedures for installation tensioning of the mooring lines and anchors shall be developed. Such loading may be performed during pre-deployment of the moorings just prior to or after hook-up.

Detailed procedures for the connection and disconnection (if applicable) of the vessel to the pre-deployed synthetic mooring system shall be developed. These procedures shall detail the type of installation vessel, special equipment required, towing procedures, towing vessel requirements and connection sequence.

If there is a significant risk that synthetic rope segments and other mooring line segments can be damaged during installation and/or hook-up, suitable spare components, repair kits, and service personnel should be available to repair or replace damaged mooring line components or equipment.

Suitable means for stopping off synthetic ropes shall be defined, and tested if required. Typical means of stopping off steel lines, such as shark jaws, pelican hooks, carpenter stops, linear winch grippers, etc. are generally not suitable for direct contact with synthetic ropes. Stoppering off synthetic ropes on suitably designed termination hardware may be safely accomplished using standard installation equipment.

### 9.5.4 Contingency and Inspection Plans

The procedures should include a list of plausible failure scenarios and their consequences. Contingency plans should be developed to mitigate or minimize these consequences.

Load testing of special installation equipment may be used to demonstrate that the equipment can handle its maximum loading in normal and contingency conditions. Detailed inspection of the equipment after load testing shall be carried out to ensure that the load test has not initiated any cracking or failure of the equipment and its tie-downs.

Installation/recovery equipment shall be inspected prior to offshore operations. If the installation / recovery equipment is used on a regular basis, regular inspections of the equipment shall be performed to ensure its integrity. Hydraulic systems, winch brakes, instrumentation, etc. should be tested to ensure the equipment is functioning properly and loads are monitored and controlled.

Procedures for the inspection of ropes, guidelines for rope acceptance/rejection, requirements for testing, and procedures for offshore repair and/or onshore repair shall be developed in accordance with API 2I and in collaboration with the rope manufacturer. If the mooring ropes are recovered and intended to be re-used, the synthetic mooring rope segments shall be carefully inspected to determine whether they are suitable for re-use. Such inspections may be performed offshore during recovery or in port (see API 2I).

# 10 In-service Inspection and Maintenance

## 10.1 General

A plan for the fiber rope inspection, maintenance, and condition assessment shall be developed as per API 2I. This plan should be developed by the operator of the mooring system and the manufacturer of the rope in conjunction with the certifying authority to provide consistency with the overall safety assessment for a given installation.

Guidance on inspection and reuse of fiber ropes for MODU moorings exposed to tropical cyclones is in API 2I.

## 10.2 Destructive Inspection of Inserts

As outlined in API 2I, the use of fiber rope test inserts for subsequent rope inspection is not generally recommended for permanent or temporary moorings. Industry experience with fiber rope test inserts indicates the information gained from the testing of test inserts has been of limited benefit [16] [17].

## 10.3 Operations

During operations, mooring line tensions or geometry should be monitored regularly, and the mooring lines should be adjusted, if needed to maintain stationkeeping performance.

# Annex A
(normative)

# Filter Barrier Particle Ingress Test

## A.1 General

Generally, particle filtering is achieved through the use of strand jacketing or filter cloths. This test addresses both strand jacketing and filter cloths and may be used for either.

## A.2 Test Specimen

At least one specimen shall be tested.

Preparation of the specimen should be as follows.

1) The specimen should comprise a typical fiber rope with a length of at least five times the diameter of the rope. If full-scale rope cannot be tested in the chamber, a scaled rope no less than half the diameter may be used.

2) The circumferential surface of the specimen shall be completely covered by the filter barrier material, applied in the same manner, and no thicker than used on the production ropes. The circumferential surface of the specimen shall then be covered by a jacket, applied in the same manner and no thicker than used on the production ropes.

3) The ends of the specimen shall be sealed with a waterproof compound or with a watertight cap.

4) For ropes designed for in-service contact with the seabed, the sample preparation should be modified as follows. The filter should be tested in the condition that is representative of the service conditions. The sample used for the filter test should be pre-stretched to a tension level equal to or exceeding the expected service tension.

## A.3 Test Procedure

A sample test procedure follows.

1) The specimen shall be placed in a hyperbaric chamber and totally immersed in water.

2) After immersing the specimen, it shall be kept at atmospheric pressure for 60 minutes.

3) Soil shall then be added to the water at a proportion of 25 % of water weight. The soil shall meet or exceed the grading shown in Figure A.1 (i.e., the soil may have a greater percentage of silt particles > 20µ).

4) Pressure shall then be increased to 10 Mpa, and shall be maintained for 72 hours. During this period the soil shall be agitated so that it is kept suspended in the water and not allowed to settle.

5) Pressure shall then be released and the specimen shall be removed from the chamber.

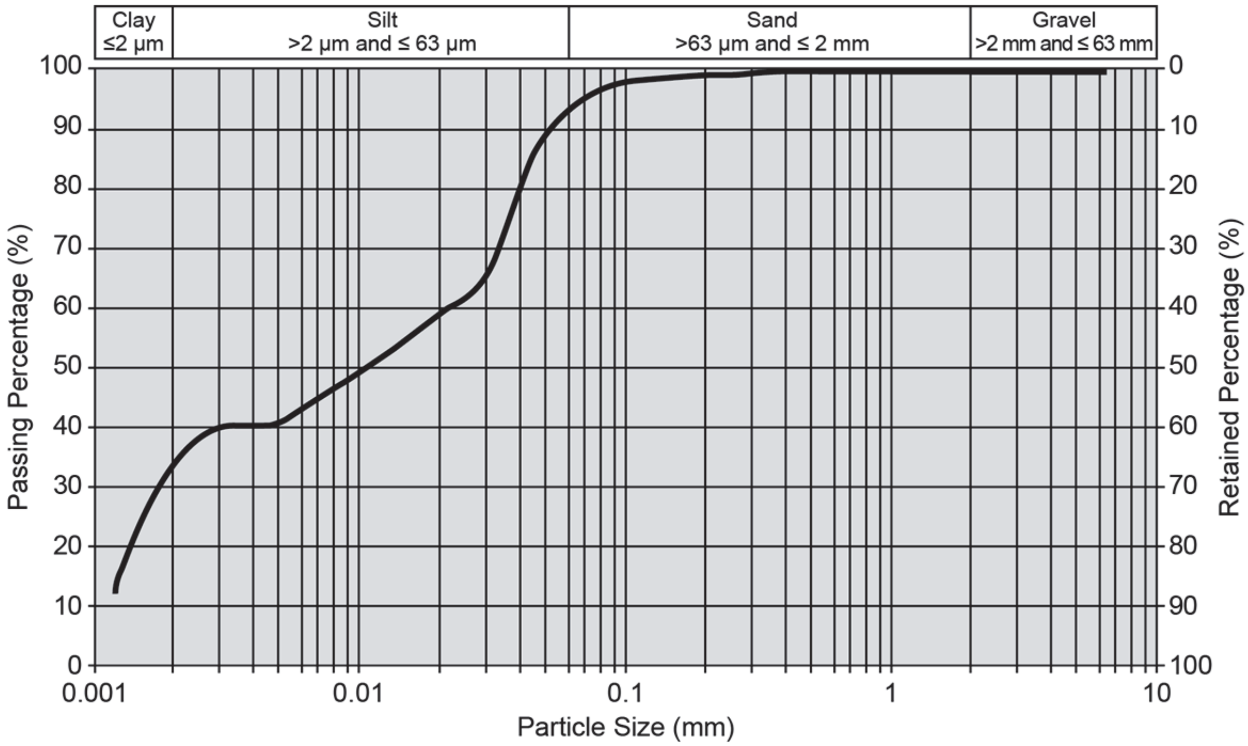


**Figure A.1—Grading of Sand for Particle Ingress Resistance Test**

## A.4 Rope Post Test Examination

a) After the test, the specimen shall be examined as follows.

b) The specimen shall be carefully dissected, to remove the jacket and the filter barrier. Photographic records of the dissection process should be taken.

c) Samples from yarns on the surface of the load bearing cores of the rope shall be examined under a Scanning Electron Microscope (SEM) to detect the presence of soil particles.

d) The presence of soil particles greater than 20 µ (microns), or as agreed between involved parties, shall be recorded. It may be of interest to record how many particles of a given size range are observed on the yarn sample.

## A.5 Data Reporting

All post-test examination results shall be reported.

# Annex B
(normative)

# Testing of Rope Load-elongation Properties

## B.1 Background

Since the original version of API 2SM was published, the industry has learned much about synthetic rope load-elongation properties and how these properties are used in mooring analysis software and in the design of offshore mooring systems. It is important to understand the system and application for which a synthetic rope is being designed so that an adequate and appropriate test can be defined. The fiber type, rope construction, installation method and loads, types of environmental actions on the vessel and mooring system, mooring analysis program capabilities and limitations, and operating considerations (length management, insert removals, and retirement criteria) should be considered when developing a synthetic rope load-elongation test.

Both static and dynamic load-elongation properties should be determined so that the non-linear fiber rope elastic and non-elastic behavior can be properly modeled. Load-elongation behavior under static, or nearly static, loads is especially important for conditions in which the mooring design is subject to high mean loads of long duration. For example, in a loop/eddy current event, the duration over which high mean loads exist is much longer than that associated with passing storm events. The near-static rope load-elongation properties should be used for calculating the mean vessel offset during other operating and survival events, such as winter storms and hurricanes.

Rope testing results have also shown that the load-elongation properties of the rope can vary appreciably when the rate of loading changes from values typically used to represent wave energy periods (5 to 25 seconds) to vessel's low frequency natural periods (100's to 1,000's of seconds) or periods that cover hours, days, and weeks for mean loads in environmental events (e.g. storm, swell, current events, etc.) of varying duration. The appropriate rope load-elongation properties should be used to calculate system response.

Permanent, non-recoverable elongation of the synthetic rope may be measured as part of the load-elongation test. Alternately, a separate test may be used to measure permanent, non-recoverable elongation. It is particularly important to consider the impact of permanent elongation in the moorings of permanent facilities where permanent elongation in a fiber rope could impair the mooring system's ability to maintain design offsets or other constraints.

There are two types of permanent non-recoverable elongation of importance to mooring designers, caused by two different load mechanisms. One type is construction stretch, due to maximum loading. Another type is creep, caused by the application of a steady load over time. For most synthetic fibers, creep is proportional to the log of time. However, creep is sometimes linear with time. Creep also depends on load magnitude and temperature.

Rope testing results have also shown that some synthetic fiber ropes exhibit delayed elastic stretch and delayed elastic recovery. Delayed elastic stretch manifests itself through rope elongation that occurs over an extended period of time (hours to days). When the rope is unloaded, delayed elastic recovery causes the rope to return to its nominal length after several hours. Understanding this behavior is necessary to develop a post-storm mooring performance monitoring plan.

For example, consider the behavior of the mooring lines during a storm, where the mooring line loads do not exceed the installation tension (i.e., no additional permanent elongation occurs). During the storm, the windward lines experience delayed elastic stretch. After the passage of the storm, the synthetic ropes become shorter over the next several days because of delayed elastic recovery. If the windward lines were re-tensioned immediately after the storm, the delayed elastic recovery would cause the mooring line pretensions to become higher than intended. However, if the windward lines are not re-tensioned, after several days, the mooring line pretensions would be at their pre-storm levels.

## B.2 General

The mooring system designer and owner shall specify load-elongation test procedures which adequately measures the synthetic rope load-elongation properties of interest and concern.

This Annex provides details for two optional testing procedures which may be used for measurement of rope load-elongation properties. Neither is required as a test procedure. The mooring system designer and owner may adapt this testing procedure as needed or may specify another more suitable test procedure.

The rope load-elongation properties of interest are:

— permanent non-recoverable elongation, due mainly to maximum load;

— load-elongation behavior under near static loading;

— load-elongation behavior under low frequency dynamic loads;

— load-elongation behavior under wave frequency dynamic loads;

— delayed elastic stretch and recovery ($\varepsilon_{des,}$ $\varepsilon_{der)}$).

Figure B.1 shows a graph of idealized synthetic rope behavior. This graph represents various load regimes of interest to the mooring designer. The case illustrated here has the following loading scenarios:

— installation tension, $T_{inst}$, typically 40 % RBS;

— the maximum intact mooring design load, $T_{int}$, typically 60 % RBS;

— the maximum damaged mooring design load, $T_{dmg}$, typically 80 % RBS.

The design load values listed above are based on API 2SM maximum allowable utilization factors. If the maximum line utilization factors for a given mooring are different from those listed, the rope load-elongation properties test shall be modified to reflect the design application.

In addition to providing graphs (plots) of the load-elongation behavior of the rope for the test load time history, the test program may be used to determine the following information.

a) Permanent strain under various maximum loads:

— $\varepsilon_{inst}$ is the permanent strain in the rope introduced during installation tensioning;

— $\varepsilon_{int}$ is the permanent strain in the rope introduced under maximum intact mooring system storm loading;

— $\varepsilon_{dmg}$ is the permanent strain in the rope introduced under maximum damaged mooring system storm loading;

— $\varepsilon_{dmg,aged}$ is the permanent strain in the rope introduced under maximum damaged mooring system storm loading after application of aging cycles.

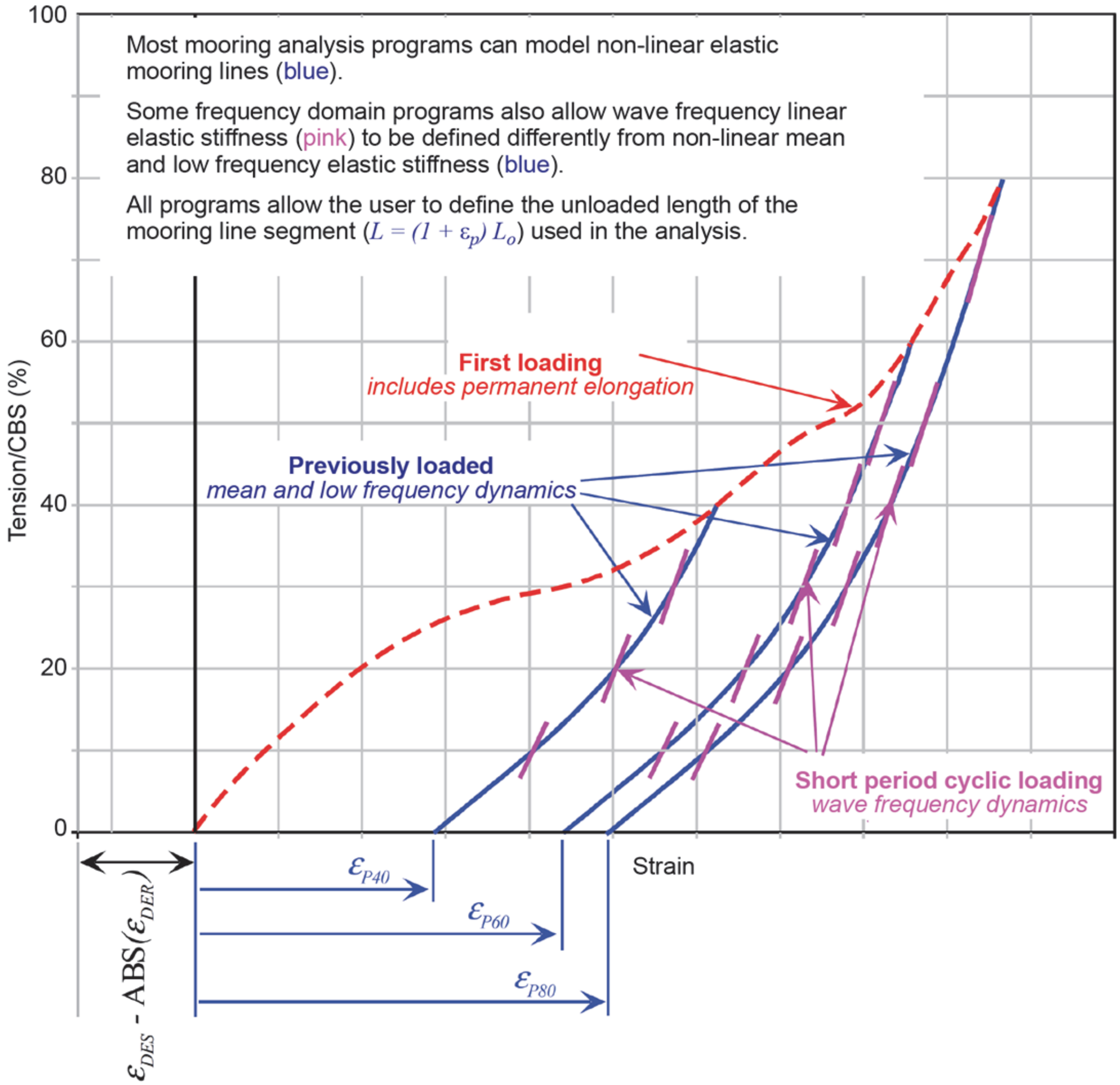


**Figure B.1—Idealized Synthetic Rope Elongation Behavior**

b) Load-elongation behavior under near static loads after exposure to various maximum loads:

— $EA_{\text{stat,inst}}$ is the static rope stiffness of the synthetic rope after installation load has been applied;

— $EA_{\text{stat,int}}$ is the static rope stiffness of the synthetic rope after the maximum intact mooring system storm load has been applied;

— $EA_{\text{stat,dmg}}$ is the static rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied;

— $EA_{\text{stat,dmg,aged}}$ is the static rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied after application of aging cycles.

c) Load-elongation behavior under low frequency dynamic loads after exposure to various maximum loads:

— $EA_{\text{lf,inst}}$ is the dynamic rope stiffness of the synthetic rope after installation load has been applied;

— $EA_{\text{lf,int}}$ is the dynamic rope stiffness of the synthetic rope after the maximum intact mooring system storm load has been applied;

— $EA_{\text{lf,dmg}}$ is the dynamic rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied;

— $EA_{\text{lf,dmg,aged}}$ is the dynamic rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied after application of aging cycles.

d) Load-elongation behavior under wave frequency dynamic loads after exposure to various maximum loads:

— $EA_{\text{wf,inst}}$ is the dynamic rope stiffness of the synthetic rope after installation load has been applied;

— $EA_{\text{wf,int}}$ is the dynamic rope stiffness of the synthetic rope after the maximum intact mooring system storm load has been applied;

— $EA_{\text{wf,dmg}}$ is the dynamic rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied;

— $EA_{\text{wf,dmg,aged}}$ is the dynamic rope stiffness of the synthetic rope after the maximum damaged mooring system storm load has been applied after application of aging cycles.

NOTE The static and dynamic rope stiffnesses defined above depends on the mean load, load amplitude, and load period.

It is necessary to address changes in length early in the mooring design cycle. Mooring line loads in excess of the installation load increase the length of the synthetic segments of the mooring line and thus reduce the mooring line pretension. If the mooring line cannot be shortened, then the vessel can be subject to excursions that exceed the design limits.

Additional permanent elongation of the fiber rope segments of the mooring line occurs when the maximum tension experienced by the fiber rope segment of the mooring line increases above that previously experienced. The result is an increase in the length of the synthetic section of the mooring line. Rope stiffness increases as the maximum tension experienced by the fiber rope segment of the mooring line increases above that previously experienced, resulting in decreased elastic-elongation of the total length of the mooring line. Thus, it is necessary to consider the impact of these two factors separately, especially if synthetic sections are removed as part of a length management plan.

Increased rope stiffness in the synthetic segment of the mooring line can impact mooring line maximum tensions and, to a lesser extent, the fatigue life of the entire mooring line.

## B.3 Test Sample Size – Subrope, Scaled Rope, and Full Rope Testing

The rope load-elongation property tests may be conducted on a representative subrope or scaled rope. Some rope constructions are not as compatible to subrope testing as others. For parallel rope constructions, subrope testing generally yields results that may be applied to full ropes. For rope constructions such as braided or wire rope type constructions, scaled rope testing, rather than subrope testing, may be used to capture accurate behavior properties of the full rope. If either subrope or scaled rope testing is utilized, sufficient full-to-subrope or scaled rope testing should be completed to establish proper scaling factors.

When appropriate, subrope or scaled rope testing is preferred over full rope testing because of a number of factors.

a) Most rope testing facilities can test only relatively short rope lengths (typically 13 meter samples). The length between ends of splices (mid-span) is very short, which is opposite from typical ropes in use in which the mid-span is a large majority of the total length of the rope section. Since the behavior of test samples is typically dominated by the behavior of the splices, a high level of precision should be used when splicing the sample to ensure equal load sharing among the subropes. Small differences in length in the subropes create uneven tension distribution among the subropes and thus create an imbalance in a splice. The true behavior and strength of the rope can be masked when such an imbalance is present in the test sample. Small absolute differences in spliced subrope lengths are far less critical with typical ropes in service, since the long mid-span length of the rope makes any differences in subrope lengths insignificant.

b) Rope jackets on short full rope size samples tend to deform (lengthen and contract) differently from the rope core within. Since measurement tools are attached to the rope jacket, the tools tend to measure the jacket deformation rather than the extension of the rope core assembly.

c) When full size rope samples are tested, the load cells used for the test fixtures often do not accurately measure small load changes. Namely, the relatively small loads typically specified for load-elongation testing can be outside of the calibration range of the load cells in a test bed used for break testing. Generally, this problem does not occur for subrope or scaled rope testing since the test loads are within the calibration range of the load cells.

In contrast to the above, single subrope testing is not likely to experience problems related to short measurement length between the toes of the splices, unequal load-sharing, and the effects of full-rope jacket displacements masking the rope core measurements. Likewise, the impact of problems listed above can be reduced for scaled rope testing.

## B.4 Test Specimen and Test Machine and Apparatus Requirements

A minimum of one specimen shall be tested.

The terminations used in this test shall be of sufficient strength to meet the loading requirements for the test program.

The length of the specimen shall be sufficient to accommodate a gauge length determined as follows.

The gauge length over which rope-elongation is measured shall be sufficient to achieve ±10 % accuracy for the expected extension [1]. This criterion is judged by the accuracy to which the extension measuring system can measure the difference between rope length (over gauge length) at trough load and at peak load for the intended load range.

The gauge marks (ends) should be no closer than five (5) times the rope diameter from the rope ends of termination. The gauge length should be no less than ten (10) times the rope diameter. Thus the specimen length should be sufficient to accommodate the gauge length ($\geq 10d$), as determined above, plus at least ten (10) times the nominal rope diameter ($\geq 10d$) between rope ends of terminations, i.e., greater than twenty nominal rope diameters ($\geq 20d$) between the ends of the terminations.

The specimen should not have been previously tensioned to more than 5 % of its estimated RBS nor have been cycled or maintained under tension.

The goal of the test is to obtain the wet rope load-elongation properties for the expected field service temperature of the rope. For some fibers, such as polyester, there is no difference in the load-elongation properties measured in dry or wet conditions. Other fibers, including nylon (polyamide), show marked differences in load-elongation properties when tested in dry and wet conditions. Some fiber types also have a negative coefficient of thermal expansion. Particularly for high load amplitude cycles and short load periods, the rope's temperature shall be maintained in a range that does not adversely affect the results.

Where rope properties differ depending on whether the rope is wet or dry, the rope shall be tested at the corresponding service conditions. The properties of nylon rope are known to be affected by wetting. Some marine finishes, splices, friction in the splices, and friction in the rope can also be affected by wetting. Wetting may also be used to prevent the rope from overheating during cyclic testing. Polyester ropes may be tested in the dry condition unless the fiber finish requires wetting.

If wet testing is required, the entire specimen including terminations should be soaked in water for approximately 24-hours before testing. The specimen should be tested as soon as practical after being removed from the water. The sample does not need to remain immersed during testing, but should be spray-soaked until the testing is complete. The temperature of the water should be maintained between 15 °C and 25 °C (59 °F and 77 °F). For nylon, the sample wetting procedure should be in accordance with the OCIMF *Guide to Purchasing Hawsers* [18].

The test machine shall have sufficient bed length, stroke, rate of loading, and force producing capacity to carry out the test as described. Consideration in selecting a test machine should include the means to control load or extension via a suitable control system and the ability to control the slow ramp up and ramp down of the load over time (i.e., over hours, not seconds). The test machine shall be equipped with a force measuring and indicating/recording device which is accurate to within ±1 % (additional consideration in lower load ranges) of the estimated breaking force for the rope specimen and shall continuously record both length and loading throughout the test. The force measuring and indication/recording device shall be calibrated by a recognized independent calibration agency, using a reference load cell traceable to applicable national standards. This calibration shall have been performed within the previous year. An original calibration certificate shall be available for examination, and a copy of this certificate shall be attached to the test report.

## B.5 Example 1: Test for Rope Elongation and Modulus Properties

### B.5.1 General

This section describes an example of a test for rope elongation and modulus properties. This section includes:

a) a list of definitions for variables associated with the test;

b) the test procedure;

c) data extraction; and

d) options for test modification.

### B.5.2 Definitions of Variables

The following variables are used in this test procedure:

a) Mooring line loads:

— RBS = reference break strength for sample under test;

— $T_0$ = reference tension; in the range of 1 % RBS to 5 % RBS;

— $T_{INST}$ = installation tension; taken as 40 % RBS in this example test procedure;

— $T_{INT}$ = maximum intact mooring tension; taken as 60 % RBS in this example test procedure;

— $T_{DMG}$ = maximum damaged mooring tension; taken as 80 % RBS in this example test procedure.

b) Measured values for load-elongation properties:

— $L_0$ = new rope length between gauge marks at $T_0$;

— $L_{INST1U}$ = rope length immediately after release of installation tension;

— $L_{INST1}$ = rope length 1 hr after installation tension release; also the installed length;

— $L_{INST2U}$ = rope length immediately after slow relaxation from $T_{INST}$;

— $L_{INST2}$ = rope length 1 hr after slow relaxation from $T_{INST}$;

— $L_{MXINT1U}$ = rope length immediately after release of $T_{INT}$;

— $L_{MXINT1}$ = rope length 1 hr after release of $T_{INT}$;

— $L_{MXINT2U}$ = rope length immediately after slow relaxation from $T_{INT}$;

— $L_{MXINT2}$ = rope length 1 hr after slow relaxation from $T_{INT}$;

— $L_{MXDMG1U}$ = rope length immediately after release of $T_{DMG}$;

— $L_{MXDMG2U}$ = rope length immediately after slow relaxation from $T_{DMG}$;

— $L_{MXDMG1}$ = rope length 1 hr after slow relaxation from $T_{DMG}$;

— $L_{MXDMG2}$ = rope length 1 hr after cyclic loading;

— $L_{MXDMGA1U}$ = rope length immediately after completion of cyclic loading;

— $L_{MXDMGA1}$ = rope length 1 hr after completion of cyclic loading;

— $L_{MXDMGA2U}$ = rope length immediately after slow relaxation from $T_{DMG}$;

— $L_{MXDMGA2}$ = rope length 1 hr after slow relaxation from $T_{DMG}$.

c) Calculated values for load-elongation properties:

— $\varepsilon_{inst}$ = permanent strain due to installation load;

— $\varepsilon_{int}$ = permanent strain due to maximum intact load;

— $\varepsilon_{dmg}$ = permanent strain due to maximum damaged load;

— $\varepsilon_{dmg,aged}$ = permanent strain due to maximum damaged load and aging;

— $EA_{stat,inst}$ = static axial rope stiffness curve for 5 % MBS to $T_{INST}$;

— $EA_{lf,inst}$ = dynamic axial stiffness curve for mean tensions up to $T_{INST}$;

— $EA_{wf,inst}$ = dynamic axial stiffness curve for mean tensions up to $T_{INST}$;

— $EA_{stat,int}$ = static axial stiffness curve for 5 % MBS to $T_{INT}$;

— $EA_{lf,int}$ = dynamic axial stiffness curve for mean tensions up to $T_{INT}$;

— $EA_{wf,int}$ = dynamic axial stiffness curve for mean tensions up to $T_{INT}$;

— $EA_{stat,dmg}$ = static axial stiffness curve for 5 % MBS to $T_{DMG}$;

— $EA_{lf,dmg}$ = dynamic axial stiffness curve for mean tensions up to $T_{DMG}$;

— $EA_{wf,dmg}$ = dynamic axial stiffness curve for mean tensions up to $T_{DMG}$;

— $EA_{stat\ aged,dmg}$ = aged rope static axial stiffness curve for 5 % MBS to $T_{DMG}$;

— $EA_{lf\ aged,dmg}$ = aged rope dynamic axial stiffness curve for mean tensions up to $T_{DMG}$;

— $EA_{wf\ aged,dmg}$ = aged rope dynamic axial stiffness curve for mean tensions up to $T_{DMG}$.

### B.5.3 Test Procedure

The test procedure herein is composed of five test series (A through E). Series A is used to determine the initial rope length. Series B is used to determine graphs (plots) of the load-elongation properties of the as-installed rope, and to define permanent elongation, static rope-stiffness, low frequency dynamic rope-stiffness and wave frequency dynamic rope-stiffness. Series C is used to provide graphs and determine load-elongation properties of the rope after it has been loaded to its maximum intact mooring design load. Series D is used to provide graphs and determine load-elongation properties of the rope after it has been loaded to its maximum one line damaged condition mooring design load. Series E is used to provide graphs and determine the rope properties after aging. The test shall be modified to reflect anticipated installation, operating and survival mooring line loads (see B.5.5).

**Series A, Initial Length $L_0$**

A-1) Tension the rope to $T_0$ (1 % RBS). Measure and record gauge-length (the length between gauge marks). This length is $L_0$.

**Series B, Load-elongation Behavior for Tensions below $T_{INST}$ (in this example $T_{INST}$ = 40 % RBS)**

B-1) Tension the rope to $T_{INST}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr.

B-2) Reduce the tension in the rope to $T_0$ while recording gauge-length. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{INST1U}$.

B-3) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{INST1}$.

B-4) Cycle the rope 10 times at mean load of 10 % RBS, 20 % RBS and 30 % RBS with a load amplitude of 5 % RBS with a constant cycle time equivalent to the low frequency natural period of the facility's motions, typically in the range of 120 s to 300 s. Record gauge-length vs. tension. The data from the last cycle of each set shall be used to calculate $EA_{lf,inst}$.

B-5) Cycle the rope 25 times at mean load of 10 % RBS, 20 % RBS and 30 % RBS with a load amplitude of 5 % RBS with a constant cycle time of 10 s to 12 s. Record gauge-length vs. tension. The data from the last cycle of each set shall be used to calculate $EA_{wf,inst}$.

B-6) Tension the rope to $T_{INST}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per min. Hold this tension for 1 h while recording gauge-length.

B-7) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{INST2U}$.

Optional steps for calculating static stiffness for up load cycle:

B-7a) Tension the rope to $T_{INST}$ while recording tension and gauge-length. The rate of loading shall be 1 % RBS per minute.

B-7b) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{INST2U}$.

B-8) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{INST2}$.

**Series C, Load-elongation Behavior for Tensions below $T_{INT}$ (in this example $T_{INT}$ = 60 % RBS)**

C-1) Tension the rope to $T_{INT}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr.

C-2) Reduce the tension in the rope to $T_0$ while recording gauge-length. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{MXINT1U}$.

C-3) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{MXINT1}$.

C-4) Cycle the rope 10 times at mean load of 10 % RBS, 20 % RBS, 30 % RBS, 40 % RBS and 50 % RBS with a load amplitude of 5 % RBS with a constant cycle time equivalent to the low frequency natural period of the facility's motions, typically in the range of 120 to 300 sec. Record gauge-length vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{lf,int}$.

C-5) Cycle the rope 25 times at mean load of 10 % RBS, 20 % RBS, 30 % RBS, 40 % RBS and 50 % RBS with a load amplitude of 5 % RBS with a constant cycle time of 10 to 12 sec. Record gauge-length vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{\text{wf,int}}$.

C-6) Tension the rope to $T_{\text{INT}}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr while recording gauge-length.

C-7) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXINT2U}}$.

Optional steps for calculating static stiffness for up load cycle:

C-7a) Tension the rope to $T_{\text{INT}}$ while recording tension and gauge-length. The rate of loading shall be 1 % RBS per minute.

C-7b) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXINT2U}}$.

C-8) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{\text{MXINT2}}$.

**Series D, Load-elongation Behavior for Tensions below $T_{\text{DMG}}$ (in this example $T_{\text{DMG}}$ = 80 % RBS)**

D-1) Tension the rope to $T_{\text{DMG}}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr.

D-2) Reduce the tension in the rope to $T_0$ while recording gauge-length. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXDMG1U}}$.

D-3) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{\text{MXDMG1}}$.

D-4) Cycle the rope 10 times at mean load of 10 % RBS, 20 % RBS, 30 % RBS, 40 % RBS, 50 % RBS, 60 % RBS and 70 % RBS with a load amplitude of 5 % RBS with a constant cycle time equivalent to the low frequency natural period of the facility's motions, typically in the range of 120 to 300 sec. Record gauge-length vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{\text{lf,dmg}}$.

D-5) Cycle the rope 25 times at mean load of 10 % RBS, 20 % RBS, 30 % RBS, 40 % RBS, 50 % RBS, 60 % RBS and 70 % RBS with a load amplitude of 5 % RBS with a constant cycle time of 10 to 12 sec. Record gauge-length vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{\text{wf,dmg}}$.

D-6) Tension the rope to $T_{\text{DMG}}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr while recording gauge-length.

D-7) Reduce the tension in the rope to $T_0$ while recording gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXDMG2U}}$.

Optional steps for calculating static stiffness for up load cycle:

D-7a) Tension the rope to $T_{\text{DMG}}$ while recording tension and gauge-length.The rate of loading shall be 1 % RBS per minute.

D-7b) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXDMG2U}}$.

D-8) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{\text{MXDMG2}}$.

**Series E, Load-elongation Behavior for Aged Rope with Tensions below $T_{\text{DMG}}$ (in this example $T_{\text{DMG}}$ = 80 % RBS)**

E-1) Cycle the rope 1000 times at a mean load of 40 % RBS with a load amplitude of 10 % RBS with a cycle time of 10 to 12 seconds.

E-2) Reduce the tension in the rope to $T_0$ while recording gauge-length. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXDMGA1U}}$.

E-3) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{\text{MXDMGA1}}$.

E-4) Cycle the rope 25 times at mean load of 10 % RBS, 20 % RBS, 30 % RBS, 40 % RBS, 50 % RBS, 60 % RBS and 70 % RBS with a load amplitude of 5 % RBS with a constant cycle time of 10 to 12 sec. Record gauge-length vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{\text{wf aged,dmg}}$.

E-5) Cycle the rope 10 times at mean load of 20 % RBS, 40 % RBS and 60 % RBS and with a load amplitude of 5 % RBS with a constant cycle time of 120 to 300 sec. Record elongation vs. tension. The data from the last cycle of each range shall be used to calculate $EA_{\text{lf aged,dmg}}$.

E-6) Tension the rope to $T_{\text{DMG}}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr while recording gauge-length.

E-7) Reduce the tension in the rope to $T_0$ while recording gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{\text{MXDMGA2U}}$.

Optional steps for calculating static stiffness for up load cycle:

E-7a) Tension the rope to $T_{\text{DMG}}$ while recording tension and gauge-length. The rate of loading shall be 1 % RBS per minute.

E-7b) Reduce the tension in the rope to $T_0$ while recording the gauge-length. The rate of unloading shall be 1 % RBS per minute. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation). This length is $L_{MXDMGA2U}$.

E-8) Hold the rope at $T_0$ for 1 hr or until rope length stabilizes. Measure and record the gauge-length at the end of the hold period. From the graph of tension vs. gauge-length determine the gauge-length at zero tension (by extrapolation) at the end of the hold period. This length is $L_{MXDMGA2}$.

This test should be completed without significant pauses and interruptions (the test is expected to take 30 to 40 hours). If testing is interrupted, the test sample shall be reconditioned for continued testing. This reconditioning procedure shall be developed by the testing facility personnel in consultation with the rope manufacturer.

The test shall be modified to reflect anticipated installation, operating and survival mooring line loads. For example, load amplitude and frequency variations may be applied representing hull vortex induced motions to investigate the impact on the variation in rope stiffness when near static loads are combined with low frequency loads.

### B.5.4 Data Reporting

All rope testing results shall be provided to the mooring designer.

The permanent strain in the rope due to maximum load shall be reported as follows:

— $\varepsilon_{inst} = (L_{INST2} - L_0)/L_0$;

— $\varepsilon_{int} = (L_{MXINT2} - L_0)/L_0$;

— $\varepsilon_{dmg} = (L_{MXDMG2} - L_0)/L_0$;

— $\varepsilon_{dmg,aged} = (L_{MXDMGA2} - L_0)/L_0$.

Static rope stiffness may be calculated from the tangent or secant slopes of the load-elongation data at a suitable number of points along the load-elongation curve. The tension range used to calculate values of secant rope stiffness should not be more than 5 % RBS. The static rope stiffness shall be reported as follows:

— $EA_{stat.inst}$ – calculated from the nonlinear load-elongation graph from Step B-7 or B-7a and the unloaded rope length $L_{INST2}$;

— $EA_{stat,int}$ – calculated from the nonlinear load-elongation graph from Step C-7 or C-7a and the unloaded rope length $L_{MXINT2}$;

— $EA_{stat,dmg}$ – calculated from the nonlinear load-elongation graph from Step D-7 or D-7a and the unloaded rope length $L_{MXDMG2}$;

— $EA_{stat\ aged,dmg}$ – calculated from the nonlinear load-elongation graph from Step E-7 or E-7a and the unloaded rope length $L_{MXDMGA2}$.

Use of the above process creates a piece-wise linear static rope stiffness curve as a function of tension for each maximum applied load. Alternately, the test data may be used to develop rope stiffness models such as

— a polynomial fit or look-up table for a continuous nonlinear load-elongation (stress-strain) curve, or

— an upper- and lower-bound linear model which is bounded by the tangent rope stiffness at zero tension and the tangent rope stiffness at the maximum tension.

The low frequency dynamic rope stiffness may be calculated from the tangent or secant slope of the load-extension data at the tested mean loads. The tension range used to calculate values of secant rope stiffness shall not be more than 10 % RBS or the double load amplitude used in the test. The low frequency dynamic rope stiffness shall be reported as follows:

— $EA_{\mathrm{lf,inst}}$ – calculated from the load-elongation data from last cycle of each set from Step B-4, using the unloaded rope length $L_{\mathrm{INST2}}$;

— $EA_{\mathrm{lf,int}}$ – calculated from the load-elongation data from last cycle of each set from Step C-4, using the unloaded rope length $L_{\mathrm{MXINT2}}$;

— $EA_{\mathrm{lf,dmg}}$ – calculated from the load-elongation data from last cycle of each set from Step D-4, using the unloaded rope length $L_{\mathrm{MXDMG2}}$;

— $EA_{\mathrm{lf\ aged,dmg}}$ – calculated from the load-elongation data from last cycle of each set from Step E-5, using the unloaded rope length $L_{\mathrm{MXDMGA2}}$.

The wave frequency dynamic rope stiffness may be calculated from the tangent or secant slopes of the load-extension data at the tested mean loads. The tension range used to calculate values of secant rope stiffness shall not be more than 10 % RBS or the double load amplitude used in the test. The wave frequency dynamic rope stiffness shall be reported as follows:

— $EA_{\mathrm{wf,inst}}$ – calculated from load-elongation data from last cycle of each set from Step B-5, using the unloaded rope length $L_{\mathrm{INST2}}$;

— $EA_{\mathrm{wf,int}}$ – calculated from load-elongation data from last cycle of each set from Step C-5, using the unloaded rope length $L_{\mathrm{MXINT2}}$;

— $EA_{\mathrm{wf,dmg}}$ – calculated from load-elongation data from last cycle of each set from Step D-5, using the unloaded rope length $L_{\mathrm{MXDMG2}}$;

— $EA_{\mathrm{wf\ aged,dmg}}$ – calculated from load-elongation data from last cycle of each set from Step E-4, using the unloaded rope length $L_{\mathrm{MXDMGA2}}$.

The low frequency and wave frequency dynamic rope stiffnesses may be calculated from several cycles near the end of each series. These additional calculations may be used to check for spurious results. A smooth curve may be fit through the stiffness vs. tension data points to determine the dynamic stiffness at intermediate tension values.

### B.5.5 Additional Data Extraction

Information on delayed elastic stretch and delayed elastic recovery may be extracted from the various steps with constant tension holds:

— delayed elastic stretch: B-6, C-6, D-6, E-6;

— delayed elastic recovery: B-3, B-8, C-3, C-8, D-3, D-8, E-3, E-8.

The test in B.7 provides an example of a creep and delayed elastic stretch and recovery test.

### B.5.6 Test Modifications

The test sequence described above may be modified to gain better understanding of the rope tension-elongation properties for a given application. Examples of modifications that a mooring designer may consider include the following.

a) Installation tensioning sequence: variation in the load $T_{\mathrm{INST}}$ and duration of load application.

b) Maximum intact and damaged mooring line tension: variation in the load $T_{\mathrm{INT}}$ or $T_{\mathrm{DMG}}$.

c) Tension range of wave frequency or low frequency cycles: the amplitude and mean tension of the wave frequency and low frequency cycles may be varied; care should be taken to ensure the maximum tension does not exceed that of Step 1 for the given test series (e.g., $T_{\mathrm{INT}}$ for Series C).

d) Number of low frequency and wave frequency cyclic tests about mean loads of 10 % RBS, 20 % RBS, 30 % RBS, etc. in steps B-4, B-5, C-4, C-5, D-4, D-5, E-5 and E-4. For example, in step D-4 low frequency cyclic testing at mean loads of 10 % RBS, 30 % RBS, 50 % RBS, and 70 % RBS could be used.

e) Placement of aging cycles: the aging cycles may be shifted to a different location in the test (e.g., at the end of Series B) to evaluate rope performance.

f) Placement of slow up-load step: optional steps 7a and 7b may be added after step 3 (before low and wave frequency cycling) if the mooring designer wants information on static stiffness of the unworked rope.

## B.6 Example 2: Test For Rope Elongation and Modulus Properties

### B.6.1 General

This section describes another example of a test for rope elongation and modulus properties. This section includes

a) a list of definitions for variables associated,

b) the test procedure, and

c) data extraction.

Tests described in this section include installation pre-load test, quasi-static stiffness test, and dynamic stiffness test. In this section, quasi-static rope stiffness is a linear stiffness value, which combines elastic stiffness and permanent (bedding-in) elongation, between pretension and maximum tension, and the delayed elastic stretch at the peak load for the desired storm duration. The quasi-static stiffness as defined here (see Figure B.2) is the slope of the line between the maximum elongation at the maximum load and the stabilized length at pretension. This stiffness is typically used when doing mooring analysis using a linear stiffness approach (e.g., as described in 6.4.1.2).

The test in B.6.2.1 is the installation pre-loading test to simulate the installation pre-loading and pre-tensioning sequence designed to remove as much permanent elongation as possible during installation and to increase stiffness of the rope. The results are used to determine the relationship between the as-installed length at pre-tension and the manufactured rope length (at 1 % RBS).

The test described in B.6.2.2 is to determine the quasi-static stiffness and elongation of a rope that has seen no prior loading other than the installation loads, i.e., post-installation rope. The installation pre-loading test shall be run on the rope sample just prior to starting the stiffness test.

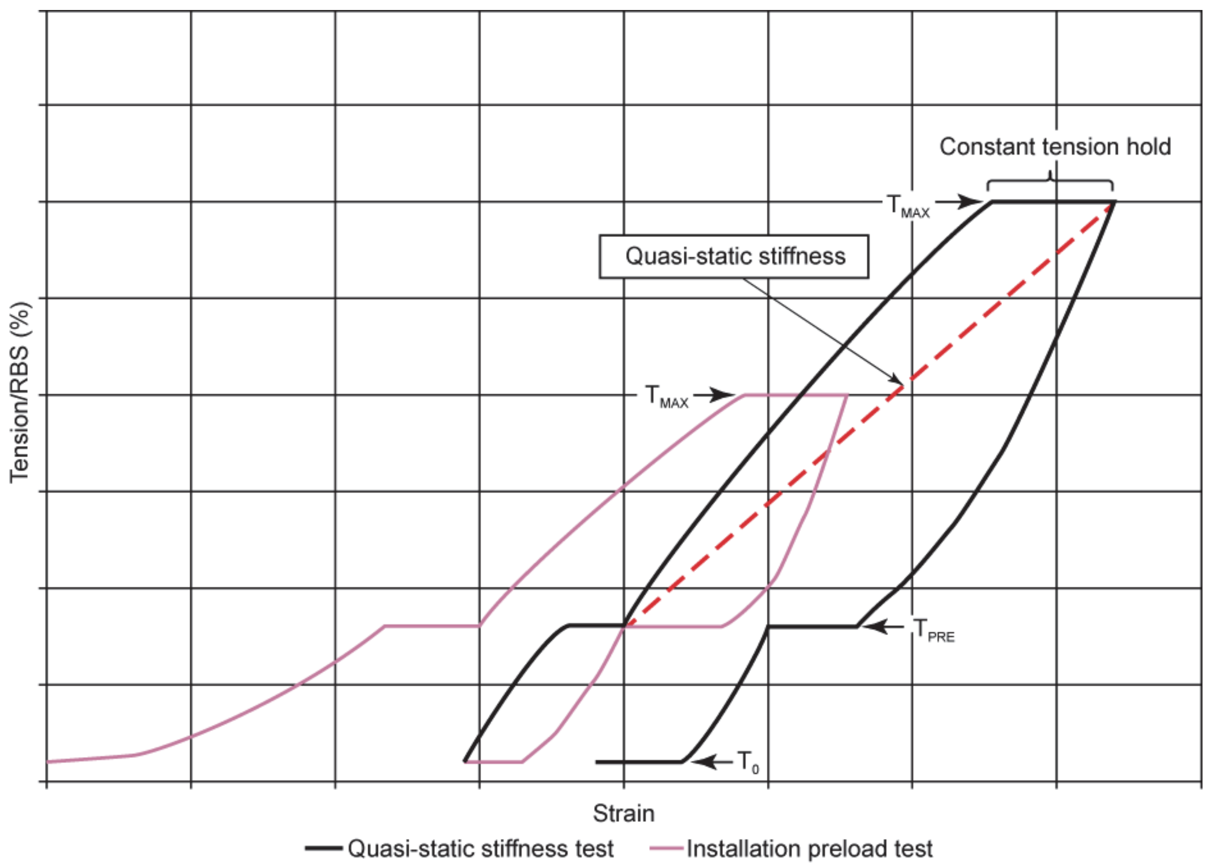


**Figure B.2—Quasi-static Stiffness**

The dynamic stiffness test, described in B.6.2.3, shall be done on the rope sample used for the installation pre-load test and the quasi-static stiffness test for post-installation rope.

Section B.6.2.4 is the test for quasi-static stiffness and elongation of a bedded-in, or aged, rope to simulate rope that has experienced a storm event. This test is done on the rope sample used for the installation pre-load test, the quasi-static stiffness test for post-installation rope, and the dynamic stiffness test.

## B.6.2 Definition of Variables

The following variables are used in this procedure.

a) Mooring line loads:

— RBS = reference break strength for sample being tested;

— $T_0$ = reference tension; typically 1 % or 2 % RBS;

— $T_{PRE}$ = pretension; starting load for calculation of quasi-static stiffness;

— $T_{INST}$ = maximum installation tension;

— $T_{MAX}$ = maximum mooring tension (taken as 60 % RBS in test procedure); ending load for calculation of quasi-static stiffness.

b) Measured values for load-elongation properties:

— $L_0$ = new rope length between gauge marks at $T_0$;

— $L_{INST.PRE}$ = rope length after relaxation at $T_{PRE}$ following loading to $T_{INST}$;

— $L_{INST.T0}$ = rope length after relaxation at $T_0$ following loading to $T_{INST}$;

— $L_{MAX.PRE}$ = rope length after relaxation at $T_{PRE}$ following loading to $T_{MAX}$;

— $L_{MAX.T0}$ = rope length after relaxation at $T_0$ following loading to $T_{MAX}$;

— $L_{MAX}$ = rope length at maximum test load ($T_{MAX}$) after hold duration;

— $L_{MAX.aged}$ = rope length at maximum test load ($T_{MAX}$) after hold duration for aged rope;

— $L_{MAX.PRE.aged}$ = rope length after relaxation at $T_{PRE}$ following loading to $T_{MAX}$ for aged rope;

— $L_{MAX.T0.aged}$ = rope length after relaxation at $T_0$ following loading to $T_{MAX}$ for aged rope.

c) Calculated values for load-elongation properties:

— $e_{inst}$ = permanent strain due to installation load;

— $e_{int}$ = permanent strain due to maximum tested load (e.g., intact maximum load);

— $e_{int.aged}$ = permanent strain due to maximum tested load for aged rope;

— $EA_{QStat.int}$ = quasi-static axial rope stiffness between pretension ($T_{PRE}$) and maximum load ($T_{MAX}$);

— $EA_{QStat.aged}$ = quasi-static axial rope stiffness between pretension ($T_{PRE}$) and maximum load ($T_{MAX}$) for bedded-in, or aged, rope;

— $EA_{lf}$ = low frequency dynamic axial rope stiffness;

— $EA_{wf}$ = wave frequency dynamic axial rope stiffness.

## B.6.3 Test Procedures

### B.6.3.1 Installation Pre-loading Test

This test shall precede the test for quasi-static stiffness for post-installation rope (see B.6.2.2). Rope shall not have seen more than 5 % RBS tension prior to starting the test.

The test procedures shall be modified to match the actual installation pre-load parameters. An example test procedure follows.

1) Tension the rope to 1 % RBS ($T_0$). Measure and record the initial rope length ($L_0$).

2) Increase the tension to the specified pre-tension ($T_{PRE}$) and hold at this tension for at least 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes, and at the end of the duration.

3) Increase the tension to the specified pre-load tension ($T_{\text{INST}}$) and hold at this tension for 2 hours. Record the extension (at least) at 1, 10, and 100 minutes, and at the end of the duration. Note that the 2 hour hold should be adjusted to match the planned pre-loading procedure.

4) Decrease the tension to pre-tension and hold at this tension for at least 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes, and at the end of the duration ($L_{\text{INST.PRE}}$).

5) Decrease the tension to $T_0$ and hold at this tension for at least 100 minutes. Record the extension at 1, 10 and 100 minutes, and at the end of the duration ($L_{\text{INST.T0}}$).

6) Report the length at the end of Step 4. This is the length accounting for permanent rope elongation due to installation load at pretension ($L_{\text{INST.PRE}}$).

7) Report the length at the end of Step 5. This is the length accounting for permanent rope elongation due to installation load at $T_0$ ($L_{\text{INST.T0}}$).

#### B.6.3.2 Quasi-static Stiffness Test for Post-Installation Rope

This test shall be carried out on the test segment that has been tested in the installation pre-loading test.

The test procedures shall be modified to obtain the required design parameters (i.e., load levels and hold times). An example test procedure follows.

1) Increase the tension from $T_0$ to pretension ($T_{\text{PRE}}$) and hold at this tension for at least 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes.

2) Increase the tension from pretension to 60 % RBS ($T_{\text{MAX}}$) at a rate of approximately 10 % RBS per minute and hold at this tension for at least 180 minutes (to simulate 3 hr storm). Record the extension (at least) at 1, 10, and 100 minutes and at the end of the duration ($L_{\text{MAX}}$). Note that the hold duration is to simulate storm event duration. The elongation during the hold is log-linear with time for polyester rope so may be extrapolated beyond 180 minutes. However, if attempting to simulate a long event such as a loop current, it may be prudent to hold at the peak load for longer than 180 minutes.

3) Reduce the tension from $T_{\text{MAX}}$ to pre-tension at a rate of approximately 10 % RBS per minute and hold for at least 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes and at the end of the duration ($L_{\text{MAX.PRE}}$)

4) Decrease tension to $T_0$ and hold for at least 100 minutes. Record the extension at 1, 10 and 100 minutes and at the end of the duration ($L_{\text{MAX.T0}}$).

The quasi-static stiffness ($EA_{\text{QStat.int}}$) is the secant stiffness from the start of Step 2 to the end of Step 2. For mooring analysis, this stiffness would be used with the initial rope length, i.e., rope length at the start of Step 2.

The length at the end of Step 3 is the length at pre-tension for the post-installation rope that has been loaded to $T_{\text{MAX}}$ ($L_{\text{MAX.PRE}}$).

The length at the end of Step 4 is the length at $T_0$ for the post-installation rope that has been loaded to $T_{\text{MAX}}$ ($T_{\text{MAX.T0}}$).

#### B.6.3.3 Dynamic Stiffness Test

This test shall be carried out on a test segment that has gone through the installation pre-load test and the quasi-static stiffness test (see B.6.2.1 and B.6.2.2).

The test procedures shall be modified to obtain the required design parameters (i.e., load levels, amplitudes and frequencies). An example test procedure follows.

1) Cycle the rope 10 times between pre-tension and 60 % RBS to bed in the rope. On the 10th cycle, hold the rope at 60 % RBS for 30 minutes and then return to pre-tension and hold for at least 60 minutes.

2) Cycle at tension between 15 % and 25 % of RBS 20 times, with the cycling period equal to the desired low frequency (or vortex-induced motion [VIM]) period.

3) Hold tension at 15 % RBS for 10 minutes.

4) Cycle at tension between 15 % and 25 % of RBS 40 times, with the cycling period less than 25 seconds.

5) Hold tension at 25 % RBS for 10 minutes.

6) Cycle at tension between 25 % and 35 % of RBS 20 times, with the cycling period equal to the desired low frequency (or VIM) period.

7) Hold tension at 25 % RBS for 10 minutes.

8) Cycle at tension between 25 % and 35 % of RBS 40 times, with the cycling period less than 25 seconds.

9) Hold tension at 30 % RBS for 10 minutes.

10) Cycle at tension between 30 % and 50 % of RBS 20 times, with the cycling period equal to the desired low frequency (or VIM) period.

11) Hold tension at 30% RBS for 10 minutes.

12) Cycle at tension between 30 % and 50 % of RBS 40 times, with the cycling period less than 25 seconds.

13) Hold tension at 40 % RBS for 10 minutes.

14) Cycle at tension between 40 % and 60 % RBS 20 times, with the cycling period equal to the desired low frequency (or VIM) period.

15) Hold tension at 40 % RBS for 10 minutes.

16) Cycle at tension between 40 % and 60 % of RBS 40 times, with the cycling period less than 25 seconds.

17) Lower the tension to $T_0$.

The dynamic stiffness is the secant stiffness between the trough and peak of the cycle. The stiffness should be taken as the average of the last 3 cycles.

The load levels (mean load and amplitude) in this procedure should be selected to acquire the desired design conditions. If using the Del Vecchio equation [13] to interpolate or extrapolate stiffness values, the test may need to include more variation in load levels, amplitudes and frequencies to provide a good fit.

#### B.6.3.4 Quasi-static Stiffness Test for Aged Rope

This test shall be carried out on a test segment that has gone through the installation pre-load test and has been bedded-in by loading to the maximum expected load, e.g. the segment already subjected to a quasi-static stiffness test (Section B.6.2.2), and has seen significant dynamic cycling such as during the dynamic stiffness test (Section B.6.2.3).

The test procedures shall be modified to obtain the required design parameters (i.e., load levels and hold times).An example test procedure follows.

1) Increase the tension from $T_0$ to pre-tension and hold at this tension for 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes.

2) Increase the tension from pre-tension to 60 % RBS ($T_{MAX}$) at a rate of approximately 10 % RBS per minute and hold at this tension for 180 minutes. Record the extension (at least) at 1, 10, and 100 minutes ($L_{MAX.aged}$).

3) Reduce the tension from $T_{MAX}$ to pre-tension ($T_{PRE}$) at a rate of approximately 10 % RBS per minute and hold for at least 100 minutes. Record the extension (at least) at 1, 10, and 100 minutes and at the end of the duration ($L_{MAX.PRE.aged}$).

4) Decrease the tension to 1 % RBS ($T_0$) and hold for at least 100 minutes. Record the extension at 1, 10, and 100 minutes and at the end of the duration ($L_{MAX.T0.aged}$).

5) The quasi-static stiffness for a bedded-in, or aged, rope is the secant stiffness from the start of Step 2 to the end of Step 2 ($EA_{QStat.aged}$).For mooring analysis, this stiffness would be used with the initial rope length, i.e., rope length at the start of Step 2.

6) The length at the end of Step 3 is the rope length at $T_{PRE}$ for an aged rope such as following a design storm event ($L_{MAX.PRE.aged}$).

7) The length at the end of Step 4 is the rope length at $T_0$ for an aged rope ($L_{MAX.T0.aged}$).

### B.6.4 Data Reporting

All rope testing results shall be provided to the mooring designer.

The permanent strain in the rope due to maximum load shall be reported as follows:

— $e_{inst} = (L_{INST.T0} - L_0)/L_0$

— $e_{max} = (L_{MAX.T0} - L_0)/L_0$

— $e_{max.aged} = (L_{MAX.T0.aged} - L_0)/L_0$

Quasi-static stiffness is calculated from the secant stiffness from the lower load level to the upper load level after the hold at the upper load level.

— $EA_{QStat.max}$ – calculated from the start of Step 2 to the end of Step 2 from the test in B.6.2.2.

— $EA_{\text{QStat.aged}}$ – calculated from the start of Step 2 to the end of Step 2 from the test in B.6.2.4.

The low frequency and wave frequency dynamic stiffnesses are calculated as the secant stiffness taken from the trough load to the peak load for each cycle and averaging the last 3 cycles.

— $EA_{lf}$ – calculated from the load-elongation data from the last 3 cycles from steps 2, 6, 10 and 14 in B.6.2.3.

— $EA_{wf}$ – calculated from the load-elongation data from the last 3 cycles from steps 4, 8, 12, and 16 in B.6.2.3.

## B.7 Testing Rope Creep and Delayed Elastic Stretch and Recovery Properties

### B.7.1 General

The creep data are intended to be used in mooring line creep calculations. The percent creep at 3 min., 30 min., 300 min. and 3000 min. may be extrapolated on a semi-log basis (creep on normal scale vs. time on log scale) to longer times.

Note that the creep data are collected at two tensions, an upper tension value and a lower tension value. For the purposes of developing this test procedure, these tensions are taken as 30 % RBS and 15 % RBS, respectively. These values may be modified to reflect the application at hand.

Delayed elastic stretch and recovery data are intended to aid the mooring designer and operator in evaluating the effects of these phenomena, as appropriate.

### B.7.2 Test Specimen and Test Machine and Apparatus Requirements

The test specimen and test machine and apparatus requirements are as discussed in B.4

The test specimen used for the test outlined in B.4 may be used for this test.

### B.7.3 Definitions of Variables

The following variables are used in this test procedure.

Mooring line loads:

— RBS = reference break strength for sample under test;

— $T_0$ = reference tension; in the range of 1 % RBS to 5 % RBS;

— $T_{\text{INST}}$ = installation tension; taken as 40 % RBS in test procedure;

— $T_{\text{UPPER}}$ = upper tension value; taken as 30 % RBS in test procedure;

— $T_{\text{LOWER}}$ = lower tension value; taken as 15 % RBS in test procedure.

Measured values for rope length:

— $L_0$ = initial rope length between gauge marks at $T_0$;

— $L_{UPPER,T}(t)$ = rope length between gauge marks with rope under tension $T_{\text{UPPER}}$ for length of time $t$;

— $L_{UPPER,0}(t)$ = rope length between gauge marks with rope under tension $T_0$ after rope has been held at tension $T_{UPPER}$ for length of time $t$;

— $L_{CR,UPPER}(t)$ = rope length between gauge marks with rope under tension $T_0$ after rope has completely relaxed after it has been held at tension $T_{UPPER}$ for length of time $t$;

— $L_{LOWER,T}(t)$ = rope length between gauge marks with rope under tension $T_{LOWER}$ for length of time $t$;

— $L_{LOWER,0}(t)$ = rope length between gauge marks with rope under tension $T_0$ after rope has been held at tension $T_{LOWER}$ for length of time $t$;

— $L_{CR,LOWER}(t)$ = rope length between gauge marks with rope under tension $T_0$ after rope has completely relaxed after it has been held at tension $T_{LOWER}$ for length of time $t$.

Calculated values for creep properties:

— $\varepsilon_{CR,UPPER}(t)$ = rope elongation after rope has been held at tension $T_{UPPER}$ for length of time $t$;

— $\varepsilon_{CR,LOWER}(t)$ = rope elongation after rope has been held at tension $T_{LOWER}$ for length of time $t$.

Calculated values for delayed elastic stretch properties:

— $\varepsilon_{DES,UPPER}(t)$ = rope elongation after rope has been held at tension $T_{UPPER}$ for length of time $t$;

— $\varepsilon_{DES,LOWER}(t)$ = rope elongation after rope has been held at tension $T_{LOWER}$ for length of time $t$.

Calculated values for delayed elastic recovery properties:

— $\varepsilon_{DER,UPPER}(t)$ = rope elongation after rope has been reduced from tension $T_{UPPER}$ to $T_0$ for length of time $t$;

— $\varepsilon_{DER,LOWER}(t)$ = rope elongation after rope has been reduced from tension $T_{LOWER}$ to $T_0$ for length of time $t$.

### B.7.4 Test Procedure

Prior to conducting the following test, the mooring designer, rope manufacturer and testing facility should be aware of the following items.

— Test specimen selection: the initial condition of the test specimen may affect interpretation of the test results. Namely, the addition of construction stretch during the test may make interpretation of test results difficult. Use of a well-worked rope sample is preferred.

— Loading and unloading rates: unless specified, the rope should be loaded and unloaded as rapidly as possible. Transients should be minimized.

The specimen should be tested for elongation, extension, and creep properties as follows.

#### A1 Measurement of initial length $L_0$ for previously tested rope

Tension the rope to $T_0$. Measure and record the initial length between gauge marks. This length is $L_0$.

## A2 Measurement of initial length $L_0$ and application of $T_{INST}$ for new rope

1a) Tension the rope to $T_0$. Measure and record the original initial length between gauge marks.

1b) Tension the rope to $T_{INST}$ while recording tension and gauge-length. The rate of loading shall be 10 % RBS per minute. Hold this tension for 1 hr.

1c) Reduce the tension in the rope to $T_0$ while recording gauge-length. Hold the rope at $T_0$ for 1 hr or until the measured length of the rope has stabilized. Measure and record the stabilized length of the rope. This length is $L_0$.

## B Stretch and Recovery behavior for $T_{UPPER}$

1) Tension the rope to $T_{UPPER}$ as rapidly as possible. Maintain this tension for 3 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{UPPER,T}$ (3 min).

2) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{UPPER,0}$ (3 min).

3) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{CR,UPPER}$ (3 min).

4) Tension the rope to $T_{UPPER}$ as rapidly as possible. Maintain this tension for 30 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{UPPER,T}$ (30 min).

5) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches T0, immediately record length between gauge marks. This length is $L_{UPPER,0}$ (30min).

6) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{CR,UPPER}$ (30 min).

7) Tension the rope to $T_{UPPER}$ as rapidly as possible. Maintain this tension for 300 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{UPPER,T}$ (300 min).

8) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{UPPER,0}$ (300 min).

9) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{CR,UPPER}$ (300 min).

10) Tension the rope to $T_{UPPER}$ as rapidly as possible. Maintain this tension for 3000 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{UPPER,T}$ (3000 min).

11) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{\mathrm{UPPER,0}}$ (3000 min).

12) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{\mathrm{CR,UPPER}}$ (3000 min).

## C Stretch and Recovery Behavior for $T_{\mathrm{LOWER}}$

13) Tension the rope to $T_{\mathrm{LOWER}}$ as rapidly as possible. Maintain this tension for 3 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{\mathrm{LOWER,T}}$ (3 min).

14) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{\mathrm{LOWER,0}}$ (3 min).

15) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{\mathrm{CR,LOWER}}$ (3 min).

16) Tension the rope to $T_{\mathrm{LOWER}}$ as rapidly as possible. Maintain this tension for 30 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{\mathrm{LOWER,T}}$ (30 min).

17) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{\mathrm{LOWER,0}}$ (30 min).

18) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{\mathrm{CR,LOWER}}$ (30 min).

19) Tension the rope to $T_{\mathrm{LOWER}}$ as rapidly as possible. Maintain this tension for 300 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{\mathrm{LOWER,T}}$ (300 min).

20) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{\mathrm{LOWER,0}}$ (300 min).

21) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{\mathrm{CR,LOWER}}$ (300 min).

22) Tension the rope to $T_{\mathrm{LOWER}}$ as rapidly as possible. Maintain this tension for 3000 minutes while recording tension and gauge-length. Continuously record the length between gauge marks. This length is $L_{\mathrm{LOWER,T}}$ (3000 min).

23) Reduce rope tension to $T_0$ as rapidly as possible. When the tension reaches $T_0$, immediately record length between gauge marks. This length is $L_{\mathrm{LOWER,0}}$ (3000 min).

24) Hold the rope at $T_0$ until the measured length of the rope has stabilized. Continuously record the length between gauge marks. Measure and record the stabilized length of the rope. This length is $L_{CR,LOWER}$ (3000 min).

### B.7.5 Data Reporting

**B.7.5.1** All rope testing results should be provided to the mooring designer.

**B.7.5.2** When a synthetic rope is subject to a tensile load over time, the length of the rope may be given as

$$L_S(T,t) = L_0 + L_{Elastic}(T) + L_{CR}(T,t) + L_{DES}(T,t)$$

where

$T$ is the load on the rope;

$t$ is the duration of the load;

$L_0$ is the initial length of the unloaded rope;

$L_{Elastic}(T)$ is the elastic stretch of the rope at tension $T$;

$L_{DES}(T,t)$ is the delayed elastic stretch as a function of tension $T$ and time $t$;

$L_{CR}(T,t)$ is the rope creep (permanent increase in length at zero tension) as a function of tension $T$ and time $t$.

**B.7.5.3** The convention used to define delayed elastic recovery, $L_{DER}$, is arbitrary. $L_{DER}$ may be defined as starting at zero and decreasing (negative) or starting at $L_{DES}$ and decreasing (positive). When the tension is reduced from $T$ to $T$, the length of the rope may be given as

$$L_R(T',t',T,t) = L_0 + L_{Elastic}(T') + L_{CR}(T,t) + L_{DER}(T',t',T,t)$$

where

$T$ is the higher tension just released from the rope;

$t$ is the duration that the higher tension was held for;

$T'$ is the reduced (lower) tension that the rope is relaxed to;

$t'$ is the time that has elapsed since the load was reduced to $T'$;

$L_0$ is the initial length of the unloaded rope;

$L_{Elastic}(T')$ is the elastic stretch of the rope under a tension of $T'$;

$L_{DER}(T',t',T,t)$ is the delayed elastic recover as a function of previous higher tension $T$ held for time $t$, and the reduced (lower) tension and the elapsed time $t'$ since the tension was reduced. With $L_{DER}(T',t'=0,T,t)$ defined as = $L_{DES}(T,t)$, i.e., $L_{DER}$ starts at $L_{DES}$ and decreases with time $t'$;

$L_{CR}(T,t)$ is as previously defined.

Immediately after the tension is reduced to zero, $L_{Elastic}(T' = 0) = 0$, the rope length becomes

$$L_R(T'=0,t'=0,T,t) = L_0 + L_{CR}(T,t) + L_{DES}(T,t) = L_0 + L_{CR}(T,t) + L_{DER}(T'=0,t'=0,T,t)$$

where by definition

$$L_{DER}(T' = 0, t' = 0, T, t) = L_{DES}(T, t).$$

After the rope length has stabilized, the rope length becomes

$$L_R(T'=0,t'=\infty,T,t) = L_0 + L_{CR}(T,t)$$

or

$$L_{CR}(T,t) = L_R(T'=0,t'=\infty,T,t) - L_0$$

From the above relationships, the following values may be calculated for both upper and lower tensions:

$$L_{Elastic}(T) = L_S(T,t) - L_R(T'=0,t'=0,T,t)$$

Delayed elastic stretch and delayed elastic recovery of the rope may then be calculated as a function of time from the test results as

$$L_{DES}(T,t) = L_S(T,t) - L_0 - L_{Elastic}(T) - L_{CR}(T,t)$$

$$L_{DER}(T'=0,t',T,t) = L_R(T'=0,t',T,t) - L_0 - L_{CR}(T,t)$$

More generally, when $T'$ is less than $T$ but not zero, delayed elastic recovery is given by

$$L_{DER}(T',t',T,t) = L_R(T',t',T,t) - L_0 - L_{Elastic}(T') - L_{CR}(T,t)$$

Calculate the rope elongation $\varepsilon_{CR,UPPER(t)}$ at $T_{UPPER}$ after 0.05 hr (3 min.), 0.5 hr (30 min.), 5 hr (300 min.) and 50 hr (3000 min.) as percent of initial length by the following formula:

$$\varepsilon_{CR,UPPER}(t) = 100\% \times \frac{L_{CR,UPPER}(t) - L_0}{L_0}$$

Likewise, calculate the rope elongation $\varepsilon_{CR,LOWER}$ at $T_{LOWER}$ after 0.05 hr (3 min.), 0.5 hr (30 min.), 5 hr (300 min.) and 50 hr (3000 min.) as percent of initial length by the following formula:

$$\varepsilon_{CR,LOWER}(t) = 100\% \times \frac{L_{CR,LOWER}(t) - L_0}{L_0}$$

**B.7.5.4** Plot rope creep ($\varepsilon_{CR,UPPER}$ and $\varepsilon_{CR,LOWER}$) vs. time on a semi-log graph with time in minutes on the logarithmic scale. Fit a straight line through the data. If the plot is nonlinear, then fit the straight line through the longer duration (300 and 3000 minute) data points only. Determine the creep over one log cycle from the slope of this line. Alternatively, a suitable curve-fit equation may be used to fit the data points.

If the creep-log time plot becomes increasingly nonlinear with time, then the creep may actually be linear with time. In this case, plot rope creep vs. time in minutes and use a suitable curve-fit equation to fit the data points.

Report the creep-log time plot (or linear time) and the percent creep per log cycle for each of the upper and lower tension values.

These data can be extrapolated to estimate the creep which will occur over longer time intervals. These data can also be extrapolated to estimate the static load-extension characteristics after longer times.

Rope length changes due to delayed elastic stretch and delayed elastic recovery can be extracted from the results of the test presented above. As these phenomena are not well understood at this time, no firm guidance can be provided for interpretation or application of these results. However, the following items should be taken into consideration.

— Delayed elastic recovery test data should be corrected for the appropriate amount of creep.

— Delayed elastic stretch test data should be corrected for elastic stretch.

— Delayed elastic stretch test data should be corrected for creep. However, it may be difficult to estimate the amount of creep for each time step with the rope under tension.

— Use the corrected test data values to calculate $\varepsilon_{DES,UPPER}(t)$, $\varepsilon_{DES,LOWER}(t)$, $\varepsilon_{DER,UPPER}(t)$ and $\varepsilon_{DER,LOWER}(t)$ for each of the four durations.

Plot the four sets of $\varepsilon_{DES,UPPER}(t)$, $\varepsilon_{DES,LOWER}(t)$, $\varepsilon_{DER,UPPER}(t)$ and $\varepsilon_{DER,LOWER}(t)$ vs. time on a semi-log graph with time in minutes on the logarithmic scale. Fit a straight line through the linear portion of the data. If any of these data sets reach steady state values, report the times and lengths for the steady state. See Figure B.3.

### B.7.6 Test Application and Modifications

Delayed elastic stretch, delayed elastic recovery and creep are properties that are largely functions of the rope fiber material (basic fiber composition plus additional treatment) and, to a lesser extent, the rope construction. Therefore, it is recommended that this test be performed on subropes or scaled ropes that are representative of a manufacturer’s product line for a particular base fiber type, It is not necessary to perform this test for each prototype rope assembly.

The tension levels provided above are for guidance only. It may be desirable to test the sample at different tension levels (10 % RBS, 20 % RBS, 40 % RBS, 60 % RBS, 80 % RBS) to provide an improved understanding of these rope properties.

This test is lengthy. If a project specific test is required by the operator, it is strongly recommended that the test specification be developed in close cooperation with all parties (operator, designer, test facility, rope supplier and base fiber supplier) so as to get the most useful information from the test.

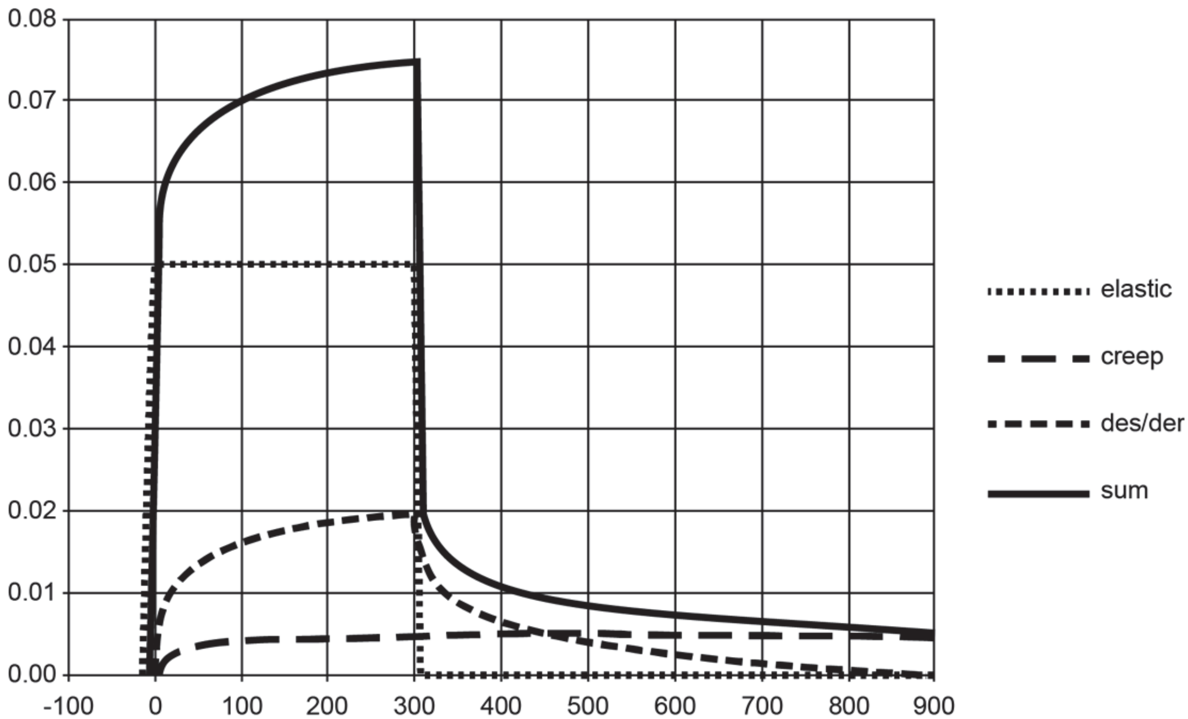


**Figure B.3—Strain Component for DES/DER/Creep Test**

# Annex C
(normative)

# Torque and Rotation Tests

## C.1 General

When torque and rotation properties are of concern, the tests described below shall be conducted.

Rope/splice torque compatibility shall be established for ropes where torque and rotation characteristics of the splice are different from those of the rope itself, and in applications where such differences can have an impact on the performance of the rope or splice.

The following torque and rotation test may be performed on full scale rope, scaled rope, or subrope (see 7.3.8).

## C.2 Test Specimen

At least one specimen, either new or previously worked, shall be tested.

The terminations shall be of sufficient strength to safely withstand 50 % of the RBS of the test specimen. Both end terminations should resist rotation in a manner which does not affect the measured rope torque and rotation characteristics. The terminations should constrain all components, which can significantly influence rotation and torque properties, including the rope jacket.

The recommended specimen should have a length of at least 40 times nominal rope diameter between rope ends of terminations.

## C.3 Test Machine and Apparatus

The test machine shall have a bed length, stroke, rate of loading, and force capacity sufficient to carry out the test.

The test machine shall be equipped with a torque measuring device coupled in series with the rope. This torque measuring device should resist any tendency of the rope to rotate. The torque measuring device should have an accuracy of ± 1 % of the expected maximum rope torque.

The test machine shall also be equipped with a rotation measuring device that should incorporate a friction compensated swivel. This friction compensated swivel should have a means of preventing rotation during the first steps of the test. This friction compensated swivel should sense and record the total rotation with an accuracy of ± 0.3 degrees per meter of rope length (± 0.1 degree per ft) up to the intended maximum tension.

## C.4 Test Procedure

1) Mount the rope specimen in the test machine and properly align the terminations to eliminate any rope twist.

2) With the friction-compensated swivel fixed to resist rotation, tension the rope to 1 % of RBS. Measure and record the torque as the rope is loaded to 1 % of RBS. Measure the length between terminations at 1 % of RBS.

3) Cycle the rope 100 times between 1 % and 35 % of RBS, measuring and recording torque vs. tension over the whole tension range on cycles 1, 10, and 100.

4) Relax the rope. Release the friction compensated swivel to allow one end of the rope to freely rotate while recording the rotation. Tension the rope to 1 % of RBS. Measure and record the rotation at the swivel as the rope is loaded to 1 % of RBS.

5) Tension the rope 100 times between 1 % and 35 % of RBS, measuring and recording rotation vs. tension over the whole tension range on cycles 1, 10, and 100.

6) Relax the rope to 1 % of RBS, hold for one hour, then measure the length between terminations.

## C.5 Data Reporting

Report the lengths measured at Steps 2 and 6.

Plot torque vs. tension during Step 2 as the specimen is first loaded to 1 % of RBS.

Plot torque vs. tension for cycles 1, 10, and 100 during step 3.

Report the rotation which occurred when the swivel was released after 100 cycles.

Plot rotation vs. tension during Step 4 as the specimen is first loaded to 1 % of RBS.

Plot rotation vs. tension for cycles 1, 10, and 100 during step 5.

# Annex D
(normative)

# Testing of Rope Tension-tension Fatigue Qualification

## D.1 General

This test is intended to demonstrate that the synthetic rope has fatigue resistance that exceeds one of the design curves shown on Figure 1 and tabulated in Table 4, and the design equation may subsequently be applied in the fatigue design of the rope. The testing parameters specified in Table 4 should be utilized for this purpose. However, regardless of the tension range used in the qualification, testing shall continue for a minimum of 5500 cycles.

## D.2 Test Specimen

At least one specimen shall be tested.

The specimen shall be terminated in the same manner as used for production ropes. The specimen length should be a minimum of 40 times nominal rope diameter between rope ends of terminations.

In accordance with 7.3.2.3, if the fatigue resistance is unaffected by wetting and such testing is approved by the RCS and the owner, the rope may be tested in the dry condition.

If wet testing is required, the specimen shall be conditioned in water as described in Annex B.

## D.3 Test Machine and Apparatus

The rope shall be tested on a tension test machine with a bed length, stroke, rate of loading, and force capacity sufficient to carry out the tests as described.

Thermal couples or other suitable temperature measuring devices should be placed firmly on the rope and insulated from the water bath.

## D.4 Test Procedure

An example tension-tension fatigue test procedure follows.

Cycle the rope about a mean tension of between 30 % and 35 % of the RBS with a tension range of between 30 % and 50 % of RBS at an agreed upon period.

The maximum temperature needs to be controlled based on the type of fiber, fiber grade, and rope construction. If the surface temperature of the rope exceeds manufacturer's limits, suspend cycling and allow the rope to relax in the water bath until its surface temperature falls to within the manufacturer's recommended temperature range. If the test is stopped because of heat, it may be desirable to increase the cycling period.

Continue cycling for the number of cycles stated in Table 4 corresponding to the tension range selected in Step 1 (but not less than 5500 cycles) to qualify for the selected design curve.

## D.5 Rope Post Test Examination

After cycling, examine the entire length of the rope, including termination, in detail for any evidence of damage, such as fiber kinking, abrasion or wear, broken fibers, etc. A break test may also be conducted on the rope or a subrope to determine the residual strength of the rope.

## D.6 Data Reporting

Record the number of applied cycles and signs of deterioration, if any. Report the visual condition of the rope and its terminations after cycling.

Synthetic ropes that pass the cycle requirements of Table 4 as per the tension range are qualified for that selected design curve.

To qualify the rope for higher fatigue endurance curves refer to Table 4 for the number of cycles required depending upon the tension range and the design TN curve selected.

# Annex E
(normative)

# Testing of Rope Strength

## E.1 Test Specimen

A minimum of five specimens shall be tested.

The specimens shall be terminated in the same manner as used on the production rope assembly, including the bush or thimble design (see 7.2.4.4). The specimen length between the ends of termination (between the ends of the splices) should be at least 40 times nominal rope diameter.

The specimen should not have been previously tensioned to more than 5 % of its estimated breaking strength nor have been cycled or maintained under tension. If this test is for used ropes, this criterion does not apply.

This testing procedure also applies to subropes as discussed in Section 7.

In accordance with 7.3.2.3, if the break strength is unaffected by wetting and such testing is approved by the RCS and the owner, the rope may be tested in the dry condition.

If wet testing is required, the entire specimen including terminations shall be soaked in water for approximately 24-hours before testing. The specimen shall be tested as soon as practical after being removed from the water. If there is a delay of more than 12 hours after soaking, the specimen shall be soaked for an additional 2 hours for each 24 hour period of delay up to a maximum of an additional 24 hours of soaking before the rope is tested. The temperature of the water shall be maintained between 15 °C and 25 °C (59 °F and 77 °F).

## E.2 Test Machine

The test machine shall have sufficient bed length, stroke, rate of loading, and force producing capacity to carry out the test as described in one pull without pause (final pull to break shall be continuous).

The test machine shall be equipped with a force measuring and recording device that is accurate to within ± 1 % of the estimated breaking force for the rope specimen. The force measuring and recording device shall be calibrated by a recognized independent calibration agency, using a reference load cell traceable to applicable national standards. This calibration shall have been done within the previous year. An original calibration certificate shall be available for examination, and a copy of this certificate shall be attached to the test report.

## E.3 Test Procedure

The specimens shall be tested as follows.

1) Cycle the rope ten times from 1 % of estimated RBS (initial tension) to 50 % of estimated RBS at the rate described below.

2) On the eleventh cycle, apply force to the rope at the rate described below until it breaks.

3) The rate of travel of the pulling head during the break test shall be such that the rope is loaded to 20 % of its estimated RBS in neither less than 2 seconds nor more than 30 seconds. The pulling head

shall then continue moving without pause at approximately that same rate of travel until the rope breaks.

4) Record the breaking force (maximum force applied to the rope). Record the location at which the rope broke, e.g. between splices, at end of splice, at crotch of splice, in back of eye, or other description of break location.

NOTE Using 10 cycles of load from reference load to 50 % RBS as well as holding the load at 50 % RBS afterwards has been used as a minimum criterion for bedding-in the rope or setting the splices. In reality, each rope or splice design has its own number of bedding-in cycles, as determined by test cycling.

See CI 1500 [1] for more information on determination of cycled strength.

## E.4 Data Reporting

The following information shall be reported for each specimen:

— the breaking tension and corresponding elongation;

— the load-elongation chart;

— the location and nature of break;

— test conditions (e.g. ambient temperature, wet or dry, any deviations, etc.).

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

The average break strength and the standard deviation of break strength should be calculated, using the data from all tests (minimum of five), and reported. Standard deviation should be computed by the n-1 formula.

# Annex F
(normative)

# Testing of Rope Axial Compression Performance

## F.1 General

This test only applies to ropes made from fibers subject to axial compression fatigue damage. This test need not be performed on polyester, nylon and HMPE ropes or subropes.

A test for axial compression performance shall be performed if the low tension design criteria in 6.3.2 are not accepted. The test specified in this annex is an example of an axial compression test which may be modified by the user.

## F.2 Test Specimen

At least one specimen shall be tested.

The specimen shall be terminated in the same manner as for the production ropes. The recommended specimen length should be a minimum of 40 times nominal rope diameter between terminations.

If wet testing is required, the specimen shall be conditioned in water as described in Annex B.

## F.3 Test Machine and Apparatus

The rope shall be tested on a tension test machine with a bed length, stroke, rate of loading, and force capacity sufficient to carry out the tests as described.

Thermal couples or other suitable temperature measuring devices should be placed firmly on the rope and insulated from the water bath.

## F.4 Test Procedure

An example test procedure follows.

1) Cycle the rope from a trough tension of 1 % of RBS to a peak tension of 25 % of RBS at a period of less than 1 minute per cycle.

2) If the surface temperature of the rope exceeds 70 °C (158 °F), suspend cycling and allow the rope to relax in the water bath until its surface temperature falls to within 10 °C (18 °F) of the temperature of the water bath.

3) Continue cycling for at least 10,000 cycles.

4) After cycling, examine the entire length of the rope, including termination, in detail for any evidence of damage, such as fiber kinking, abrasion or wear, broken fibers, etc.

5) Tension the rope to break, using the test procedure in Annex E, to determine residual strength.

## F.5 Data Reporting

The following shall be reported upon completion of the axial compression test:

a) the residual strength, both in absolute terms and as a percent of RBS;

b) the number of applied cycles;

c) the visual condition of the rope and its terminations after cycling.

If the rope does not fail below the RBS, it may be considered to endure the axial compression fatigue cycles.

# Annex G
(informative)

# Polyester Mooring Analysis Example

## G.1 General

The mooring analyst shall determine which load-elongation model to use to represent the nonlinear behavior of the polyester rope segments of the mooring line. To illustrate differences in predicted maximum offsets and tensions calculated using different load-elongation models for polyester rope, results of intact mooring analyses for a wire, polyester, chain mooring system are presented in this annex.

The two types of polyester rope load-elongation models used for this exercise are:

a) simplified constant stiffness load-elongation model (see 6.4.1.2) – four stiffness values; and

b) non-linear load-elongation model (see 6.4.1.4) – three non-linear stiffness curves.

It should be noted that neither method of analysis used in this section is a complete representation of rope behavior and should be considered approximate solutions. Therefore, the reader should not draw conclusions about the comparison of results for offsets or tensions.

Section G.4 discusses the impact of stiffness model on mooring system analytical results. The analysis for delayed elastic stretch is accounted for in G.5 onwards.

When using the linear stiffness models, the low values of stiffness used to calculate offset, typically account for the total elongation and not just the elastic stretch. The non-linear model is only one representation of stiffness, whereas the rope will have different non-linear stiffness curves for static and dynamic stiffness and the dynamic stiffness will be a function of load range as well as mean load.

The dynamic mooring analyses are consistent with API 2SK. The same mooring software was used for all cases, the only difference in the inputs to the analyses are in the load-elongation properties of the polyester rope segments.

## G.2 Mooring System Description

The vessel is a semisubmersible with two pontoons and six columns, the analyzed draft is 50 ft and the displacement is 89,400 kips. Figure G.1 shows a mooring system consisting of eight identical lines equally spaced at 22.5, 67.5, etc., degrees.

The main mooring line segments consist of 1855 ft of wire rope at the fairlead, followed by three polyester segments each of 2000 ft, and then 3600 ft of chain at the anchor, see Table G.1. The length and weight of the connectors between the wire or chain and the polyester segments and between the polyester segments themselves are included approximately in the modeled mooring line. The length of these connectors represents the pin-to-pin length of the connector only, while the weight of the connector includes the weight of the connector, thimble, and additional weight of the polyester in the splice.

In all cases, a constant water depth of 4317 ft over the anchor pattern is used and pretensions at the fairlead, in quiescent environmental conditions, are 250 kips for all lines. Consequently the anchor distance and grounded line length varies depending on the load-elongation model used for the polyester segments.

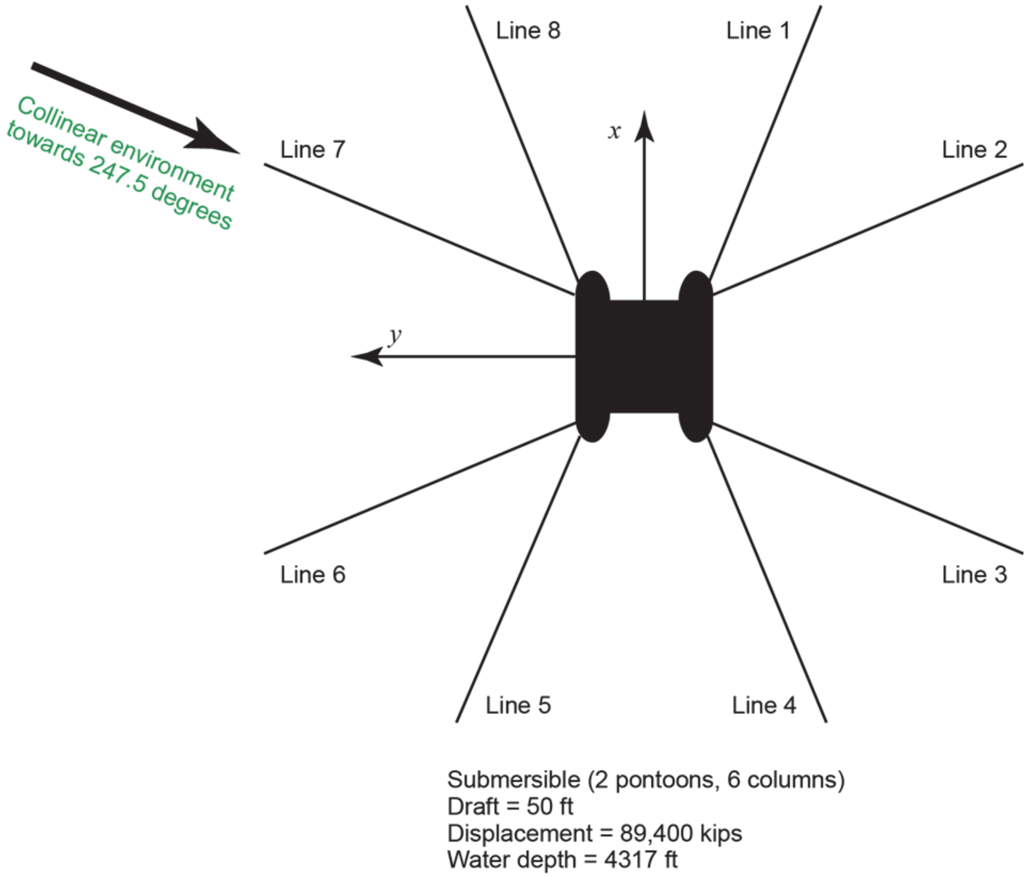


**Figure G.1—Mooring Pattern for Identical Eight Line Equally Spaced Mooring System**

**Table G.1—Mooring Line Properties, Eight Identical Lines**

| Segment | Type | Length ft | Diameter In. | Weight in Water lb/ft | CBS kip | Stiffness kip |
|---|---|---|---|---|---|---|
| Segment 1 (at fairlead) | Wire | 1855 | 3.5 | 22.1 | 1450 | 93,460 |
| Connector | Steel | 6 | 10.0 | 405.0 | -- | -- |
| Segment 2 | Polyester | 2000 | 7.0 | 2.9 | 1764 | Varied |
| Connector | Steel | 6 | 10.0 | 405.0 | -- | -- |
| Segment 3 | Polyester | 2000 | 7.0 | 2.9 | 1764 | Varied |
| Connector | Steel | 6 | 10.0 | 405.0 | -- | -- |
| Segment 4 | Polyester | 2000 | 7.0 | 2.9 | 1764 | Varied |
| Connector | Steel | 6 | 10.0 | 405.0 | -- | -- |
| Segment 5 (at anchor) | Chain | 3600 | 3.0 | 74.8 | 1356 | 102,350 |
| | Total = | 11,479 | | | | |

NOTE All lengths are unloaded lengths, i.e., lengths under zero tension.

The four linear and three nonlinear curves used to represent the load-elongation properties of the polyester rope segments are shown in Figure G.2. These load-elongation models are intended to approximately bound the range typically used to represent polyester rope stiffness over the life of the rope (5 < EA/CBS < 40, see Table 3).

Table G.2 summarizes, for the seven polyester load-elongation curves, the anchor distances and grounded line lengths for fairlead pretensions of 250 kips, where the total unloaded length of the three polyester segments in each line is 6000 ft.

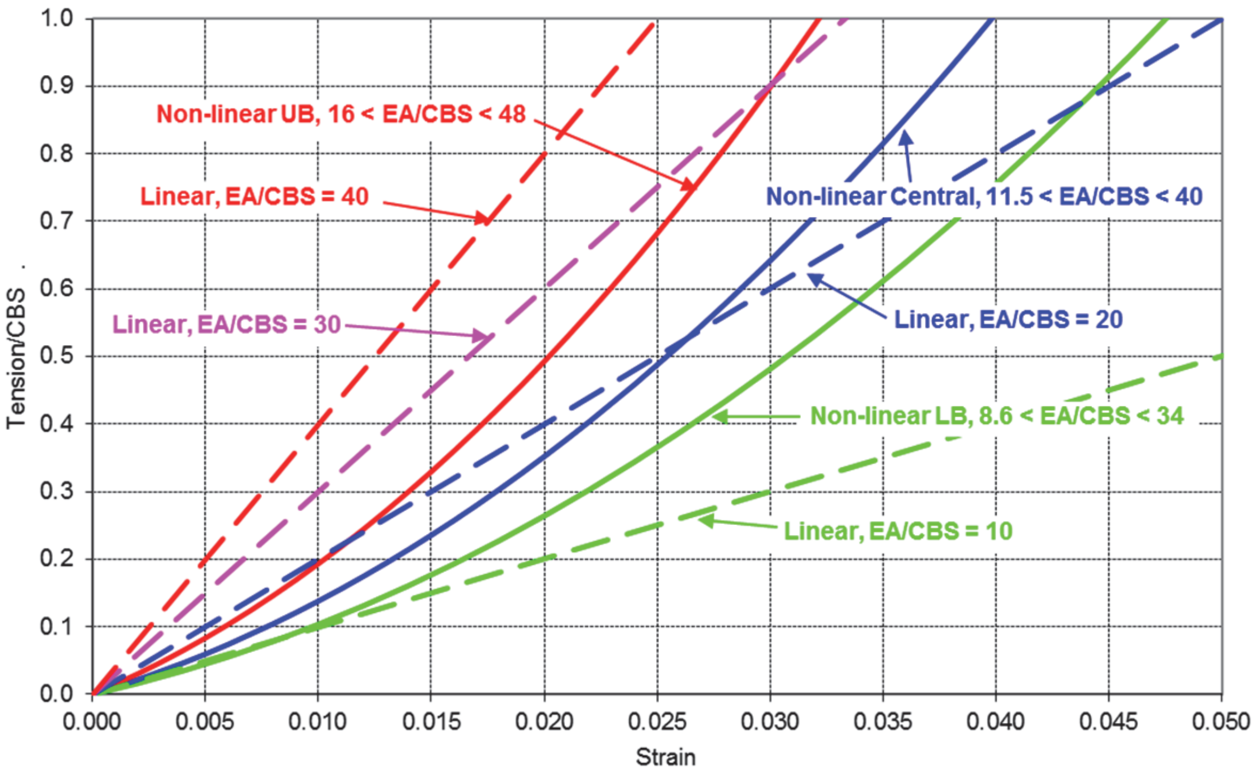


**Figure G.2—Linear and Nonlinear Polyester Load-elongation Models**

**Table G.2—Anchor Distances and Grounded Lengths for Pretensions of 250 kips**

| Description | | Range of EA/CBS | | | Anchor Distance ft | Grounded Length ft |
|---|---|---|---|---|---|---|
| | | 0 % CBS | 50 % CBS | 100 % CBS | | |
| Nonlinear | Lower bound (LB) | 8.6 | 25 | 34 | 10,392 | 2369 |
| | Central | 11 | 29 | 40 | 10,376 | 2367 |
| | Upper bound (UB) | 16 | 35 | 48 | 10,360 | 2365 |
| Linear | EA/CBS = 10 | 10 | | | 10,402 | 2370 |
| | EA/CBS = 20 | 20 | | | 10,360 | 2365 |
| | EA/CBS = 30 | 30 | | | 10,346 | 2363 |
| | EA/CBS = 40 | 40 | | | 10,339 | 2362 |
| NOTE | Anchor distance is the horizontal distance measured from the fairlead. | | | | | |

## G.3 Metocean Conditions

Hurricane metocean conditions for return periods of between 5 and 40 years are used in this example and are summarized in Table G.3.

**Table G.3—Hurricane Metocean Conditions and Mean Loads for Return Periods between 5 and 40 Years**

| **Return Period** Years | **Wind Speed at 10 m** | | **Waves** | | | **Surface Current** knots | **Total Mean Load** kips |
|---|---|---|---|---|---|---|---|
| | **1-hr** knots | **1-min** knots | $H_s$ ft | $T_p$ s | $\gamma$ | | |
| 5 | 44.7 | 53.7 | 23.0 | 12.0 | 2 | 1.75 | 497 |
| 7.5 | 54.9 | 67.2 | 28.0 | 12.7 | 2 | 2.20 | 735 |
| 10 | 62.2 | 77.1 | 31.5 | 13.2 | 2 | 2.53 | 930 |
| 12 | 65.8 | 82.0 | 35.2 | 13.6 | 2 | 2.78 | 1062 |
| 14 | 68.5 | 85.8 | 37.7 | 14.0 | 2 | 2.96 | 1165 |
| 16 | 70.6 | 88.8 | 39.6 | 14.2 | 2 | 3.10 | 1247 |
| 20 | 73.8 | 93.3 | 42.3 | 14.6 | 2 | 3.31 | 1372 |
| 25 | 76.6 | 97.3 | 44.4 | 14.9 | 2 | 3.48 | 1482 |
| 30 | 78.6 | 100.2 | 45.8 | 15.0 | 2 | 3.60 | 1563 |
| 40 | 81.3 | 104.2 | 47.5 | 15.3 | 2 | 3.76 | 1673 |
| NOTE Total mean load is based on the 1-hour wind speed and collinear wind, wave, and current towards 247.5 degrees | | | | | | | |

## G.4 Mooring Analyses

### G.4.1 General

Dynamic frequency domain mooring analyses were performed based on collinear wind, wave, and current with the current uniform over the draft of the vessel. The environmental direction used for the mooring analyses is towards 247.5 degrees (down line 7, see Figure G.1), as this direction results in the largest line tensions and very nearly the largest offsets. The ISO wind gust spectrum, defined by the 1-hour mean wind speed at 10 m above mean water level, is used with waves defined by the JONSWAP wave spectrum. Current is modeled as steady.

### G.4.2 Comparison of Linear and Nonlinear Load-Elongation Models

#### G.4.2.1 General

In all cases, the only input that was varied in the mooring analyses was the stiffness model used for the polyester rope segments; all polyester line segments are modeled with an unloaded length of 2000 ft, a total of 6000 ft per line. Mooring line components are modeled as purely elastic, that is the permanent construction stretch, delayed elastic stretch and delayed elastic recovery are not modeled in the software and needs to be accounted for separately either by adjusting the unloaded lengths of the mooring lines or by making some adjustment to the load-elongation model used. Note that changing the load-elongation model used to account for permanent and/or recoverable stretch, rather than changing the unloaded length of the line, affects the mooring line and system stiffnesses used to calculate low frequency responses as well as wave frequency dynamic tensions.

Each mooring analysis uses the same linear or nonlinear polyester load-elongation curve for all of the eight lines and for calculating the mean offsets and tensions, low frequency vessel motions and tensions, and wave frequency dynamic line tensions. So, for the four linear load-elongation curves, the same value of polyester rope stiffness (EA/CBS equal to 10, 20, 30, or 40) is used for windward, leeward, and side lines. While, for the three nonlinear load-elongation curves, the polyester rope tangent stiffness under mean load is higher for the windward lines than for the leeward lines, with the side lines having intermediate tangent stiffness values. Similarly, the polyester tangent stiffness used to calculate wave frequency tensions depends not only on the line's direction (windward, leeward, or side) but also on which of API 2SK's two offset or tension combinations (mean plus low frequency maximum plus wave frequency significant or mean plus low frequency significant plus wave frequency maximum) is being evaluated.

Table G.4 and Table G.5 summarize maximum offsets and tensions for the three nonlinear and four linear load-elongation curves respectively.

### G.4.2.2 Maximum Offsets

The maximum offsets predicted by the nonlinear and linear load-elongation models summarized in Table G.4 and Table G.5 are plotted in Figure G.3.

For the nonlinear models, the maximum offset predicted by the lower bound stiffness curve for the 5-year return period condition is 17.6 ft (0.41 % WD) greater than that predicted by the upper bound stiffness curve. While for the 40-year return period conditions the maximum offset is 37.2 ft (0.86 % WD) greater for the lower bound curve than for the upper bound curve.

Over the full range of linear stiffness curves considered, i.e., EA/CBS = 10 to EA/CBS = 40, the maximum offsets predicted vary by 51 ft (1.18 % WD) for the 5-year return period environment and by 209 ft (4.84 % WD) for the 40-year return period. However for a linear stiffness range of EA/CBS = 20 to EA/CBS = 40, the predicted maximum offsets vary by 18 ft (0.41 % WD) for the 5-year return period environment and by 74 ft (1.71 % WD) for the 40-year return period condition.

In general, the three nonlinear load-elongation curves predict maximum offsets that lie between those predicted by the linear stiffness curves with EA/CBS values of 20 and 30.

**Table G.4—Maximum Vessel Offsets and Tensions—Nonlinear Load-elongation Curves**

| Return Period years | Nonlinear Upper bound | | Nonlinear Central | | Nonlinear Lower Bound | |
|---|---|---|---|---|---|---|
| | **Offset** ft | **Tension** % CBS | **Offset** ft | **Tension** % CBS | **Offset** ft | **Tension** % CBS |
| 5 | 181 | 32 | 190 | 32 | 198 | 32 |
| 7.5 | 259 | 41 | 272 | 41 | 283 | 41 |
| 10 | 322 | 49 | 337 | 49 | 349 | 49 |
| 12 | 362 | 55 | 379 | 55 | 392 | 55 |
| 14 | 391 | 61 | 409 | 61 | 422 | 61 |
| 16 | 412 | 65 | 431 | 65 | 445 | 66 |
| 20 | 443 | 73 | 463 | 73 | 476 | 73 |
| 25 | 467 | 80 | 488 | 80 | 502 | 80 |
| 30 | 484 | 86 | 505 | 86 | 519 | 86 |
| 40 | 505 | 94 | 528 | 93 | 542 | 93 |

NOTE Offsets and tensions are the larger of the two API 2SK combinations of mean plus low frequency maximum plus wave frequency significant or mean plus low frequency significant plus wave frequency maximum.

**Table G.5—Vessel Offsets for Four Linear Load-Elongation Curves**

| Return Period years | Linear EA/CBS = 40 | | Linear EA/CBS = 30 | | Linear EA/CBS = 20 | | Linear EA/CBS = 10 | |
|---|---|---|---|---|---|---|---|---|
| | Offset ft | Tension % CBS | Offset ft | Tension % CBS | Offset ft | Tension % CBS | Offset ft | Tension % CBS |
| 5 | 166 | 33 | 172 | 33 | 184 | 32 | 217 | 31 |
| 7.5 | 239 | 42 | 248 | 41 | 266 | 40 | 316 | 39 |
| 10 | 297 | 50 | 309 | 49 | 333 | 48 | 398 | 46 |
| 12 | 335 | 56 | 349 | 55 | 376 | 54 | 452 | 51 |
| 14 | 362 | 61 | 378 | 60 | 408 | 58 | 494 | 56 |
| 16 | 383 | 66 | 400 | 64 | 433 | 63 | 526 | 59 |
| 20 | 411 | 73 | 431 | 71 | 468 | 69 | 573 | 65 |
| 25 | 434 | 80 | 456 | 78 | 497 | 75 | 613 | 70 |
| 30 | 450 | 85 | 473 | 83 | 518 | 80 | 642 | 74 |
| 40 | 471 | 92 | 496 | 90 | 544 | 86 | 679 | 79 |

NOTE Offsets and tensions are the larger of the two API 2SK combinations of mean plus low frequency maximum plus wave frequency significant or mean plus low frequency significant plus wave frequency maximum.

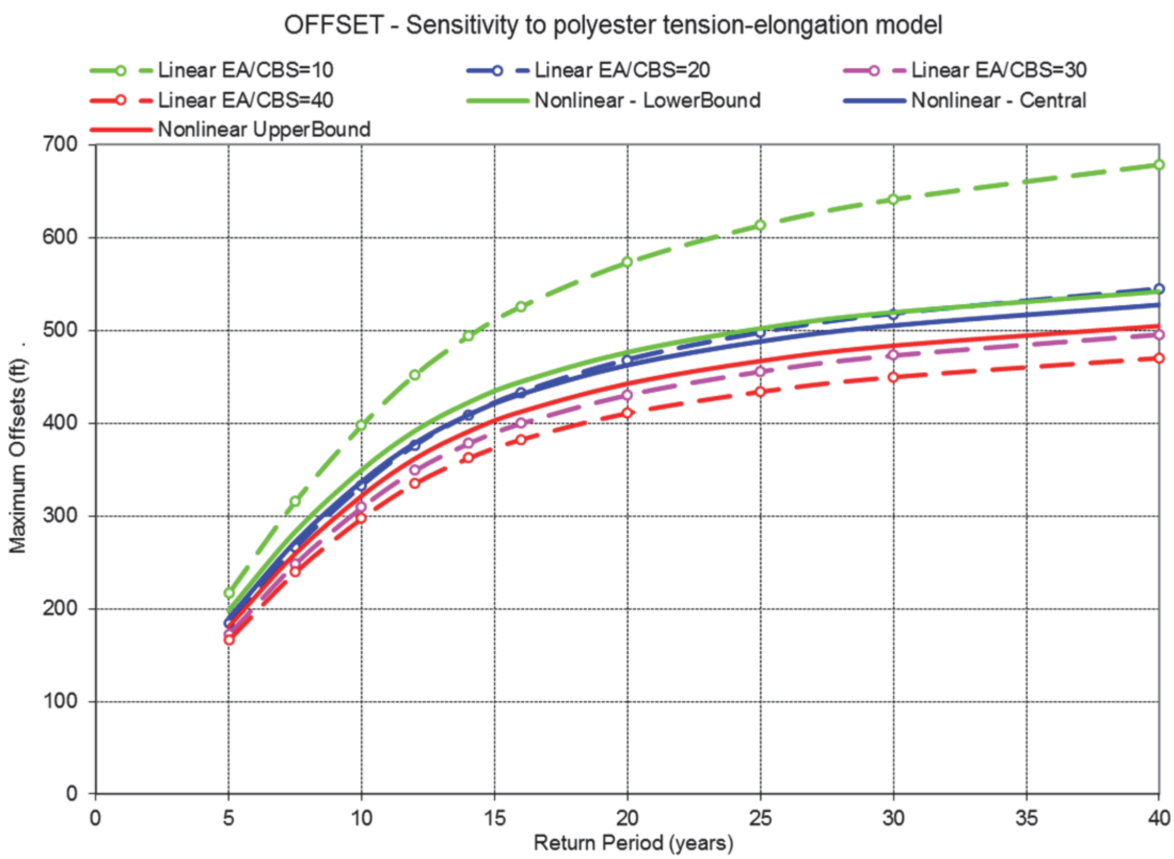


**Figure G.3—Maximum Vessel Offset, Nonlinear and Linear Load-elongation Curves**

### G.4.2.3 Maximum Tensions

The maximum tensions predicted by the nonlinear and linear load-elongation curves summarized in Table G.4 and Table G.5 are plotted in Figure G.4.

The maximum tensions predicted by the lower and upper bound nonlinear stiffness curves for the 5-year return period environmental conditions are practically identical at 32 % CBS. For the 40-year return period environmental condition, the maximum tension predicted by the upper bound stiffness curves is 1 % CBS greater than that predicted by the lower bound model.

Over the full range of linear stiffness curves considered, maximum predicted tensions vary by 2 % CBS for the 5-year return period environment and by 13 % CBS for the 40-year return period. However, for linear stiffness in the range of EA/CBS = 20 to EA/CBS = 40, the predicted maximum tensions vary by between 1 % CBS at the 5-year return period and 6 % CBS for the 40-year return period environment.

In general, the four constant stiffness curves predict lower tensions than the three nonlinear load-elongation curves. Only for maximum tensions less than 60 % CBS does the constant stiffness curve with a stiffness of EA/CBS = 40 predict slightly larger tensions than the nonlinear curves.

## G.5 Un-stretched Line Length and Length Management

In addition to the instantaneous elastic strain or stretch, polyester rope displays two additional types of stretch:

a) permanent or construction stretch; and

b) delayed elastic stretch and delayed elastic recovery, this can be seen on the graph of polyester rope load-elongation test results (DNV rope test) in Figure 2.

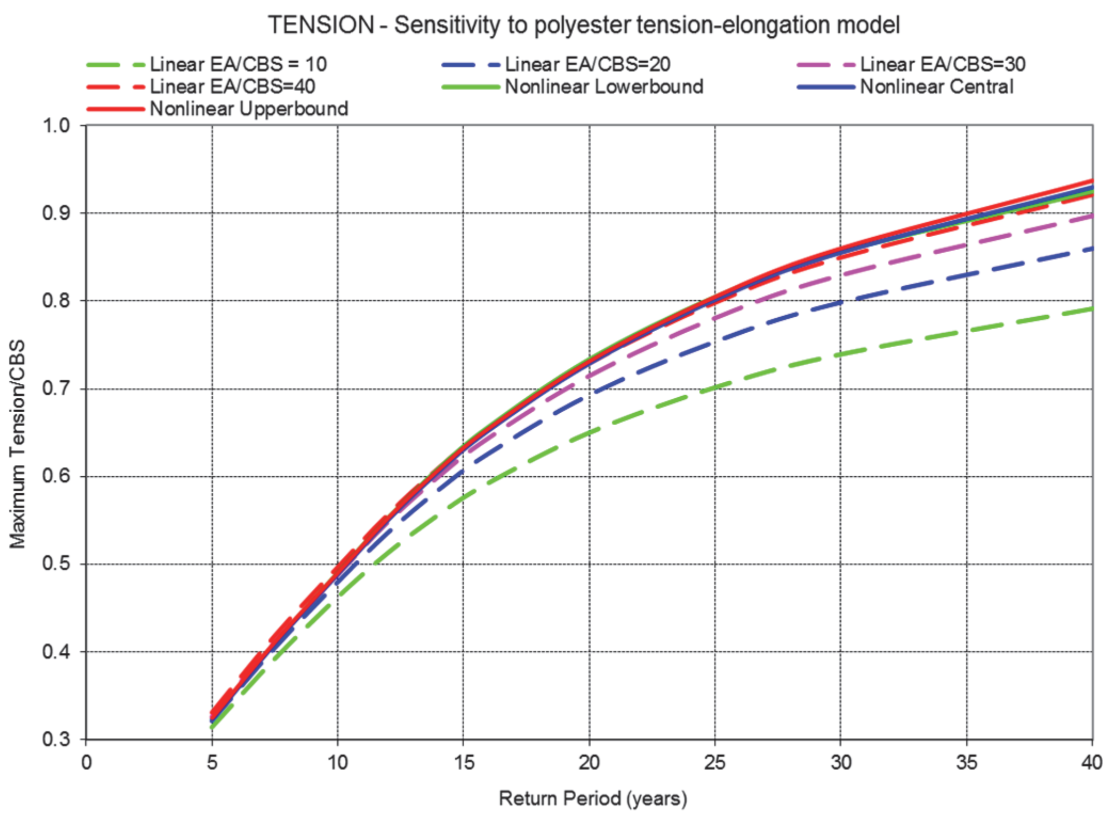


**Figure G.4—Maximum Tensions, Nonlinear and Linear Load-elongation Curves**

The permanent construction stretch that results when the rope is loaded above its previous maximum load is indicated along the x or strain-axis of Figure 2. For the test rope, the permanent construction stretch is approximately 4.3 % for a maximum tension of 40 % CBS, 5.2 % for 60 % CBS, and 6.0 % for a maximum tension of 80 % CBS.

The delayed elastic stretch and delayed elastic recovery may be evaluated by plotting the change in strain against time for the portions of the load-elongation test where the rope was held at constant tension for 1-hour. Figure G.5 shows the absolute value of the change in strain over the four 60 minute periods that a constant tension of either 60 % or 1 % CBS was maintained for part C of the load-elongation test. The dashed portions of the curves in the top graph are extrapolated from the recorded results. The bottom graph in Figure G.5 shows the tension time history for parts B and C of the load-elongation test. In the top graph, the curve labeled C1 is the change in strain (measured from the start of the constant tension period) for the first time that the rope was loaded above 40 % CBS to 60 % CBS and held at 60 % CBS for 1-hour. Consequently, the stretch or strain for the C1 curve includes some permanent construction stretch in addition to the delayed recoverable stretch and shows larger strain rates than the C3 curve. The C2 and C4 curves show that the rate of stretch recovery (the absolute value of the strain is plotted) at 1 % CBS is greater than the rate of delayed stretch at 60 % CBS.

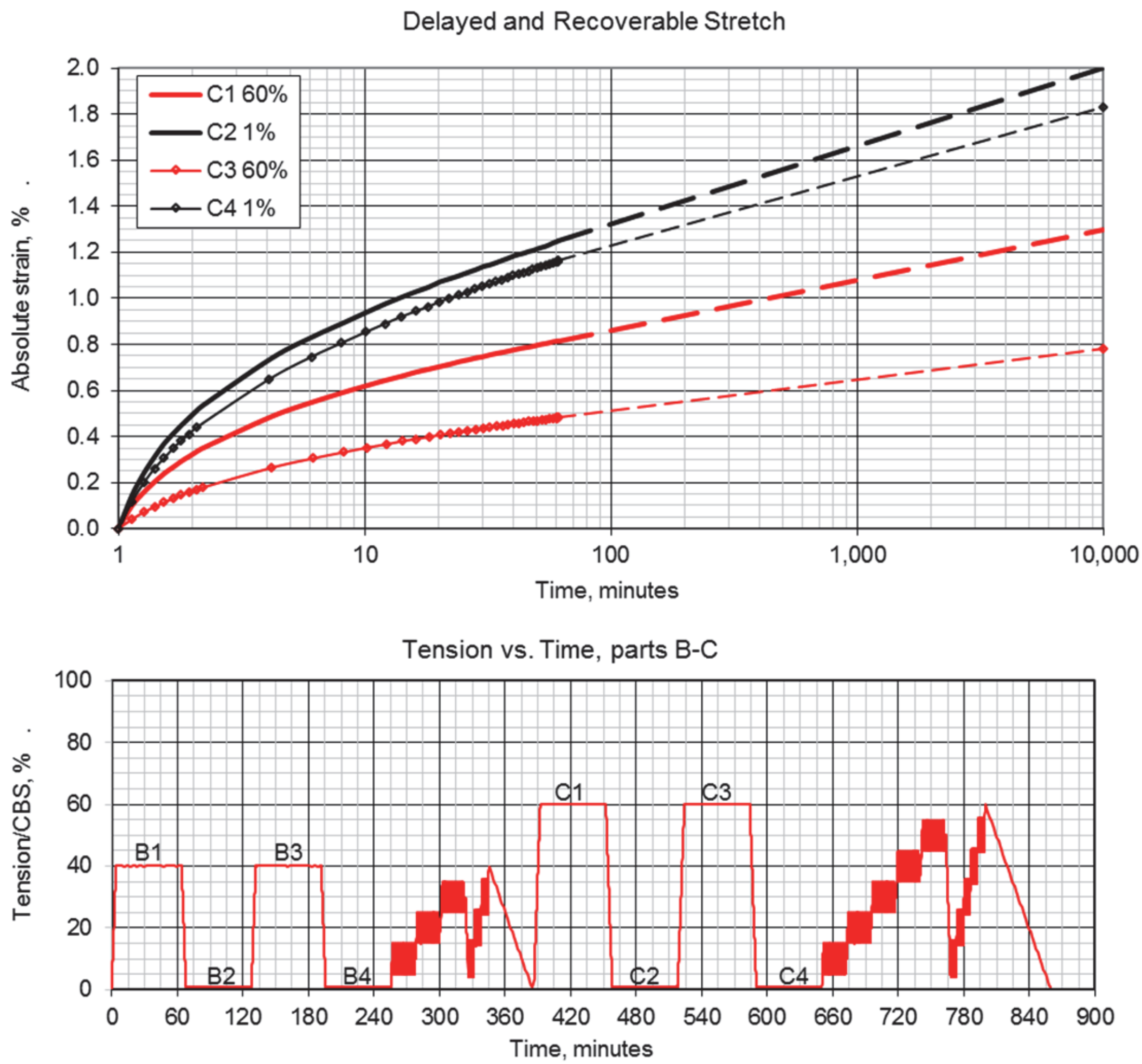


**Figure G.5—Polyester Rope Delayed and Recoverable Elastic Stretch**

It is quite possible that the length of the polyester rope segments in a mooring system could increase by 2 % or more with respect to the post-installation length, depending on the load history for the line, in particular the maximum load and the duration of sustained loads. Depending upon the length management procedures, adjusting the outboard length of the line segment at the fairlead can be used to compensate for the increase in length of the polyester rope. Alternatively, the system may be designed such that change in polyester rope length does not require adjustment of the fairlead segment.

To illustrate the effect that polyester line length and length management has on the maximum offsets and tensions, two additional mooring systems have been analyzed using the central nonlinear load-elongation model. Table G.6 summarizes the total polyester lengths for each mooring line, the outboard lengths of the fairlead wire rope segments, and the pretensions. In these cases the fairlead to anchor distance was fixed at 10,376 ft with a constant anchor chain length of 3600 ft for all lines. For these analyses the same collinear environmental direction of 247.5 degrees, “down line 7”, is used, see Figure G.1.

Case 1 is the previously analyzed mooring system with a total unloaded polyester length of 6000 ft for all eight lines. This case may be considered representative of conditions immediately after the mooring system is installed and test tensioned to the installation tension.

In Case 2-a the total polyester segment lengths of the windward lines (7 and 8) are increased by 1 % while the length of the side lines are increased by 0.5 % and leeward line lengths are unchanged. This case could represent the condition of the mooring system at the end of a significant storm in which lines 7 and 8 were the windward lines, seeing the maximum tensions, while lines 3 and 4 were the slack or leeward lines.

In Case 2-b the permanent stretch of the polyester rope segments is the same as for Case 2-a, 1 % for windward lines and 0.5 % for side lines, with leeward lines unchanged. However, in this case the length of the fairlead wire segments are adjusted to return the vessel to a position with nominal pretensions of 250 kips.

**Table G.6—Unstretched Total Polyester Rope Lengths, Outboard Wire Rope Lengths, and Pretensions for Three Moorings**

| Line Number | Case 1 | | | Case 2-a | | | Case 2-b | | |
|---|---|---|---|---|---|---|---|---|---|
| | Poly Length ft | Wire Length ft | Tension kips | Poly Length ft | Wire Length ft | Tension kips | Poly Length ft | Wire Length ft | Tension kips |
| 1 | 6000 | 1855 | 250 | 6030 | 1855 | 234 | 6030 | 1824 | 249.8 |
| 2 | 6000 | 1855 | 250 | 6030 | 1855 | 211.3 | 6030 | 1824 | 250 |
| 3 | 6000 | 1855 | 250 | 6000 | 1855 | 225.5 | 6000 | 1855 | 252 |
| 4 | 6000 | 1855 | 250 | 6000 | 1855 | 225.5 | 6000 | 1855 | 252 |
| 5 | 6000 | 1855 | 250 | 6030 | 1855 | 211.3 | 6030 | 1824 | 250 |
| 6 | 6000 | 1855 | 250 | 6030 | 1855 | 234 | 6030 | 1824 | 249.8 |
| 7 | 6000 | 1855 | 250 | 6060 | 1855 | 215.9 | 6060 | 1793 | 249.7 |
| 8 | 6000 | 1855 | 250 | 6060 | 1855 | 215.9 | 6060 | 1793 | 249.7 |
| | | average = | 250 | | | 228 | | | 249.9 |

NOTE 1 Case 1 – is the previous case; all polyester segments are equal length

NOTE 2 Case 2-a – windward polyester lengths (lines 7 and 8) increased by 1 %, side lines (lines 1, 2, 5, 6) increased by 5 %, and leeward lines unchanged. All wire rope outboard lengths unchanged.

NOTE 3 Case 2-b – as for case 2-a with wire rope lengths adjusted to maintain nominal pretensions of 250 kips.

The vessel's offset under quiescent environmental conditions for the three mooring systems are summarized in Table G.7.

**Table G.7—Quiescent Equilibrium Vessel Offsets for Three Moorings**

| Case | global-x ft | global-y ft | Total ft | Direction deg |
|---|---|---|---|---|
| Case 1 | 0 | 0 | 0 | – |
| Case 2-a | – 21.8 | – 21.8 | 38 | – 135 |
| Case 2-b | 17 | 17 | 24 | 45 |

The cases in Table G.7 are not intended to be representative of the line length scenarios that should be considered by the mooring designer or analyst. Rather, they have been constructed as simple cases to illustrate the sensitivity of maximum offsets and tensions to difference in polyester segment lengths and length management scenarios that are within the realm of possibility.

Maximum vessel offsets and line tensions for the three moorings summarized in Table G.6 and Table G.7 are presented in Table G.8 and plotted on Figure G.6 and Figure G.7.

**Table G.8—Maximum Vessel Offsets and Tensions for Three Moorings**

| Return Period years | Nonlinear Central C1 | | Nonlinear Central C2-a | | Nonlinear Central C2-b | |
|---|---|---|---|---|---|---|
| | Offset ft | Tension % CBS | Offset ft | Tension % CBS | Offset ft | Tension % CBS |
| 5 | 190 | 32.3 | 236 | 30.4 | 189 | 32.3 |
| 7.5 | 272 | 41.0 | 326 | 39.6 | 271 | 41.0 |
| 10 | 337 | 48.9 | 395 | 47.9 | 336 | 48.9 |
| 12 | 379 | 55.1 | 438 | 54.1 | 378 | 55.1 |
| 14 | 409 | 60.6 | 470 | 59.6 | 408 | 60.5 |
| 16 | 431 | 65.3 | 493 | 64.4 | 430 | 65.3 |
| 20 | 463 | 72.9 | 525 | 72.1 | 462 | 72.9 |
| 25 | 488 | 80.2 | 551 | 79.4 | 487 | 80.1 |
| 30 | 505 | 85.5 | 569 | 84.8 | 504 | 85.5 |
| 40 | 528 | 93.0 | 592 | 92.3 | 527 | 93.0 |
| NOTE Collinear environmental direction is down line 7. | | | | | | |

The maximum offsets for the three mooring systems summarized in Table G.8 are plotted on Figure G.6. Maximum vessel offsets are almost identical for mooring Case 1 and Case 2-b, which includes line management to achieve nominal pretensions of 250 kips. However, the offsets for Case 2-a (polyester segment lengths increased by 1 % for windward lines, 0.5 % for side lines and unchanged for leeward lines) are between about 47 and 64 ft greater than for Case 1 for return periods of 5 and 40 years, respectively. These differences in maximum offset are significantly larger than those resulting from the lower and upper bound nonlinear load-elongation models reported in Table G.4.

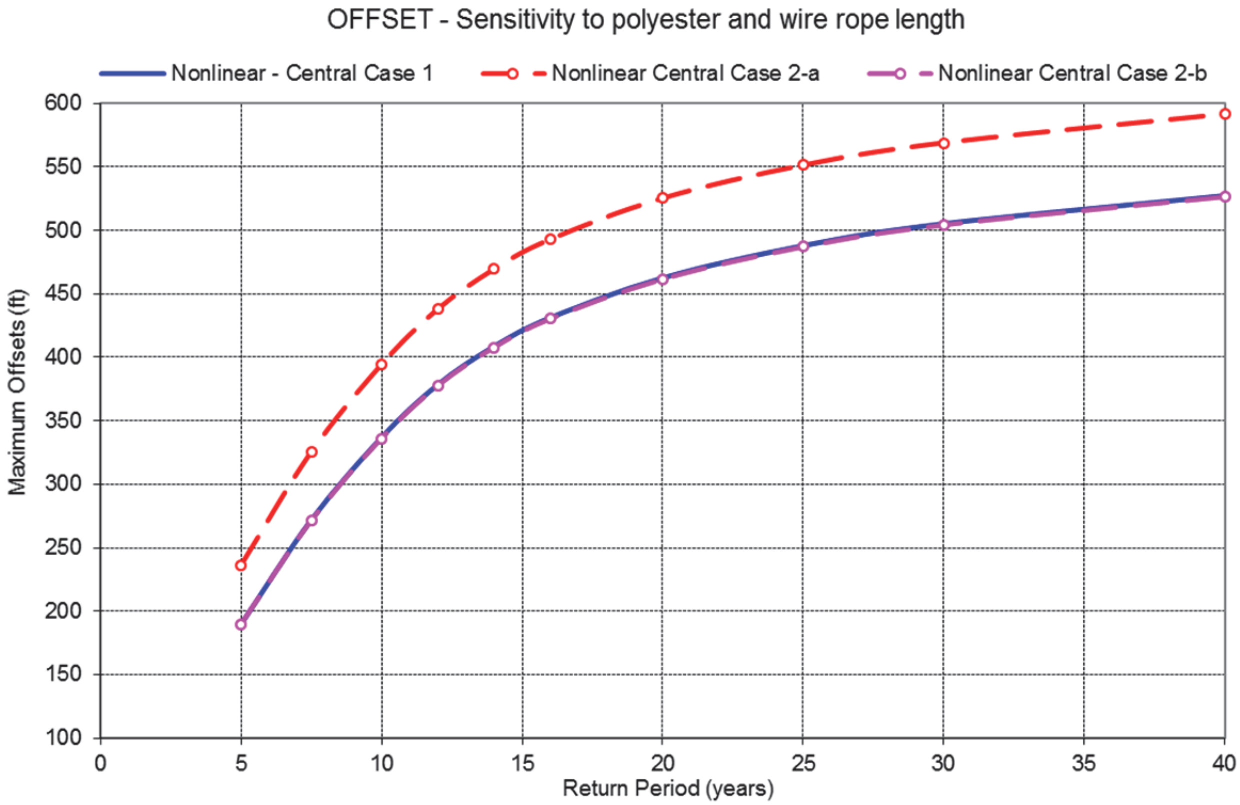


Figure G.6—Maximum Vessel Offsets for Three Nonlinear Moorings—Cases 1, 2-a, and 2-b

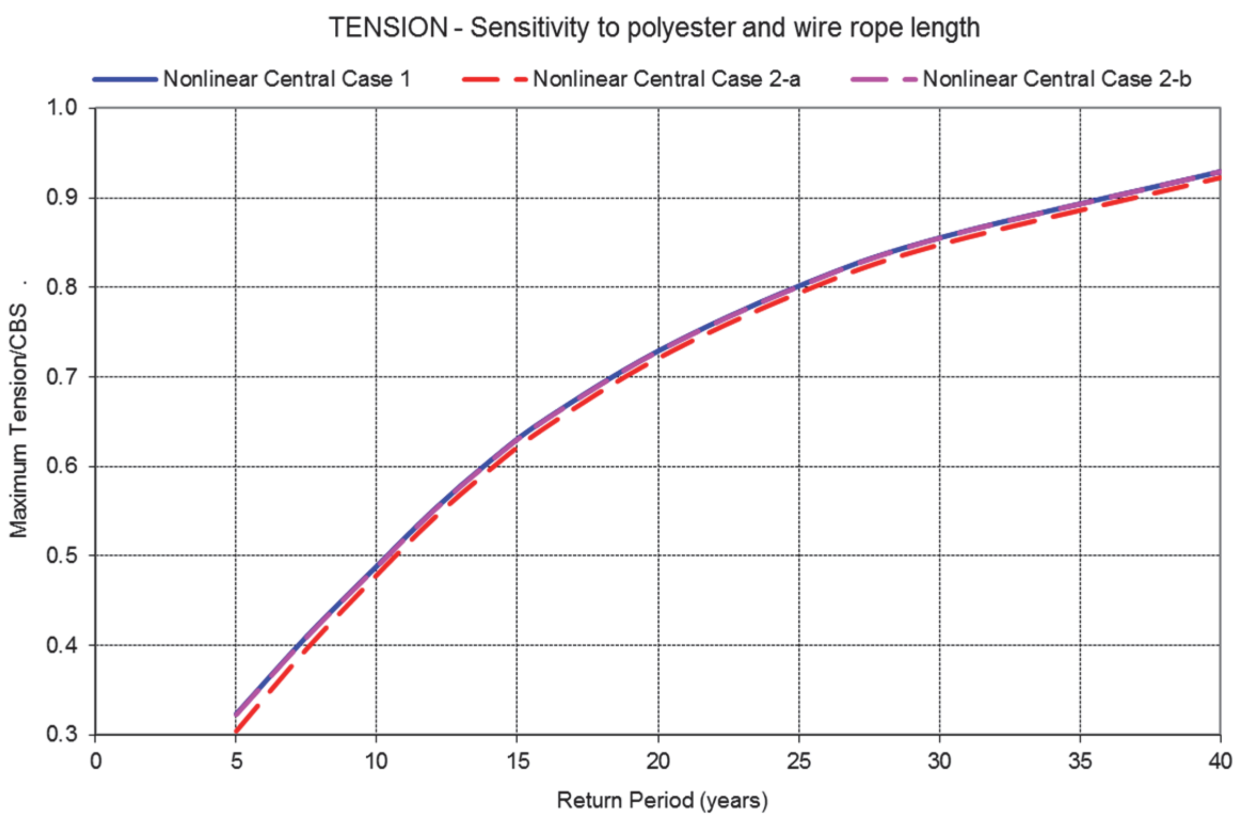


Figure G.7—Maximum Tensions for Three Nonlinear Moorings—Cases 1, 2-a, and 2-b

Maximum tensions for the three mooring systems summarized in Table G.8 are plotted in Figure G.7. Maximum tensions are practically identical for the nonlinear mooring Case 1 and Case 2-b, which includes line adjustment to achieve nominal pretensions of 250 kips. The differences in the maximum tensions between Case 1 and Case 2-a are slightly larger than 1 % CBS for tensions below about 45 % CBS and slightly less than 1 % CBS for tensions above 45 % CBS.

For the particular mooring system analyzed, the results indicate that maximum vessel offsets are more sensitive to variations in the unloaded length used in modeling the polyester rope segments and line length management, than they are to uncertainties in the nonlinear (instantaneous) elastic load-elongation model. For the extreme environmental conditions analyzed, maximum tensions are fairly insensitive to the unloaded line length of the polyester rope segments, length management, and the nonlinear elastic load-elongation modeling of the polyester rope.

# Bibliography


[1] CI[4] 1500, *Test Methods for Fiber Rope.*

[2] CI 2003, *High Tenacity Fibers Chart.*

[3] ISO 2307, *Fiber ropes—determination of certain physical and mechanical properties.*

[4] *New Facts on the Use of Dyneema Ropes in Offshore Applications*; Bosman, R., ISS 2005.

[5] *On The Origin of Heat Buildup in Polyester Rope*; Bosman, R.L.M., IEEE 1996.

[6] *Fiber Rope Testing 1995-97 Final Report Phase 1 and 2-A Study into the Mechanical Properties and Heat Build-up Characteristics of Small Scale and Full Scale Polyester and Aramid Rope*; Norsk Hydro JIP (1997).

[7] *The Durability of Polyester Ropes*; National Engineering Laboratory and Tension Technology International, Joint Industry Project, 2005.

[8] *Tensions and Bending Fatigue Test Results of Synthetic Rope*; Karnoski S.R., Liu F.C., OTC 5720 (1988).

[9] *Fiber Tethers 2000, High Technology Fibers for Deepwater Tethers*; NDE/TTI Joint Industry Study, Phase 1, NDE/NEL/TTI, Noble Denton Report L17317/NDE/rwps, February 10, 1995 with Rev 1 additions dated June 20, 1995.

[10] *Avoiding Fiber Axial Compression Fatigue in the Design and Use of Tension Members*; Flory, J.F., IEEE, 1986 (pg 93-104).

[11] *Engineers Design Guide for Deepwater Fibre Moorings*; NDE/TTI Joint Industry Study, including design practice document and engineering commentary, First Edition, January 1, 1999. (OPL Publication).

[12] *Yarn-on-Yarn Abrasion Testing of Rope Yarns. Part III: The Influence of Aqueous Environments*; Goksoy and Hearle, J. Textile Inst. 79 443-450.

[13] *Lightweight Materials for Deepwater Moorings*; Del Vecchio, C.J.M., PhD. Thesis, Reading Univ. 1992.

[14] *Fatigue of SPM Mooring Hawsers*; Parsey, M.R., Paper No. 4307, Offshore Technology Conference, Houston, May 1982.

[15] *Procedures for Quality Control and Inspection during Production of Hawsers*; OCIMF, Published by Witherby & Co. Ltd, London on behalf of OCIMF (1987).


---

[4] The Cordage Institute, 994 Old Eagle School Road, Suite 1019, Wayne, PA 19087, www.ropecord.com.

[16] *Polyester Rope Degradation Under Storage Conditions*; Ricardo Celio Freire Goncalves, Alexandro Voronoff, DOT 2004, New Orleans, Louisiana.

[17] *Polyester Mooring Systems - Petrobras Experience*; Costa, Luis C.S., Castro, Gustavo A.V., Goncalves, Ricardo C.F., Araujo, Ricardo T., Dot 2001.

[18] *Guide to Purchasing Hawsers*; OCIMF, Published by Witherby & Co. Ltd, London on behalf of OCIMF (1987).

[19] *Glossary of Marine Fiber Rope Terms*; Task Committee on Marine Fiber Rope of the Waterway, Port, Coastal and Ocean Division of the American Society of Civil Engineers (1993).

[20] *Appraisal of Lightweight Moorings for Deep Water Applications*; Chaplin C.R., Del Vecchio C.J.M., OTC 6965 (1992).

[21] *Prototype Rope Testing*; OCIMF, Published by Witherby & Co. Ltd, London on behalf of OCIMF (1987).

[22] *Admiralty Manual of Seamanship Volume 1*; B.R. 67(1), Her Majesty's Stationery Office (1964).

[23] *Admiralty Manual of Seamanship Volume 2*; B.R. 67(2), Her Majesty's Stationery Office (1967).

[24] *Yarn on Yarn Abrasion Testing of Rope Yarns. Part III: The Influence of Aqueous Environments*; Goksoy and Hearle, J. Textile Inst. 79 443-450.

[25] *Monitoring Fishbite Activities and Protecting Synthetic fiber Ropes Used in Deepsea Moorings*; Berteaux, H.O., Prindle, B, Putman, S., 1993.

[26] *Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring*; August 2011, American Bureau of Shipping.

[27] *Guidance Notes for Certification of Synthetic Fiber Ropes for Mooring Systems*; Document Reference NI 432 DTO R00 E, Bureau Veritas, Paris La Defense, 1997.

[28] *Certification of Offshore Mooring Fiber Ropes*; DNV-OS-E303 Det Norsk Veritas (1998) Certification Note 2.13, Draft in Progress, 1998.

[29] *Fiber Ropes in Offshore Mooring Systems*; Lloyds Register (1999), LR Report OS/TR/97008, Rev. B, Draft in Progress, March 1999.

[30] *The Installation of Spiral Strand Mooring Cables in Deep Water*; Firth, K.M., and Sefton, S.L., Bridon Structural Systems, Technical Report, Bridon, Doncaster, October 1997.

[31] *Continuous Advances in Mooring and Anchoring*; IBC 2nd Annual Conference on June 2, 1997.

[32] *Development of API 2SM for Synthetic Fiber Rope Moorings*; Lee, Ming-Yao, Devlin Paul and Kwan Chi-Tat Thomas, OCT 12178 (2000).

[33] *Polyester Moorings Reliability and Data Uncertainty Assessment*; EQE International.

[34] *Defining, Measuring, and Calculating the Properties of Fiber Rope Deepwater Mooring Lines*; Flory, J.F., Banfield, S.P. and Petruska, D.J, OTC 16151, 2004 Offshore Technology Conference Proceedings, SPE, Richardson, TX, 2004.

[35] *Durability of Polyester Ropes Used as Deepwater Mooring Lines*, Flory, J.F and S.J. Banfield, Oceans 2006 Conference Proceedings, MTS, Columbia MD, IEEE, Piscataway, NJ, 2006.

[36] *The Effect of Specimen Length on Testing of Parallel-element Ropes*; Flory, J.F, Proceedings of Oceans 2002 Conference Proceedings, MTS, Columbia MD, IEEE, Piscataway, NJ, 2002.

[37] *Factors Affecting the Measurement of Rope Under Sinusoidal Loading; Casey*, N.F. and S.J. Banfield, OTC 17068, 2005 Offshore Technology Conference Proceedings, SPE, Richardson, TX, 2005.

AMERICAN PETROLEUM INSTITUTE

1220 L Street, NW
Washington, DC 20005-4070
USA

202-682-8000

**Additional copies are available online at www.api.org/pubs**

Phone Orders: 1-800-854-7179 (Toll-free in the U.S. and Canada)
303-397-7956 (Local and International)
Fax Orders: 303-397-2740

Information about API publications, programs and services is available on the web at www.api.org.

**Product No. G2SM02**