

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

API RECOMMENDED PRACTICE 2SM
FIRST EDITION, MARCH 2001
ADDENDUM, MAY 2007



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Upstream Segment

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FOREWORD

API RP 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.

Thus, this document covers the following:

- 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.

This Addendum updates the current edition of API RP 2SM with the latest knowledge on key issues, particularly for polyester mooring rope. Each numerated section below references the existing section and notes the changes to the document. Also included in this Addendum is a new Appendix on minimizing fiber rope damage during installation.

Suggested revisions are invited and should be submitted to the Director of the Standards Department, Upstream Segment, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

CONTENTS

	Page	
1	SCOPE.....	1
2	DEFINITIONS.....	1
3	BASIC CONSIDERATIONS.....	3
3.1	General.....	3
3.2	Synthetic Ropes for Offshore Mooring.....	4
3.3	Main Characteristics of Synthetic Fiber Ropes.....	4
		07
4	ROPE DESIGN AND PROPERTIES.....	5
4.1	General.....	5
4.2	Rope Material.....	5
4.3	Rope Construction.....	6
4.4	Rope Jacket.....	6
4.5	Rope Termination.....	6
4.6	Rope Assembly Properties.....	8
		07
5	MOORING DESIGN AND ANALYSIS.....	14
5.1	General.....	14
5.2	Mooring Configuration.....	14
5.3	Design Criteria.....	14
5.4	Mooring Analysis.....	15
5.5	Model Testing.....	16
		07
6	ROPE SPECIFICATION AND TESTING.....	16
6.1	General.....	16
6.2	Rope Specification.....	17
6.3	Rope Testing.....	20
		07
7	ROPE MANUFACTURE, INSPECTION, AND QUALITY ASSURANCE.....	22
7.1	General.....	22
7.2	Rope Fiber Material.....	22
7.3	Rope Manufacturing.....	23
7.4	Termination.....	23
7.5	Assembly.....	23
7.6	Inspection.....	23
7.7	Quality Control and Assurance.....	24
8	ROPE HANDLING AND INSTALLATION.....	25
8.1	General.....	25
8.2	General Storage, Handling and Installation Considerations.....	25
8.3	Installation Design Considerations.....	26
8.4	Installation/ Recovery Procedures.....	29
		07
9	IN-SERVICE INSPECTION AND MAINTENANCE.....	31
9.1	General.....	31
9.2	Inspection and Testing Techniques.....	31
9.3	Fiber Rope Inspection Procedure.....	32
9.4	Rope Retirement Criteria.....	33
9.5	Maintenance Procedures For Permanent Moorings.....	33
		07

	Page	
10 DESIGN EXAMPLES	34	
10.1 General	34	
10.2 Mooring System Description	34	
10.3 Extreme Response Analysis Example	36	
10.4 Fatigue Analysis Example	40	
APPENDIX A—TESTING OF ROPE WET STRENGTH	43	
APPENDIX B—TESTING OF ROPE ELONGATION AND MODULUS	45	07
APPENDIX C—TESTING OF ROPE TENSION-TENSION FATIGUE QUALIFICATION	49	
APPENDIX D—TESTING OF ROPE AXIAL COMPRESSION PERFORMANCE ...	51	07
APPENDIX E—COMMENTARY ON MARINE FINISH	53	
APPENDIX F—REFERENCES	55	
APPENDIX G—STRATEGY FOR MINIMIZING FIBER ROPE DAMAGE DURING INSTALLATION	57	07
Tables		
4.6.2 Typical Rope Weights and Sizes for 10,000 kN (1,000 tonne) Break Strength	8	
4.6.4.2 Typical Secant Stiffness Values	11	
6.3.6 Fiber Rope Fatigue Qualification Test Specification	21	
8.2.1 Resistance to Chemical and UV Weakening	25	
10.3.3 Fairlead Motion Complex RAO	38	
10.3.4.1 Maximum Tensions of No. 11 Mooring Line	38	
10.3.5 Calculation of Number of Cycles	39	
10.4.1 Environmental Condition, Mean Loads and Low-frequency Motions for the Analyzed Direction	39	
10.4.2 Polyester Rope Segment Fatigue Damage	41	
Figures		
4.6.4a Typical Elastic Properties for Polyester Fibers	8	
4.6.4b Typical Elastic Properties for Steel Wires	9	
4.6.4c Typical Stiffness Limits for 10000 KN Breaking Strength Polyester Mooring Ropes	10	
4.6.4.1 Typical Linearized Stiffness Limits for Use in Mooring Analysis of Polyester Mooring Lines	11	
4.6.7.2 Polyester Rope Fatigue Data and Design Curve	12	
6.2.7.3 Diagram of Eye Splice Showing Features and Tolerances	19	
6.2.7.7 Typical Storage Reel and Lifting Arrangement	21	
8.3.8a Surface Buoys Tensioned Together to Maintain Fiber Rope in Tension	30	
10.2 Mooring System and Environmental Directions	35	
10.3.6 Effect of Rope Stiffness	40	

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

1 Scope

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.

Since synthetic fiber rope properties will 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. Thus this document covers primarily the following aspects:

- 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.

The contents of this document should be read in conjunction with API RP 2SK, *Design and Analysis of Stationkeeping Systems for Floating Structures*, Second Edition, December 1996 [1]. Where the mooring design, construction and installation details are similar or equivalent to steel wire/chain mooring systems, no further comments are included in this document.

The production of this document reflects the potential growth in offshore mooring applications for synthetic fiber ropes and the need for a consolidated written guidance. At this time the design, analysis, manufacture, testing and installation procedures vary, and there is limited in-situ experience with synthetic rope moorings. Thus where committee members have reached consensus, more specific recommendations are provided in the document. Specifically, those items for which the committee members have reached consensus as being recommended or essential for an adequate mooring system are identified in the text in conjunction with the word “should”. In other areas, general guidance is included in the document as general statements and/or commentary notes. The technology in synthetic fiber rope moorings is growing rapidly. Designers are advised to take appropriate measures to ensure that their practices incorporate all research advances available to them. A technical commentary, which provides a detailed discussion on deepwater polyester rope mooring

technology, has recently been made available through the DeepStar Joint Industry Project [31].

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 FPSOs.
- b. Semi-submersible based FPU's.
- c. Mobile Offshore Drilling Units (MODU).
- d. SPAR Buoy platforms.
- e. CALM Buoy (spread mooring only).

This document is not intended to cover other marine applications of synthetic fiber ropes such as tanker mooring at piers and harbours, towing hawsers, mooring hawsers at SPMs, and TLP tethers. Additionally, very little test data is 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.

The fiber materials covered in this document include polyester,

, HMPE and nylon; and the rope structures include “wire-rope-construction” and “parallel-strand” types. Other fiber materials and rope structures may be used, but the recommendations given must 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 are advised to consult rope manufacturers when other types of ropes are considered.

As more experience is gained from relevant applications, this recommended practice will be subject to additions, comments and revisions. These and continued research and development efforts in this area will be considered in future editions of this recommended practice.

2 Definitions

For purposes of this recommended practice, the following definitions apply. Other terminology can be found in Appendix C, References [2, 3, and 4] part of this document.

2.1 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.

2.2 bend restrictor: A device placed on the rope adjacent to a termination to prevent abrupt bending at the termination.

2.3 catenary mooring: The catenary mooring system uses chain or steel wire at the seabed to provide a catenary,

which provides both compliance and weight to prevent the anchor from experiencing vertical loads.

2.4 certified verification agent (CVA): An independent third party who verifies that all applicable technical specifications and drawings are adhered to during the rope design, manufacturing process, and deployment. The CVA acts on behalf of, and is certified by, the owner and/or pertinent regulatory agency.

2.5 creep: The strain increase in rope length under sustained tension or cyclic loading.

2.6 creep-log time plot: A graph of creep (ordinate) against the log of time under tension (abscissa).

2.7 dynamic rope modulus: The ratio of rope stress to strain between the lower (trough) and upper (peak) stresses imposed during dynamic testing.

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

2.9 fiber finish: A designation of the process and finish used on a fiber for a particular purpose, e.g., "marine finish".

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

2.11 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.

2.12 intermediate yarn: A yarn-like component assembled from twisting or otherwise combining smaller components and used in assembling larger components, up to the rope yarn. Sometimes called ply.

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

2.14 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.

2.15 lay length: The length along the axis of a rope in which a strand makes one complete spiral around the rope axis. Also, the length along the axis of a strand in which a yarn makes one complete spiral around the strand axis.

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

2.17 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.

2.18 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.

2.19 material chemical composition: The generic designation of a specific chemical composition and process of material used in the fiber, i.e., nylon, polyester, aramid, high-modulus polyethylene.

2.20 minimum bend 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).

2.21 minimum break strength (MBS): The value determined by subtracting two standard deviations of breaking strength from the average breaking strength.

2.22 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.

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

2.24 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.

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

2.26 quality assurance supervisor: An employee of the manufacturer who is responsible for adhering to all quality assurance procedures.

2.27 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.

2.28 quality control report: A document prepared at the completion of rope making and assembly which includes the completed quality control checklists, material certificates, and inspection reports.

2.29 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.

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

2.31 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.

2.32 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).

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

2.34 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.

2.35 rope modulus: The ratio of rope stress to strain.

2.36 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.

2.37 rope stress: The applied tension on the rope divided by the rope fiber area.

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

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

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

2.41 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.

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

2.43 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.

2.44 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.

2.45 taut leg mooring: The taut leg mooring system 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.

2.46 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.

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

2.48 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.

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

2.50 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.

2.51 yarn break strength: The average breaking load from several yarn break tests.

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

2.53 yarn elongation: The average elongation at break from several yarn break tests.

2.54 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 Basic Considerations

3.1 GENERAL

This section provides a brief overview of mooring systems incorporating synthetic fiber ropes. Requirements as specified in the API RP 2SK [1] are generally applicable unless otherwise provided. Key design considerations in using syn-

thetic fiber materials are discussed. Detailed information can be found in later sections of this document.

3.2 SYNTHETIC ROPES FOR OFFSHORE MOORING

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

Advantages of using synthetic fiber moorings include a reduction in mooring line weight and hence increases vessel payload, 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 tensile stiffness, reduction in expensive handling equipment, and possible reduction in installation cost. Disadvantages of using synthetic fiber moorings are limited design data for large-size ropes and lack of long-term service experience.

Fiber ropes may be used as segments in steel catenary systems, or in taut leg mooring systems. This is discussed further in 5.2. The differences from steel wire/chain mooring systems include: non-linear stiffness, different handling procedures, necessity to keep fiber rope away from fairlead, necessity in some cases to keep fiber rope away from sea floor, axial compression fatigue considerations for aramid rope, and creep rupture considerations for HMPE rope.

3.3 MAIN CHARACTERISTICS OF SYNTHETIC FIBER ROPES

3.3.1 Fiber Materials

The fibers currently being evaluated for use in permanent or temporary deepwater moorings are polyester (polyethylene terephthalate), aramid (aromatic polyamide), HMPE (high modulus polyethylene) and nylon (polyamide). Detailed data and discussions are available from well-known JIPs [e.g., Refs. 2 and 3]. This does not exclude the use of other synthetic fibers in the design of mooring systems, provided that good engineering practice is followed and all fiber properties are considered.

For taut leg mooring (TLM) systems, the synthetic fiber rope axial stretch provides load extension characteristics which the catenary geometry traditionally supplied in the conventional steel system. The lower modulus of elasticity of polyester compared with steel, and relatively low cost makes it suitable for many deepwater TLMs. Other fibers such as HMPEs and aramids may be more suitable for applications where a smaller rope diameter is required (e.g., for frequent handling) or for ultra-deep water TLM applications [5].

Currently, polyester is considered to be a good candidate for the offshore mooring application due to its low stiffness which induces less tension during design storm, good resis-

tance to axial compression fatigue, good fatigue properties, good strength to weight ratio, and good creep resistance.

3.3.2 Rope Construction

There are many different rope construction types. Based on test data currently available, two types of rope construction, "wire-rope construction" (WRC, as used in steel wires) and "parallel strand," are considered in this document.

3.3.3 Rope Elongation and Stiffness

Fiber ropes are constructed from fiber materials that display visco-elastic properties. The rope exhibits a non-linear behavior that is dependent on mean load, load range, rate of loading and load history. After the rope has been tensioned to allow bedding-in, and cyclic load and relaxation has occurred, the stiffness changes with mean load and load range. The rate of loading will also have an effect on dynamic stiffness. As the rope is loaded beyond its previous maximum load, it undergoes a permanent increase in length. The combination of increased length and change in stiffness can result in a softer mooring system.

During initial installation and tensioning, and prior to bedding-in and relaxation, it is difficult to define stiffness. In this case the static stiffness can be bounded by the minimum (lower post installation stiffness) and maximum (higher post installation stiffness) values. Similarly, the dynamic stiffness can be bounded by the intermediate and storm stiffness values. This simplified approach, discussed further in 4.6.4, may be used in lieu of a more appropriate stiffness model that matches the non-linear, time dependent nature of polyester rope.

For moorings with large synthetic ropes, the installation tension is generally much lower than the maximum design tension. When the mooring line is loaded beyond its installation tension, there are two effects that can change the performance of the mooring system. First, the synthetic rope will lengthen due to additional bedding-in or fiber elongation. Second, the static and dynamic stiffnesses of the rope will increase. The overall effect of the increase in line length combined with the increase in mooring line stiffness may be a reduction in effective mooring system stiffness at low loads. Conversely, the mooring system stiffness may increase if the base fiber exhibits low elongation.

Platform offsets are a primary concern for risers. Proper evaluation of offsets requires detailed information on the permanent elongation (bedding-in) and static stiffness of the synthetic rope over a range of tensions. Furthermore, the permanent elongation and static stiffness data 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 system stiffness. These influences

include: rope age and usage history, manufacturer and construction, and base fiber properties.

A general indication of the effects of creep is given by yarn data from other sources [2]. Some newer HMPE fibers show reduced creep, and creep in rope is less than creep in yarn.

Permanent elongation—whether due to creep or construction stretch or other mechanisms—may lead to the need to adjust the length of the mooring lines. In most fibers, creep rate reduces with time and is approximately the same for equal increments of log (time), e.g., creep over 1 decade of log (time).

3.3.4 Durability and Fatigue

Factors which may limit the life of synthetic fiber ropes for deepwater mooring and which should be checked include hydrolysis, heating and internal abrasion, tension-tension fatigue and axial compressive fatigue. The possibility of creep rupture was commented on in the previous section.

3.3.5 External Abrasion and Cut Resistance

Jacketing should be used on fiber ropes where external abrasion is expected to occur while in service and during installation and recovery (if applicable for movable temporary moorings). Certain rope constructions may need a protective jacket to keep the strength core strands together, such as parallel strands. In case a protective 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 HMPEs, which have demonstrated to possess high wear resistance may be used without jacketing if it can be shown that the wear resistance will be adequate for the intended application.

To date there have been no recorded incidents of detrimental fishbite damage to large diameter fiber ropes, and therefore this is not expected to be a concern for large deepwater fiber rope moorings. If damage due to fishbite becomes a concern for a specific application and/or location, means for minimizing such damage should be considered in the selection and design of the fiber rope, and the frequency of subsea inspection may have to be increased.

4 Rope Design and Properties

4.1 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 makers, which are used in the main load-bearing core of the rope. The rope core may also contain marine finishes such as lubricants and fillers, and other materials.

4.2 ROPE MATERIAL

4.2.1 Fiber Types and Properties

The choice of a particular fiber material depends on the nature of the application and on the level of confidence in the material. Polyester and aramid ropes do not have potential creep rupture problems. HMPE and aramids have better strength to weight ratios and are stiffer than polyester and nylon, which has different wet and dry abrasive properties. Nylon's low stiffness (lower than polyester) may be useful where a more compliant system is desired.

4.2.2 Yarn Quality

Quality control procedures stated in Section 7 of this document should be used to ensure that yarn quality is maintained.

4.2.3 Marine Finish

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

- Increasing the initial strength (translational efficiency) of the rope.
- Providing lubrication to assist bedding-in of the rope during initial tensioning.
- Increasing the rope's service life by reducing yarn-to-yarn abrasion.

Minimum requirements on the quality of marine finish and its long-term durability are described below. A more detailed discussion on these requirements can be found in Appendix E.

4.2.3.1 Quality of Marine Finish

Due to the potential importance of marine finishes on deepwater moorings, the following should be followed:

- Fiber, yarn and rope data used for design of deepwater moorings should explicitly denote whether the data was generated from samples which included a marine finish, and give the descriptive designation of the marine finish with the manufacturer's fiber certification.
- As part of the prototype rope fatigue qualification testing (6.3.6), post-test analysis of the fibers (see 4.2.3.2) should demonstrate that the finish remains effective during wet cyclic fatigue for at least the duration of the testing. In addition, as part of the rope specification (6.2) the fiber or rope supplier should demonstrate that the marine finish remains effective in seawater for at least one year.
- As part of deepwater mooring procurement quality control, metrics of finish quality such as yarn-on-yarn abrasion resistance or overfinish add-on level should be used to confirm that the yarn used in the production ropes has characteristics comparable to yarn used in the prototype rope (see 7.2.2).

4.2.3.2 Long-Term Durability of Marine Finish

Until such time as standard accelerated processes for finish analysis have evolved, marine finish effectiveness and durability should be demonstrated by subjecting yarn or ropes to continuous seawater exposure (ASTM seawater or ocean field trials) for a fixed time period of at least 1 year, followed by:

- a. Measuring the post-exposure yarn-on-yarn abrasion cycles-to-failure and comparing with control yarns not exposed to the seawater environment.
- b. Measuring the post-exposure level of the marine finish and comparing with control yarns not exposed to the seawater environment.

Note: Marine finish level should be determined by the fiber supplier, rope manufacturer or qualified third-party with adequate understanding of analytical chemical techniques as well as the chemistry of the particular fiber and finish being evaluated.

For permanent mooring applications the above testing should be repeated on yarns taken from fiber rope inserts whenever these inserts are removed as discussed in 9.3.3. In this way marine finish level in the ropes can be monitored throughout the life of the installation.

4.3 ROPE CONSTRUCTION

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

Typical rope construction types suitable for deepwater fiber moorings are wire rope constructions (WRC), and parallel strand types. The main structural levels in a fiber rope, although not all present in every construction, are:

- “Textile yarns,” as made by the fiber producer and typically consisting of hundreds of individual filaments.
- Rope yarns, assembled from a number of textile yarns by the ropemaker.
- Strands made up from many rope yarns.
- Sub-ropes of several strands.
- The complete core rope assembly.
- Rope, sub-rope and strand jackets.

In general, ropes with load bearing yarns essentially aligned with the rope axis will provide the highest axial break strength and stiffness; 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 6 provides general guidelines for specification and testing of ropes. The engineer may find it useful to follow the philosophy of first building and testing a prototype rope as prescribed in the OCIMF hawser guidelines [7, 8 & 9]. It is noted that testing and termination techniques for deepwater fiber moorings will differ from those for the marine hawsers

specified in the OCIMF guidelines because of the very different application requirements.

4.4 ROPE JACKET

4.4.1 Jacket Design

An important function of the jacket is to protect the rope from external abrasion, which may occur during transportation, handling at installation or other causes.

Design of the protective jacket will depend critically on location, depth and installation technique. In general, external abrasion, friction and wear can be avoided or mitigated by the appropriate selection of a jacket. Typical jackets may be braided, extruded, tape-wound or otherwise applied. Rope jackets should be tightly fixed to the termination area to prevent slippage of the jacket away from the termination and exposure of core strands. A clearly visible marking on the jacket or visible portion of the rope should be provided to allow for monitoring of twisting in the rope.

4.4.2 Particle Ingress (Internal Abrasion) and Air Pocket Suppression

Strength loss in fiber ropes can be attributed to internal abrasion due to water-borne particles such as sand. The fiber rope assembly should not be used in areas of high turbidity unless protected by suitable jackets which exclude particle penetration while allowing water ingress [Refer to 8.3.3 for dropped ropes].

The extent to which water is able to displace air completely from the spaces between strands, yarns and fibers may need to be investigated. The presence of air pockets may lead to undue heat build-up during cyclic loading. If fiber ropes are used where cyclic loading can cause excessive heat build-up, the ropes should be freely flooded.

4.4.3 Jacket Bending Rigidity

The jacket should be sufficiently flexible to permit the fiber rope assembly to be safely deployed over rollers or sheaves of diameter specified under the design deployment loads. Limiting bend radius based on jacket or rope bending rigidity should be established for short periods during installation and for prolonged periods when wound onto the specified transportation drums.

4.5 ROPE TERMINATION

4.5.1 End Termination and Construction Types

Three main types of end terminations may be considered for synthetic fiber rope assemblies for deepwater mooring

though other terminations could be developed in the future. These terminations are generally known as:

- a. 'Spliced eye'.
- b. 'Resin socket', or 'resin potted socket,' or 'conventional socket'.
- c. 'Barrel-and-spike,' or 'socket and cone,' or 'wedged socket'.

The key merits and disadvantages of each of the termination types are largely beyond the scope of this document.

Of the termination types listed above, only the spliced eye presently has been qualified for strength and resistance to hysteresis heating at sizes of synthetic fiber rope appropriate for deepwater mooring of large structures. Research is currently underway in developing other types of terminations for synthetic fiber ropes [2].

There are many ways in which a spliced eye can be constructed. Splicing may take form of tucking, braiding or wrapping strands back into the main body of the rope. Presently, one of the most common rope splices involves tucking the strands back into the main body of the rope [10 & 11]. In this instance, it is of primary importance that adequate tucks are used in the splice and that the last tucks of the splice are tapered. Splicing procedures for a particular rope design should be developed by the rope manufacturer, taking into account the rope construction and material.

4.5.2 Termination Design Consideration

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

Termination connecting hardware may be of steel construction, and therefore considerations should be given to the added weights and excessive bending moments at these in-line joints.

When terminations between rope lengths are stored on reels, means should be provided to prevent the termination from damaging the rope.

Limitation on the minimum bending radius near terminations should 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 does provide a gradual change in rope flexural stiffness which will reduce excessive stress from rope bending at the terminations.

4.5.3 Protection for Spliced Eyes

For spliced eye terminations, means should be provided to minimize friction and maximize wear resistance between the fiber rope and the pin or bush that fits through the eye. Fiber cloth, elastomeric materials, Teflon coatings, etc. may be used for this purpose.

4.5.4 Termination Strength

Traditionally, termination strength has not been quantified as a separate item to the rope core strength. In most cases, rope Minimum Breaking Strength (MBS) is representative of the rope assembly break strength, which includes termination and/or rope core failures. MBS of the fiber rope as quoted by the rope supplier should take into account the strength efficiencies of all terminations within the rope assembly. Break strength of the rope should be determined through testing on prototype or production ropes of the same rope construction, material and termination design as those which will be used in the actual mooring installation.

4.5.5 Spliced Eye Hardware

Spliced eyes will require hardware in the form of a pin, bush or thimble fitted into the eye to make a connection between a fiber rope and other components in the mooring system.

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. The D/d ratio should be sufficiently high to ensure that the full MBS of the assembly is achieved but low enough to avoid excessive abrasion and fusion between rope and spool due to rope stretch and pressure.

The pin or bush to rope diameter ratio for a particular rope design as suggested above should be in accordance with the rope manufacturer's recommended value, and should be validated by both strength and fatigue testings in accordance with Section 6 of this document.

4.5.6 Strand Splicing

Strand splicing is defined here as the substitution of one strand for another by any means such as overlapping, tucking, intertwining or interbraiding. In this context, strand is defined as the major component of the rope structure. In parallel strand rope, this also applies to the first subcomponent which makes up the major strand, that is the substrand or major yarn unless there are more than 25 such subcomponents.

Specifications should be prepared and adhered to covering how the individual strands (and substrands) are prepared for splicing, the process of splicing, the process of finishing the splice, and all critical dimensions. The minimum spacing of such strand splices along the axial length of the finished rope (and in the case of substrand splices along the length of the strands) should be specified. Means of marking the locations of strand splices (and substrand splices) on the individual strand should be provided.

If the total number of strands (or substrands) within the rope is less than fifty, the strand splices (and substrand splices) should not be included in rope splices or other terminations nor within a specified distance from the rope ends of terminations.

If strand splices are to be used in the rope, then such strand splices should be included in the prototype or production ropes prepared for break and cyclic tests in accordance with Section 6 of this document.

4.6 ROPE ASSEMBLY PROPERTIES

4.6.1 Introduction

The key technical characteristics for synthetic fiber rope assemblies, combining rope and terminations are described in this section.

4.6.2 Sizes and Strength

The strength of a terminated fiber rope assembly is defined by the MBS. In this document, the MBS is defined as the average break strength minus two standard deviations from a total of at least five test samples. Testing details for break strength definition are described in Section 6 of this document.

Typical values of weight in water and rope diameter (with jacket) for fiber rope assemblies of 10,000 kN ((1,000 tonne) MBS are set out in Table 4.6.2. For preliminary design, rope size may be scaled with weight in air or diameter squared. For final design, data from the rope manufacturer should be used.

4.6.3 Creep Rupture

Some polymer based fiber ropes are subject to creep, potentially leading to creep rupture. HMPE ropes may experience significant creep, leading to creep rupture. 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.

HMPE yarns creep substantially, although the rate of creep is very dependent on the particular HMPE yarn in question. When using HMPE ropes for deepwater mooring the risk of creep rupture should be evaluated in consultation with the yarn supplier and rope maker, taking into account the expected loading history, rope construction and other conditions.

Table 4.6.2—Typical Rope Weights and Sizes for 10,000 kN (1,000 tonne) Break Strength (including Jacket)

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

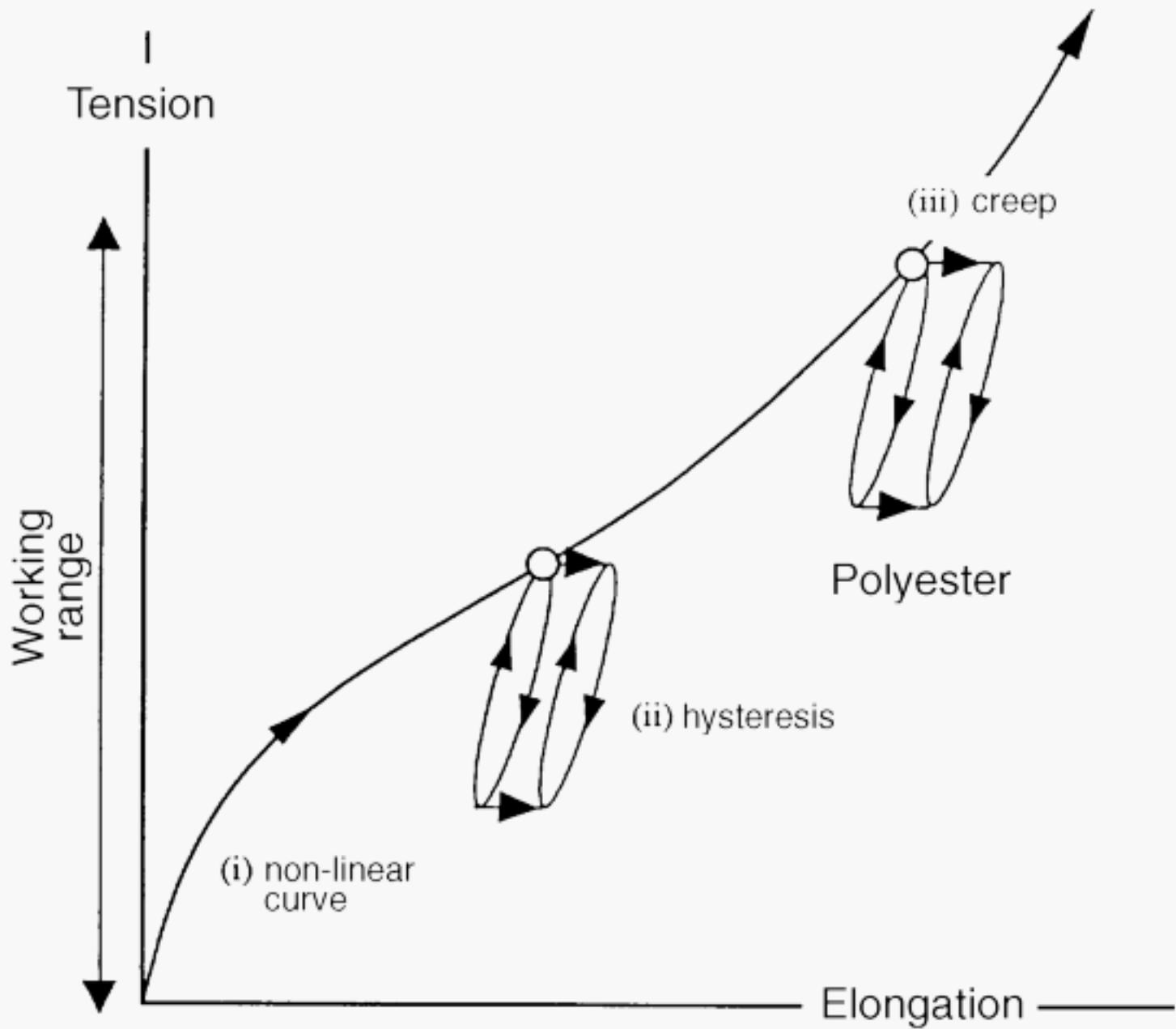


Figure 4.6.4a—Typical Elastic Properties for Polyester Fibers [6] Showing:
(i) Initial non-linear load-extension
(ii) Hysteresis loops
(iii) Creep at constant tension within the working load range

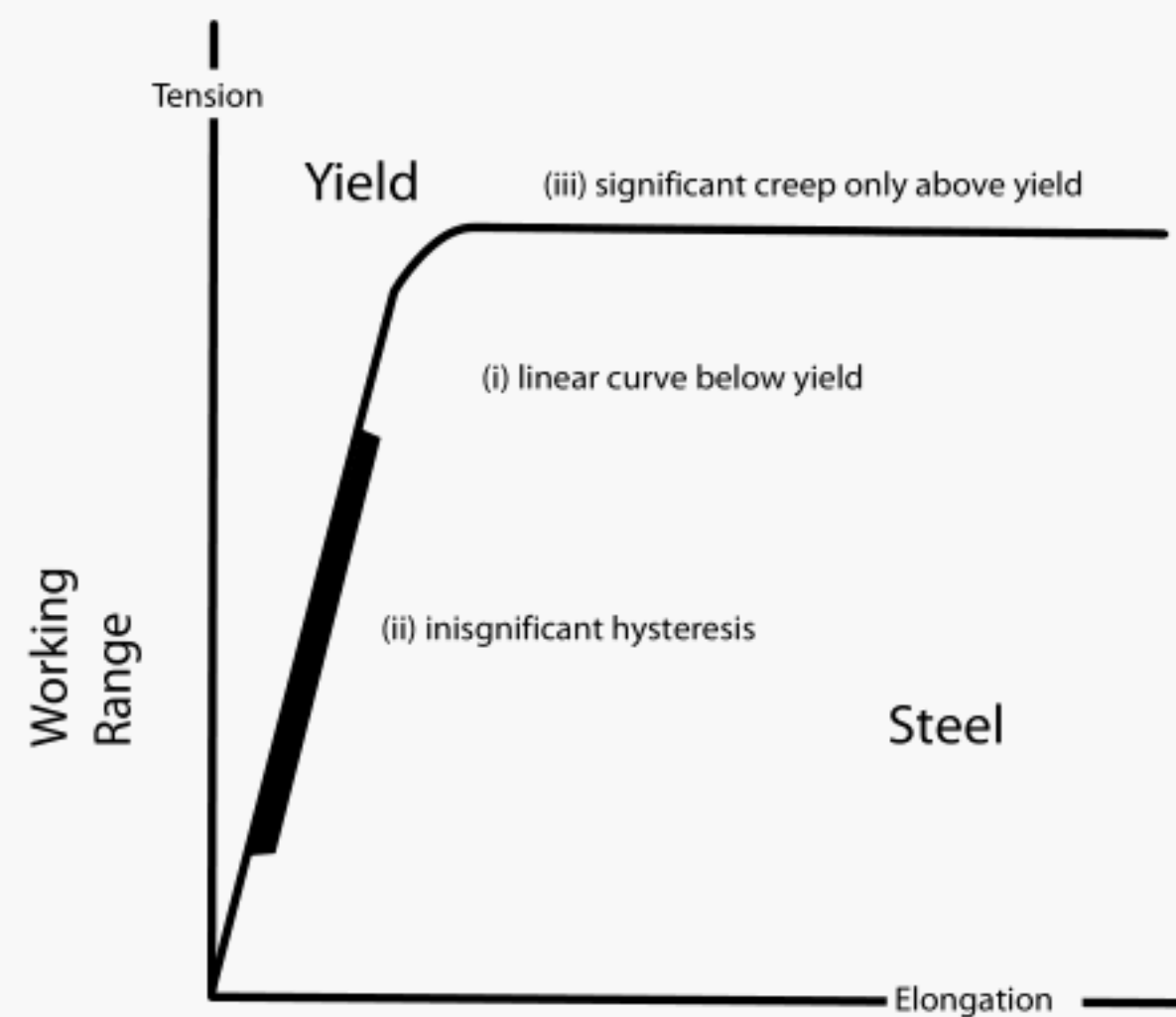


Figure 4.6.4b—Typical Elastic Properties for Steel Wires Showing:
 (i) Highly linear load extension graph to yield point
 (ii) Insignificant hysteresis loops up to yield point
 (iii) Significant creep only above yield point

4.6.4 Elongation and Stiffness

Figure 4.6.4a shows the elongation properties for a rope-making polyester yarn (other fiber materials will show a similar trend) as measured by Bosman, 1996 [6], compared with the ideal elastic-plastic response assumed for steel shown in Figure 4.6.4b. The complications to note are the non-linearity and the lack of recovery to the initial state (inelasticity), the cyclic loop giving energy dissipation (hysteresis), and the continuing elongation with time (creep).

The deformation rate is changing with time due to the visco-elasticity of the polymer material. Rope construction brings in two other effects. First, the values of strength and resistance to extension (stiffness), will be reduced by a conversion factor due to the angles of the fibers in the rope. Second, the rope is pulled into a tighter and thus stiffer structure when load is initially applied. This gives additional elongation, known as bedding-in, which should be considered in evaluating stiffness.

The elongation of a synthetic fiber rope is composed of recoverable (time independent) and non-recoverable (time dependent) components. The elongation of a fiber mooring assembly depends partly on the applied force acting on the rope and partly on unrecovered elongation resulting from previous loading. The stiffness of a fiber mooring assembly depends on many parameters including load, strain range, loading history and, in some specific cases, cycling frequency.

A simple approach is to separate the rope responses into upper and lower bounds in order to deal with different engineering design considerations. As shown in Figure 4.6.4c and

as discussed in this document, the lower and upper bound stiffnesses can be used to treat post installation, and storm loading respectively over appropriate tension ranges.

In this document, the rope stiffnesses in any cycle are based on the elongation from the rope length prior to that cycle, and not from new rope length. The minimum stiffness values are then used to calculate maximum platform offset and the maximum stiffness to determine line loadings. This is the simplified approach for design provided by this document as described in Section 5. The unrecovered elongation is assumed to be covered by mooring analysis or taken up by retensioning the lines.

If the mooring analysis is to use non-linear rope load-extension curves, which are different in recovery and change with history, then either extensive testing will be needed or an enhanced, computable rope extension model will be required together with validation data.

4.6.4.1 Stiffness Definition

Stiffness is a measure of resistance to deformation. In this document, it refers to axial stiffness and is defined as incremental rope tension divided by incremental rope strain. It thus equates both to spring constant times length ($k \times L$) and modulus times rope area (EA), and are used interchangeably within this document.

The minimum and maximum linearized static stiffness values that are recommended for use in a simplified representation of fiber rope stiffness are defined as:

- Lower Post-Installation Stiffness: the secant stiffness over the load or strain range of interest in quasi-static loading

immediately after installation and prior to any significant environmental events that lead to rope tension higher than the installation load. It is the stiffness which corresponds to the extensibility of the mooring lines under quasi-static load once the Minimum Installation Tensioning (see 8.3) has been performed during installation.

- **Higher Post-Installation Stiffness:** the secant stiffness over the load or strain range of interest in quasi-static loading immediately after extreme loading approaching the maximum design tension.

The minimum and maximum linearized dynamic stiffness values that are recommended for use in a simplified representation of fiber rope stiffness are defined as:

- **Intermediate Stiffness:** represents the secant stiffness in cycling about the mean load during normal operating conditions.
- **Storm Stiffness:** represents the maximum secant stiffness in cycling about the mean load during the maximum design storm to the cyclic strain limits predicted in the maximum design storm. This stiffness will result in the largest loads being generated in the mooring lines as the platform moves compliantly in the storm.

All stiffness values should be calculated from a reference length as defined in 6.2.7.2 prior to the cycle in question and not from the original rope length.

4.6.4.2 Typical Rope Stiffnesses

Typical values of static and dynamic stiffness data for fiber rope mooring lines, based on polyester, Aramid and HMPE ropes, are given in Table 4.6.4.2 [2]. To a first approximation, these stiffness values will scale with the breaking strength of the rope. Table 4.6.4.2 only gives typical values for indicative or comparative purposes only and shall not be used for design. Actual values as determined by the test methods in Section 6 should be used in design and analysis.

4.6.5 Unrecovered Elongation/Creep Elongation

Total elongation of the fiber rope assembly throughout the mooring design life should not lead to creep rupture. Elongation in fiber rope assemblies results from bedding-in of the rope structure and terminations and from both instantaneous extension and creep in the yarns. It will occur in all fiber rope assemblies under both steady and cyclic loads.

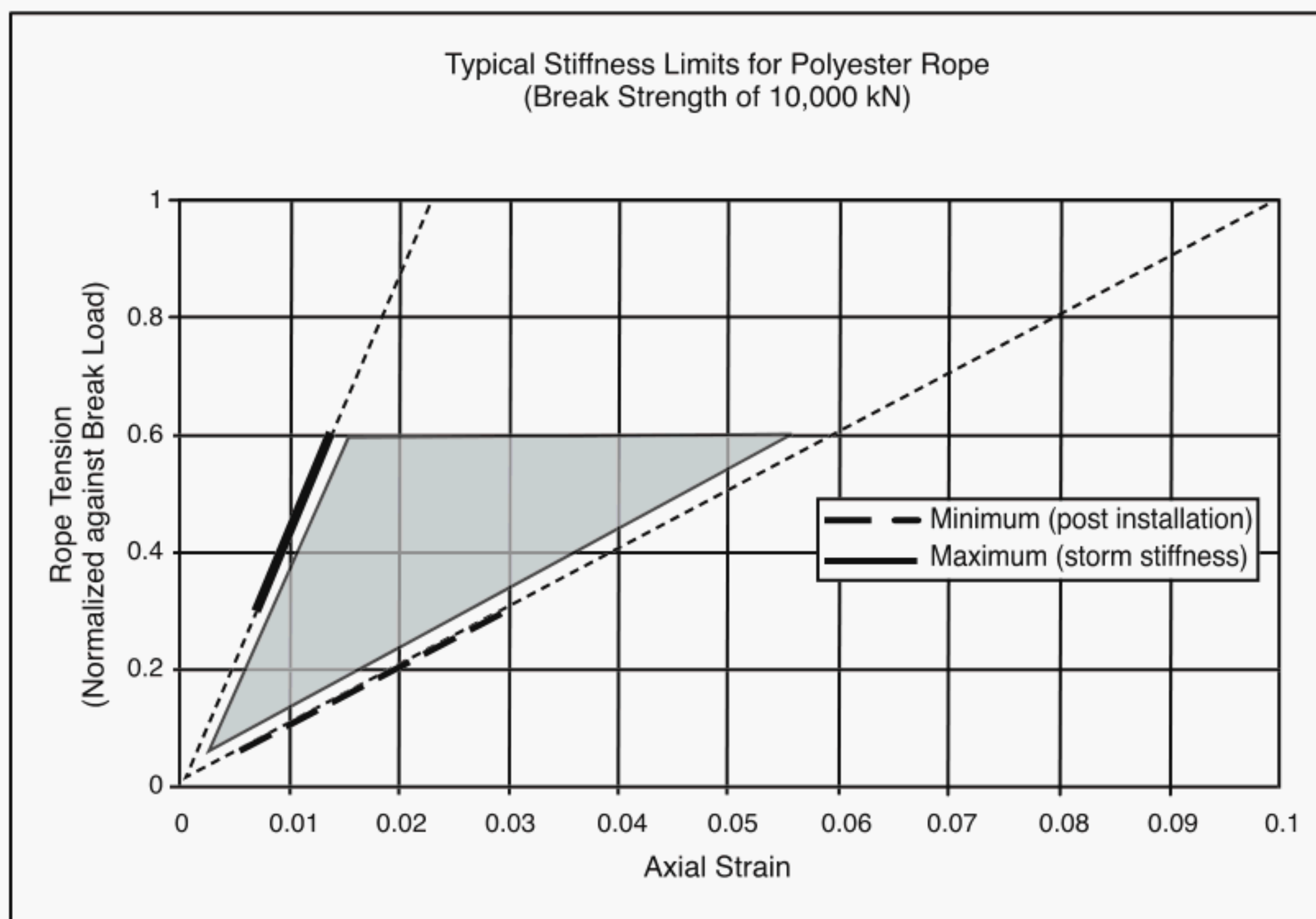


Figure 4.6.4c—Typical Stiffness Limits for 10000 KN Breaking Strength Polyester Mooring Ropes

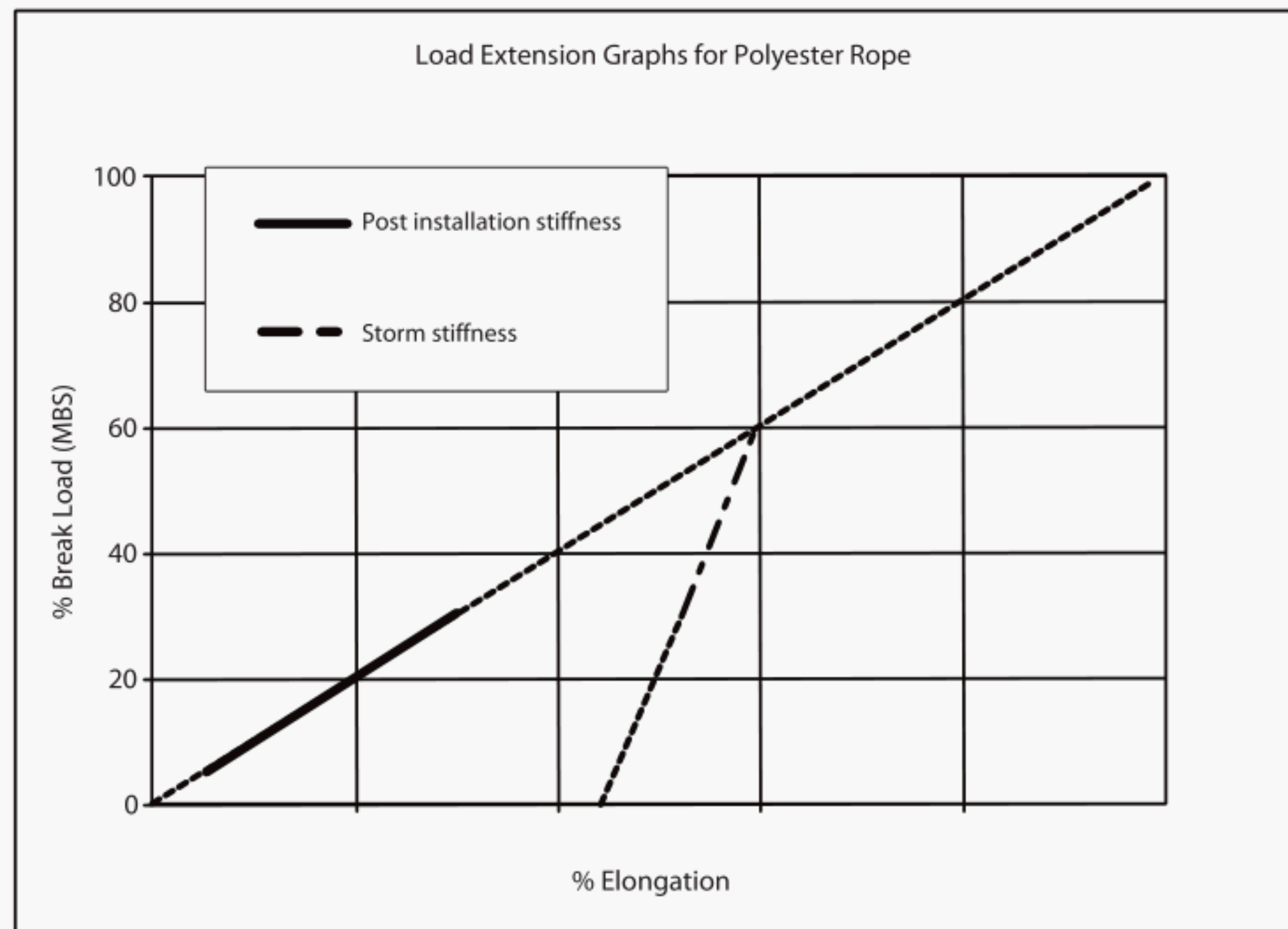


Figure 4.6.4.1—Typical Linearized Stiffness Limits for Use in Mooring Analysis of Polyester Mooring Lines

Table 4.6.4.2—Typical Secant Stiffness Values (E·A, in kN) for Parallel Yarn, Parallel Strand, and Wire-Rope Construction Ropes (Based on a 10,000 kN (1,000 tonne) Breaking Strength Rope)

Rope Material	Post-installed Stiffness	Intermediate Stiffness	Storm Stiffness
Polyester	100,000	100,000 – 300,000	300,000 – 450,000
Aramid	330,000	330,000 – 600,000	600,000
HMPE	350,000	350,000 – 700,000	700,000

Rope manufacturer should provide the designer and installer the information necessary to estimate the amount of elongation due to bedding-in and creep expected during the initial installation period and during the design life of the project based on expected mean and maximum design loads. Bedding-in and creep elongation estimates should be based on rope test data. The designer should calculate the effect of increase of line length in order to provide appropriate mooring line length management. Length management may be achieved through winching or the removal of relatively short sections (e.g., 100 ft – 250 ft).

For polyester and aramid ropes, the continuing elongation due solely to creep is not expected to exceed 1% – 2% during the life of a typical offshore installation. For HMPE and nylon ropes, creep elongation can be much higher and care should be taken to acquire test data that demonstrates adequate resistance to elongation and creep rupture.

4.6.6 Hysteresis Heating

High internal temperatures can develop in tension-tension fatigue cycling of ropes at high strain amplitudes. The maximum temperature rise depends on diameter, internal pressure, constructional type, sheath type and thickness, lubricant, presence of water or fillers and many other factors. Joint industry studies indicate that heating effects will be small in large polyester ropes for strain amplitudes less than 0.25% [6].

Temperature limits for polyester, HMPE, nylon and aramid fibers can be determined from 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.

Additional lubricants and fillers may also be used to provide heat transfer and reduce the formation of hotspots within the rope [12] provided they are compatible with the yarn finishes.

4.6.7 Fatigue

4.6.7.1 Fatigue Excitation Modes

Deepwater fiber mooring assemblies are subject to fatigue loading. The effect of fatigue on the mooring system should be considered.

Since the fiber mooring assemblies covered by this document will be terminated to chafe-chain or wire rope at both ends, bend-over-sheave fatigue loading will be limited to any which occurs in deployment or retrieval operations.

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

Two forms of axial fatigue loading are discussed below.

4.6.7.2 Tension-Tension Fatigue

Fatigue test data for fiber ropes are quite limited, and most of the available fatigue test data are for polyester ropes. Figure 4.6.7.2 presents polyester rope test data available in the public domain and a design curve based on a regression analysis of 11 data points. This figure also contains fatigue design curves for spiral strand and six/multiple strand wire ropes specified in API RP 2SK [1]. Comparison of these design curves indicates that polyester ropes have much better fatigue resistance than steel wire ropes.

In the next several years we expect to have better data to define the rope fatigue curves. In the absence of better information, the “mean minus two standard deviation” curve from the regression analysis can be used for polyester rope fatigue design provided that at least one qualification test as detailed in 6.3.6 is conducted.

Note: The statistical variation represented by this standard deviation is due to tests being conducted on different ropes and by different methods and does not necessarily represent the performance variation which might occur in ropes of identical design in actual service.

This design curve is represented by the following design equation:

$$NR^M = K$$

where

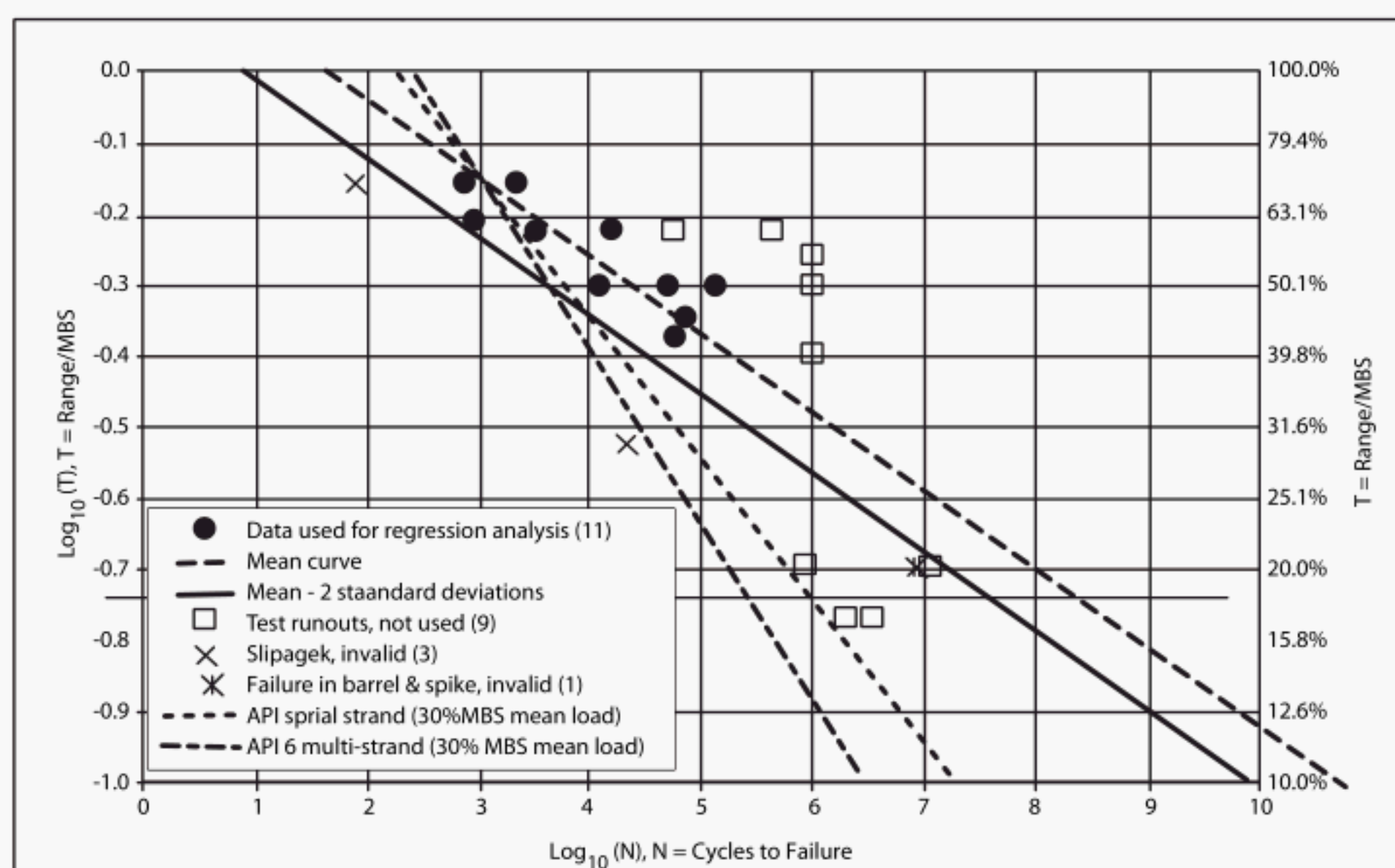
N = number of cycles,

R = ratio of tension range (double amplitude) to MBS,

M = 9.0 (slope of T-N curve),

K = 7.5 (intercept of T-N).

For other fiber ropes, such as aramid, HMPE, and nylon ropes, fatigue test data is insufficient for developing fatigue design curves. There are indications, however, that they also have better fatigue resistance than steel wire ropes. In the absence of better information, either the spiral strand curve or the six/multiple strand curve can be selected for the fatigue design of these fiber ropes; however, at least one fatigue qualification test as detailed in 6.3.6 should be carried out to demonstrate that the rope has at least equivalent fatigue resistance represented by the selected design curve. This approach can also be applied to polyester ropes if a lower design curve is sufficient for the intended rope usage. K and M values for the wire rope design curves can be found in Figure 4.6.7.2.



	Polyester Rope Data, $N_s = 11$		Wire Rope, API RP 2SK (30% MBS mean load)	
	Mean-1	Mean-2	Spiral Strand	Six-strand Multi-strand
I	1.69	0.875	2.22	2.36
$K=10I$	48.8	7.50	166	231
M	9.0	9.0	5.05	4.09

Figure 4.6.7.2—Polyester Rope Fatigue Data and Design Curve

4.6.7.3 Axial Compression Fatigue

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

Axial compression fatigue may occur in an aramid rope when it experiences many cycles to a low trough tension. Precautions should be taken to keep sufficient tension on aramid rope mooring lines, especially on leeward lines during storm conditions. Axial compression fatigue damage can be avoided with proper rope design and use. The provisional guideline is to not permit aramid fiber rope mooring lines to experience more than 500 cycles below a trough tension of 10% MBS 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% MBS threshold at any time in the cycle, then that cycle is counted toward the design limit. The user may always choose to utilize rope testing to establish compression fatigue performance, which can supersede the provisional guideline outlined above.

Table 4.6.7.3 removed.

4.6.7.4 Residual Strength

Limited data currently exists to quantify the rate of strength fall-off experienced by full scale synthetic fiber rope assemblies for FPS moorings; however, there is no evidence to suggest performance inferior to that of steel wire rope. For steel ropes it is assumed that breaking strength and fatigue life are independent of each other, and similar behavior is evident for polyester [2]

4.6.8 Delayed Elastic Recovery

Instantaneous elastic extension is recovered when loads are reduced; however, part of the creep under high loads is primary creep, which is recovered over time when loads are reduced. This is known as delayed elastic recovery and can occur after storm conditions and affect mooring line tensions.

4.6.9 Torque and Twist Effects

Torque compatibility should be considered among different mooring components consisting of synthetic fiber rope, chain and wire, and also the clear fiber rope torsional compatibility with rope terminations. Excessive twisting from unbalanced torque should be avoided during handling, installation, operation and recovery. For example, a short section of six-strand wire rope in series with a long torque-balanced fiber rope of low rotational stiffness may allow excessive twist to occur in the wire rope, hence significantly shortening the design life of the wire rope.

Two categories of torsional imbalance problem should be considered:

- a. Twist introduced into components and transferred between them during installation, which may then cause operational problems.
- b. Incompatibility between installed components in operation.

Models of component behavior should be used to predict problems during installation and information of the response of the installed components to imposed twist, both statically and in fatigue.

Other torsional imbalance may occur from:

- rope variability which may lead to twisting.
- buckling which is accompanied by twist.

Where twist may be a problem, a marking stripe should be placed on the outside of the rope so that twist can be monitored externally.

The rope manufacturer should verify the maximum allowable twist for any particular rope design.

The testing of fiber rope torque and rotation properties as described in Section 6 may be used to determine the torsional characteristics of the rope.

4.6.10 Other Environmental Effects

Most fiber ropes are highly resistant to Ultra Violet (UV) and chemical attack even when unsheathed [2]. Other external causes of degradation such as fishbite and external wear are a function of jacketing material, as discussed in 4.4.

Synthetic fibers suitable for moorings are unlikely to show any chemical degradation as a result of exposure to marine growth.

Loss of strength due to hydrolysis in aramid and polyester ropes will not occur to an appreciable extent unless the temperature is greater than 30°C for long periods of time. HMPE is not subject to hydrolysis. Aramid yarns are more affected by hydrolysis and, although this will not be a problem in most circumstances, the possible loss of strength should be evaluated in consultation with the yarn supplier.

Another environmental aspect is the formation of salt water crystals following wetting and drying. Once salt crystals form, internal rope abrasion has been shown by the dry testing of yarns which were immersed in salt water [15]. Therefore, this document recommends that fiber rope designated for offshore moorings should only be used where fiber ropes remain totally immersed in seawater. These ropes should not be used in dry applications followed by a return to offshore usage unless recommended by the rope manufacturer or that additional rope tests in dry environment following soaking in standard salt water. Additional comments on salt crystallization are contained in 8.2.10.

4.6.10.1 Fishbite Resistance

Fishbite is a potential problem in some locations at some water depths. If fiber ropes are used where serious fishbite

can occur, the rope should be adequately protected (either by appropriate jacket design or fish repellent, etc.) and its condition monitored over the lifetime of the installation [16].

4.6.10.2 UV Resistance

Polyester ropes have excellent resistance to UV light, and jacket design need not take account of this aspect. Uncovered aramid ropes may suffer degradation of surface yarns if exposed to UV radiation awaiting installation or if permanently deployed, uncovered, in the upper few metres of water. In such cases an opaque cover is recommended.

4.6.10.3 Marine Growth

Minor strength loss in synthetic fiber ropes caused by marine growth or its by-products has been reported. 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 may limit visibility and hence affect the ability of an ROV to inspect the rope. Marine growth may also influence the drag loading on the line and hence loadings on the whole mooring system. For operations where marine growth is a concern, the fiber ropes should be placed below the marine growth zone. If marine growth is to be removed mechanically this should be done in such a way that damage to the rope itself is avoided.

4.6.11 Snap Back at Failure

Considerable energy will be stored elastically in the tensioned lines of a taut leg mooring and the safety implications for the crews and equipment, especially during handling and installation if one of the lines was to break, should be considered.

4.6.12 Effect of Water Depth

At 2,000 m (6,560 ft) depth, the hydrostatic pressure is 20 MPa (2,900 psi), which is about 2% of the strength of polyester or nylon yarns and a smaller fraction of the strength of the other yarns. This would have a negligible effect on yarn mechanical properties, and would only be responsible for a small transverse strain and the accompanying axial strain on a rope.

5 Mooring Design and Analysis

5.1 GENERAL

This section is based on the recommendations given in API RP 2SK [1], Sections 4 through 8. Modifications needed to cover the case of synthetic fiber rope mooring lines are provided below.

5.2 MOORING CONFIGURATION

A mooring system with synthetic fiber ropes can be configured as either a taut-leg or a catenary system. The choice depends on many considerations which are beyond the scope

of this document. A taut-leg mooring (TLM) has a smaller mooring footprint than the conventional catenary mooring system. This can be particularly important for the field layout of production installations in congested development areas. The taut leg mooring systems also differ from conventional catenary moored systems in that the anchor must resist substantial vertical load.

5.3 DESIGN CRITERIA

5.3.1 Maximum Tension Limits

Maximum tension limits and factors of safety for fiber rope should be the same magnitude as for steel and thus in accordance with 6.3.2 of API RP 2SK [1], but with the breaking strength of the new rope defined as MBS as in 4.6.2 of this document.

5.3.2 Minimum Tension and Maximum Allowable Low Tension Cycles

The previous requirement for minimum tension and maximum number of low-tension cycles is no longer applicable to polyester fiber ropes as they are not susceptible to axial compression fatigue.

As a general guideline for aramid ropes during installation and throughout the service life of the mooring line, tension should not drop below 10% MBS more than 500 times. Fiber ropes may be designed to sustain more cycles or lower tensions than indicated above before severe strength loss occurs. However, test data should be provided for justification of relaxing this general guideline.

5.3.3 Fatigue

As recommended in API RP 2SK [1] fatigue design is required for permanent moorings only. For synthetic fiber ropes, a safety factor of ten times of the design service life should be used for ropes under tension-tension fatigue loads.

5.3.4 Creep Rupture

The following discussion only applies to HMPE rope mooring lines.

Creep rupture can be caused by cumulative, irrecoverable elongation of a fiber rope under load. The factor of safety for creep rupture is defined as the predicted creep rupture life divided by service life of the mooring system. Minimum factor of safety for creep rupture is 10 for the intact condition, and 5 for the damaged condition.

For fiber ropes that require creep rupture analysis (see 5.4.4), estimates of rope creep rupture resistance should be based on the rope extension test similar to that described in Appendix B.1, but with modified tensions and duration (until the rope ruptures) to yield data for creep rupture analysis.

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5.4 MOORING ANALYSIS

5.4.1 Basic Considerations

Moorings and fatigue analysis procedures should generally follow the methods provided in API RP 2SK [1]; however, there are issues unique to fiber rope moorings that are not covered by API RP 2SK [1]. These issues, which include axial stiffness, rope length, creep rupture analysis, and axial compression fatigue analysis, are addressed in the following sections.

5.4.2 Fiber Rope Axial Stiffness

As discussed in 3.3.3, 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 load history. Therefore, a proper representation of the fiber rope axial stiffness requires a non-linear stiffness, time dependent model and the definition of the unloaded length of the fiber rope. In the simplified linearized approach, the unloaded length, dynamic storm stiffness, and static lower post-installation stiffness as defined in 4.6.4.1 can be used to estimate mooring loads and vessel offsets. 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 should be derived from rope testing as described in 6.3

For MODU moorings, it is generally sufficient to use the static lower post-installation stiffness for calculating offsets and the upper-bound dynamic storm stiffness for calculating line tensions. Use of these values for stiffness should provide conservative estimates of vessel offsets and mooring line tensions.

For permanent moorings, it is recommended to use more detailed information on static and dynamic stiffness in order to better estimate vessel offsets, line tensions, and fatigue damage. Use of the static lower post-installation stiffness and upper-bound dynamic storm stiffness may result in overly conservative estimates of vessel offsets, mooring line tensions, and fatigue life. Thus, this simplistic approach may lead to increase mooring line size, capital cost and installation cost. The designer should also be cognizant of the impact of permanent rope elongation when working with non-adjustable mooring systems (as discussed in 3.3.3).

5.4.3 Fiber Rope Length

The selection of the fiber rope length is critical for deepwater fiber mooring systems where the stiffness characteristics of the moored platform depend on the length chosen, and sufficient rope clearance from the fairlead and seabed must be maintained. The extension at installation and possible additional bedding-in and creep elongation during the mooring service life must be allowed for in the design analysis so that

the top end of the fiber rope is always clear of the platform fairlead, and the minimum tension requirements as defined in 5.3.2 are still met. The highest level of the installed fiber rope should be at a depth where it is clear of mechanical damage from workboats and surface marine activity, sunlight penetration, salt encrustation, and detrimental marine growth.

For taut line systems with no bottom line in contact with the seabed, the non-linear bottom effect traditionally associated with steel catenaries will not exist. For fiber moorings with large catenary lengths, the chain or wire rope segments will subject to contact with the seabed and should be treated accordingly as those outlined in API RP 2SK [1].

If additional short fiber rope inserts are provided for mid-life performance testing, they should be located at the end adjacent to the platform chain or wire segment so they can be easily removed to shorten the line length if unanticipated extension occurs.

5.4.4 Creep Rupture Analysis

The following discussion only applies to HMPE rope mooring lines.

As discussed in Section 4.6.3, HMPE ropes have a potential of creep rupture failure, therefore creep rupture analysis should be performed for HMPE ropes. Limited creep test data to date indicate very low risk of creep rupture failure for polyester and aramid ropes for typical mooring applications. Creep rupture analysis will not be required for these ropes unless they are subjected to unusual loading or future tests indicate increased risk of creep rupture failure. Creep rupture calculations should be based on rope creep test data instead of yarn creep test data, which may not be representative of rope creep behavior.

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

$$E = \sum \frac{c_i}{C_i} \quad (5.1)$$

where

c_i = duration per year within the tension interval i ,

C_i = creep rupture life (resistance) for the tension interval i , as determined by rope creep test.

The predicted creep rupture life for the mooring component, which is $1/E$, should be greater than the field service life multiplied by a factor of safety defined in 5.3.4. For used mooring components, creep rupture damage from previous operations should be taken into account. The recommended procedure for a creep rupture analysis is described below.

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

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

3. Compute the annual creep rupture damage from one design condition (one seastate in one direction) using Equation 5.1. Since line tensions are of random nature, it may be necessary to define different intervals of tension for the design condition and determine the associated duration for each interval. Summation of creep rupture damage from all tension intervals is the creep rupture damage for the design condition. Alternatively, a constant line tension (for example, mean or mean plus one standard deviation, etc.) instead of the random tension history can be used to simplify the calculation. This method can be used if a sensitivity study indicates that it yields acceptable approximations.

4. Repeat step 3 for all seastates and directions and compute the total annual creep rupture damage E_r , which is the sum of creep rupture damage from all seastates and directions.

5. The predicted creep rupture life of the mooring line is:

$$L = 1/E_r \quad (\text{years}) \quad (5.2)$$

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

In addition to the above analysis, the designer may 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.

5.4.5 Tension-Tension Fatigue Analysis

For fiber ropes which pass the minimum fatigue qualification test (6.3.6), the fatigue design curves as defined in 4.6.7.2 may be used in the analysis in conjunction with the fatigue analysis methodology as described in Section 7 of API RP 2SK [1].

5.4.6 Axial Compression Fatigue Analysis

This analysis is only necessary for aramid rope mooring lines.

Minimum axial tensions can be derived by analysis of the leeward mooring lines during extreme conditions. In general, it is acceptable to use the fiber rope storm stiffness for the extreme design conditions. The number of cycles of low tensions can be computed by consideration of the long-term distribution of the wave heights and their associated periods.

The minimum tension can be predicted using either the frequency or the time domain method. The frequency domain method should reflect the effect of the various parameters used to approximate the nonlinearities. The time domain method is preferred in the detailed design of permanent mooring systems.

The effect of wind dynamics should be included since this will contribute to the number and magnitude of low-tension cycles in leeward lines.

In lieu of any other data, the statistics for extremes may be used for the analysis of axial compression fatigue calculations.

5.5 MODEL TESTING

Recommendations for undertaking model tests are provided in the API RP 2SK [1].

For synthetic fiber rope moorings the special feature that the model tests account for is the non-linear load extension behavior of the line. In the absence of a more sophisticated model, the tests should at least represent the lower bound (post installation stiffness) and upper bound (storm stiffness) values of the mooring lines.

6 Rope Specification and Testing

6.1 GENERAL

This section provides guidelines on rope specification and testing methods.

All synthetic fiber rope provided for use in deepwater moorings should be accompanied by a manufacturer's test certificate issued 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.

6.2 ROPE SPECIFICATION

6.2.1 Rope Specification Documentation

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: the generic fiber material type; rope structure; termination type; MBS; overall length; and the elongation, modulus and torque (if applicable) properties.

The following documentation should be referenced in the rope specification:

- Rope design specification.
- Yarn specification.

- Termination specification.
- Manufacturing specification.

6.2.2 Minimum Break Strength

The minimum break strength is defined in accordance with 4.6.2. The rope specification should include test procedures, number of test samples and reporting methods in determining the MBS.

6.2.3 Elongation and Stiffness Properties

The elongation and creep properties are defined in accordance with 4.6.5. These properties should be included in the rope specification. Test procedures as described in Appendix B should be used to determine:

- *post installation stiffness*, after a loading sequence approximating the minimum installation routine, as defined in Section 8.
- *storm stiffness*, after a loading sequence corresponding to expected storm conditions.
- *intermediate stiffnesses* at any required intermediate loading histories.
- *unrecovered elongations* at selected loading sequences and over the rope service life, and the rope creep rupture resistance.

Values of the post installation and storm stiffness should be specified by the rope manufacturer for detailed mooring design calculations.

6.2.4 Rotation and Torque Properties

If rope rotation and torque properties are of importance, these properties should be included in the specification, indicating range of tolerances, and testing methods by which the properties were determined.

6.2.5 Cyclic Performance

The cyclic performance properties are discussed in 4.6.7. The specification should include the most appropriate rope fatigue data to be used in the fatigue design calculations. At least one tension-tension fatigue test as described in 6.2.6 and Appendix C should be conducted for the particular rope construction and termination to demonstrate that the rope possesses a minimum level of fatigue endurance.

Provisional criteria for axial compression fatigue for polyester, aramid and HMPE are given in Table 4.6.7.3. If these criteria are overly restrictive, specific rope designs may be tested for residual strength after specific cycles to minimum tensions in accordance with Appendix D.

6.2.6 Yarn Properties

The specification should include principal yarn properties such as break strength, elongation, creep, marine finish,

and yarn-on-yarn abrasion performance as further described in 4.2 and 7.2.

6.2.7 Specification of Rope Assembly

The rope specification should cover details which describe the completed rope assembly for each segment of each mooring leg, including, but not limited, to the following:

6.2.7.1 Rope Assembly Interface

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

- Strength, fatigue, torque performance of the interface, if these are different from that of the rope.
- Any critical dimensions of the interface, including tolerances if appropriate.
- Material for the interface if essential to the performance of the assembly.
- Description of processes, finish, coatings, cathodic protection, and other forms of protection for the interface if essential to the performance of the assembly.

6.2.7.2 Rope Assembly Length

The specification should include the overall installed length between the interfaces, and the corresponding installation tension or the length of rope required before installation as measured at an agreed reference tension.

The reference tension is a small tension used to straighten out the rope in order to define its length. The reference tension used for these deepwater mooring ropes may be higher than 1% of MBS as set out for ropes used in other services [21]. The same reference tension should be used for all length measurements on the particular rope during testing, production and inspection.

The length of rope produced can be determined using data on the unit rope weight also derived in accordance with ISO EN 919 [22] or Rope Test Standards by Cordage Institute [23].

The purchaser and manufacturer may need to determine a method for rope length calculation for delivery. It may be impractical or impossible to measure the entire length of the rope assembly, especially at a high tension. This might be done by determining the length per unit weight of a sample of the particular rope type at a specified tension, and then determining the length of the rope by weight. Alternatively this might be done by calibrating a pulley-like device with revolution counter, and then determining the length of rope by drawing the rope over that pulley.

The rope assembly length will change subsequent to measurement due to relaxation of the rope structure, reeling strains and changes in load, humidity and temperature during shipment and handling. The tolerance on the assembly length should be established in collaboration with the rope manufac-

turer, taking into account its effect on the mooring system installation.

6.2.7.3 Rope Termination

The types of rope terminations, e.g., splice, potted socket, wedged socket, etc., which are used to secure the rope to the interface should be specified. The purchaser may also request the rope manufacturer to provide an estimated ratio of the aggregate yarn strength to the minimum terminated rope breaking strength. The purchaser and manufacturer should agree on the method of determining the aggregate yarn strength.

A discussion of the specification for different termination types is presented below.

a. Spliced Eyes

The specification should include the splicing procedures. Unless otherwise specified, the eye size should 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 6.2.7.3. The tolerance should not be less than the stated dimension nor more than 20% greater than the stated dimension.

Hardware may 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 should be a neat fit on the shackle pin and the root diameter should be specified. The crush resistance of the bush material should be such that it can withstand the MBS of the rope assembly. This should be demonstrated through prototype testing.

Hardware should be free of sharp edges and rough surfaces which might cut or abrade the rope or chafe protection. 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 should 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 starts to yield should be greater than the MBS of a single leg of the rope assembly. The strength of the thimble should be demonstrated through testing of a prototype of a representative size of the rope to be applied.

b. Sockets and Other Terminations

As an alternative to spliced eyes the rope assemblies may be fitted with socket terminations. These may be applied using cast resin cones, by the use of barrel-and-spike or by using a combination of these techniques. The choice of termination should be suitable for the particular rope construction. The effectiveness of the termination should be demonstrated through prototype testing.

The socket should be designed to have yield strength greater than the MBS of the fiber rope so that the connection pin can be removed and replaced without unreasonable application of force on completion of a break load test.

Socket design and material selection should address factors such as fatigue and corrosion to ensure that the termination is adequate for the service life of the mooring system. Resin systems should be chosen with care to ensure chemical compatibility with the rope materials and suitability for prolonged sea water immersion.

Detailed socketing procedures which match the procedures used for the prototype testing should be specified, although the prototype work may have been carried out on dummy sockets with the same basket profile as production fittings.

6.2.7.4 Rope Jacketing and Protection

The form of jacketing or protection to be placed on the rope, e.g., braided jacket, elastomer cover, etc. should be specified.

The specification should 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 can be found in 4.4.

6.2.7.5 Assembly Marking

Appropriate markings should be placed on each rope assembly. The specification should include the location(s) and means of applying these markings.

This may include the following:

- 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.
- A serial number and/or a leg designation to uniquely identify the specific rope assembly.
- A manufacturing or inspection date.
- The name of the manufacturer.
- The material and other characteristics of the rope.

6.2.7.6 Other Assembly Features

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

6.2.7.7 Packing, Shipping and Handling

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

Details concerning limitations on handling procedures (e.g., limiting local and global pressures on rope), minimum bend radii (e.g., for spooling, etc.), should be specified.

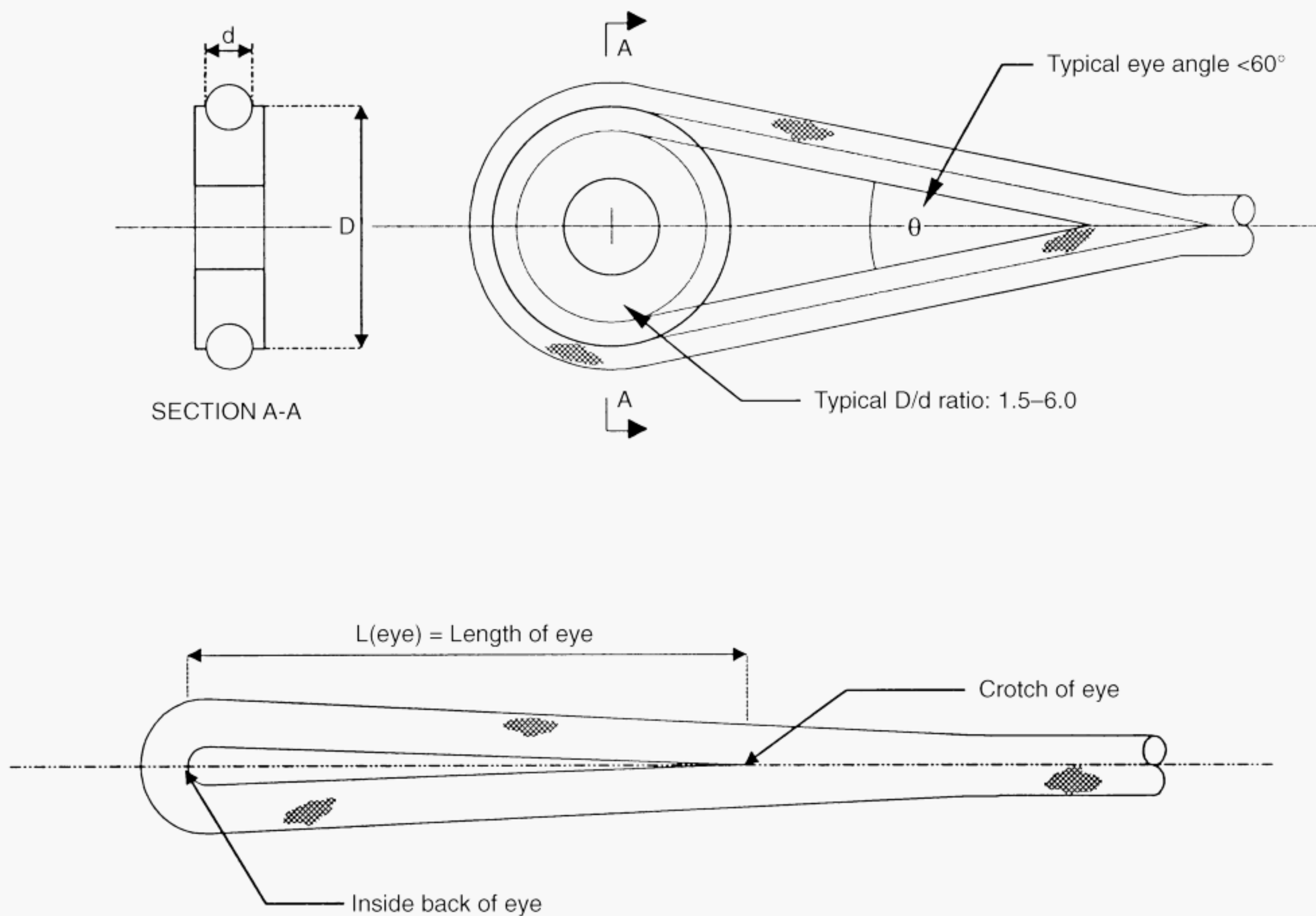


Figure 6.2.7.3—Diagram of Eye Splice Showing Features and Tolerances

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 will be supplied on reels. Logistics, installation techniques and economics will determine how installation or transportation reels are specified.

Installation reels can 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.

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.

In both cases 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 should be large

enough to accommodate the complete assembly without any portion protruding above a flange.

The reel should be provided with suitable means for lifting, which prevent damage to the reel during crane handling. Figure 6.2.7.7 shows an example of a suitable lifting arrangement using lifting lugs and a spreader bar.

Metal-end fittings should be individually wrapped or otherwise kept separate to prevent chafing of any underlying fiber rope. The finished package should be securely wrapped with weather proof material and battens secured between the flanges.

Each reel should be clearly labelled to identify the contents.

6.3 ROPE TESTING

6.3.1 General

The following rope tests should be conducted to determine or demonstrate rope properties:

- Break test.
- Static extension test.
- Dynamic extension test.

- Tension-tension fatigue qualification test.

The following rope tests may be conducted to demonstrate rope properties:

- Torque and rotation test.
- Axial compression fatigue test.

6.3.2 General Testing Practice

The rope tests can be performed on a prototype rope after the rope design is documented to demonstrate the rope properties, on a prototype rope at the beginning of production to an order, or on a sample rope taken during or after production of an order. Rope testing should be conducted according to Appendices A through D or equivalent rope testing practices as specified by a RCS.

6.3.2.1 Test Sample Length

The rope test sample for all tests should have adequate length of undisturbed rope to ensure that the test sample is representative of the actual deployed rope.

6.3.2.2 Wet Testing

- All testing should be conducted with the rope in its wetted state. This may involve submergence of the rope in water during testing, or the wetting of the rope during testing. Soaking of rope prior to testing may be adequate provided that during testing, the rope does not dry out.

6.3.2.3 Reference Load

As discussed in 6.2.7.2, a uniform reference load should be applied as part of tests involving length measurements.

6.3.2.4 Bedding-in

A few load cycles should be applied before taking length measurements and also before conducting break tests. These serve to bedding-in the rope structure, stabilizing the rope length and increasing rope and termination efficiencies.

6.3.2.5 Machine Accuracy

The test machine should be calibrated to provide at least $\pm 2\%$ accuracy of the estimated break strength of the rope. The gauge length should be of adequate length after consideration is made of the elongation measurement accuracy. A minimum of $\pm 2\%$ accuracy on the elongation measurement should be used.

6.3.3 Break Strength Test

All tests should be carried out using the same loading procedures in order to maintain consistency. This includes any cycling procedures and load ranges. This is recommended because it has been observed that average break strength gen-

erally increases while statistical scatter decreases due to the application of a few load cycles. This is due to the setting-in of splices, and the fibers becoming more orientated into the direction of load [23].

Test sample preparation and procedures should be in accordance with Appendix A.

6.3.4 Static Extension and Creep Test

These tests should be performed in order to determine the minimum post installation stiffness, the likely creep elongation during the lifetime of the unit, and the creep rupture resistance of the rope. Sample preparation and test procedures should be in accordance with Appendix B.1.

6.3.5 Dynamic Extension Test

These tests should be performed to determine the storm stiffness of the fiber rope, and also any other intermediate stiffness which may be 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 dynamic modulus is measured should also be documented. Sample preparation and test procedures should be in accordance with Appendix B.2.

6.3.6 Tension-Tension Fatigue Qualification Test

As indicated in 4.6.7.2, at least one fatigue qualification test should 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 6.3.6.

The test sample should have the same rope construction, fiber material, splice design and thimble as the production rope and have a minimum diameter scale of 50%. Sample preparation and test procedures should be in accordance with Appendix C.

6.3.7 Torque and Rotation Tests

The tests described below should be conducted where torque and rotation properties are of concern.

a. Rope Torque

The specimen should be terminated in a manner which resists rotation and which does not affect the measured rope torque and rotation characteristics. The termination should constrain all components which might significantly influence rotation and torque properties, including the rope jacket. Splices are not acceptable, as they do not provide the same torque-tension or torsional stiffness characteristics as the rope. Resin sockets are preferred.

Other means of rope termination are acceptable provided that they meet the above criteria.

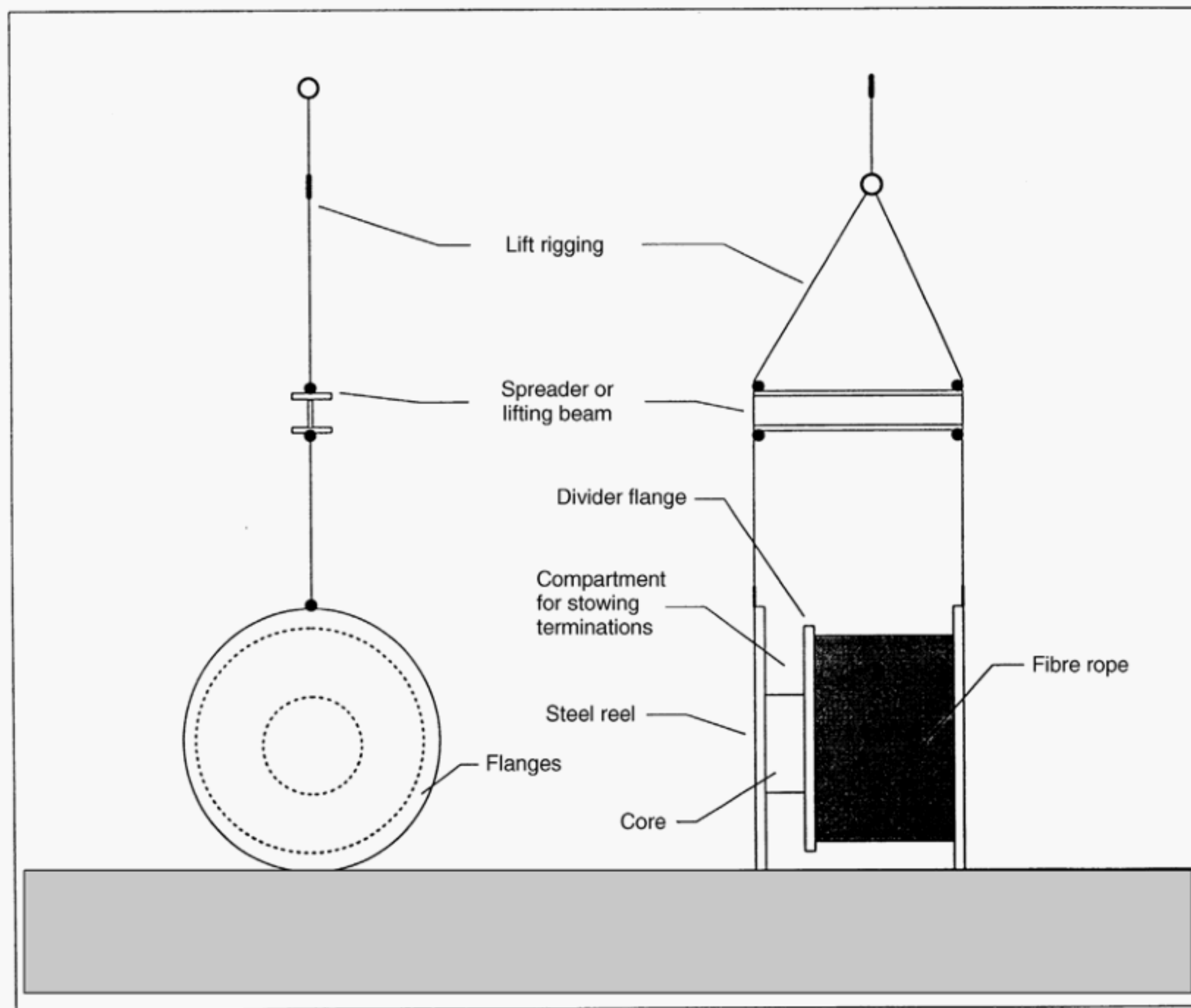


Figure 6.2.7.7—Typical Storage Reel and Lifting Arrangement

Table 6.3.6—Fiber Rope Fatigue Qualification Test Specification

Design Curve	Minimum Number of Cycles	Mean Tension (% MBS)	Tension Range (% MBS)
Polyester Rope	380,000	30	30
Spiral Strand Equivalent	80,000	30	30
Six/Multiple Strand Equivalent	30,000	30	30

The terminations should be of sufficient strength to safely withstand 50% of the minimum break strength.

The tension test machine should 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 $\pm 1\%$ of the expected maximum rope torque.

The tension test machine should also be equipped with a rotation measuring device incorporating 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.

b. Rope/Splice Torque Compatibility

This test should be performed on ropes which will be used in a mooring leg where torque and rotation properties are of concern or interest and where the rope is to be terminated by a splice or by another method which might have torque and rotation characteristics different from the rope itself.

One end of the specimen should be terminated in the same manner as that which would be used on the rope assembly. The other end may be terminated in a manner which resists rotation but which constrains all components which might

significantly influence rotation and torque properties, such as the rope jacket, or alternatively it may be terminated in the same manner as the first end.

6.3.8 Axial Compression Fatigue Test

07 | This test is only necessary for aramid rope mooring lines.

Axial compression fatigue testing may be performed to demonstrate that the synthetic rope does not lose significant strength when allowed to relax in service, and can be used as evidence that the rope can tolerate axial compression fatigue criteria less strict than those indicated in 5.3.2. Test sample preparation and procedures should be in accordance with Appendix D.

6.3.9 Scaling of Rope Data

For the above rope tests except the break strength (6.3.3), the test results can be interpolated or extrapolated for ropes made of the same material, construction and termination. A scaling ratio of up to 2:1 in rope diameter can be used provided that the appropriateness of the chosen scale ratio is demonstrated.

7 Rope Manufacture, Inspection, and Quality Assurance

7.1 GENERAL

A rope product should meet the requirements of the Rope Specification as called for in 6.1. A Quality Assurance (QA) program, as described in 7.6, should be developed prior to manufacturing prototype ropes and accepting orders for mooring ropes. This QA program should be followed when manufacturing both prototype and production ropes.

7.2 ROPE FIBER MATERIAL

The following procedures should be followed to ensure that the fiber material used in making the mooring rope is identical, and within stated tolerances, to the fiber material used in making the prototype test rope:

7.2.1 Material Certification

The fiber producer should certify 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.
- Finish solubility in water.
- Wet yarn-on-yarn abrasion.

The fiber producer should conduct tests to verify these properties for the particular grade, type, and designation of fiber and finish at least once each year.

7.2.2 Material Quality Testing

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

- Yarn size (linear density).
- Dry break strength.
- Dry elongation to break and either.
- Marine finish level.
- wet yarn-on-yarn abrasion.

7.2.2.1 Responsibility for Material Quality Testing

If the fiber producer is ISO 9000 qualified, then 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 should conduct these tests on representative samples removed at random from yarn shipments as received from the fiber producer.

7.2.2.2 Frequency of Material Quality Testing

At least one yarn sample should be taken at random from each 5,000 kg (1,100 lb) of material and tested for yarn size (linear density), dry break strength, and dry elongation to break.

At least four yarn samples should be taken at random from each 20,000 kg (4,400 lb) of material, and at least once from the material for any rope order, and tested for either finish level or wet yarn-on-yarn abrasion as described below.

Finish level should be determined by Soxhlet extraction (e.g., ASTM D2257) or by an equally accurate analytical technique. Testing should be conducted by the fiber supplier, rope manufacturer, or qualified third-party laboratory with an adequate understanding of analytical chemistry methods and a knowledge of the chemistry of the particular fiber and finish to be removed.

Wet yarn-on-yarn abrasion testing should be done in accordance with CI 1503 [30] 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 5,000 cycles.

7.2.3 Material Storage and Handling

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

Each fiber material package and each container of fiber material packages should be distinctly labelled with the identity of the fiber material.

Once the fiber material enters the rope manufacturing process, each material container or major package should be labelled whenever it moves to another manufacturing step or is placed in storage. If the container might be used for other materials, the label should be removed from the container as soon as the material is taken from it.

7.3 ROPE MANUFACTURING

The rope manufacturer should prepare a manufacturing specification which 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 described in the OCIMF Hawser Guidelines [8], including quality control checklists.

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

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

7.4 TERMINATION

The rope manufacturer should 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 [8], 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 (whichever comes first).

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

7.5 ASSEMBLY

The rope manufacturer should assemble the rope in accordance with the purchaser's specifications and instruction, and the details as called for in 6.1.7.

7.6 INSPECTION

7.6.1 Introduction

A third-party inspector, who represents the RCS and/or the purchaser and is knowledgeable of rope designs, manufacturing processes and termination procedures, should be employed to conduct the rope inspection.

The rope manufacturer should prepare appropriate inspection checklists and report forms. These should be at least as comprehensive as those given in the OCIMF Hawser Guidelines [8].

7.6.2 Review of Rope Documentation

The inspector should have access to all relevant rope documentation, even though these may be proprietary.

7.6.3 Inspection During Production

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

At the option of the certification authority and with the agreement of the rope manufacturer, the inspection steps and procedures may be carried out during one visit or may be carried out during several visits.

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

7.6.4 Selection of Sample Rope Section

The inspector should select the end of rope from which the sample rope section is taken prior to splicing. One such sample rope section should be taken for 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 length of rope should be pulled from the reel on which it was made, laid out on a smooth surface, and loaded to a reference tension agreed by the rope manufacturer for two minutes by means which do not damage the rope. At the end of this time, a length of 2 m (6.6 ft) should be marked accurately on the surface of the rope. The load should be released, the rope cut cleanly and squarely at these marks and the ends suitably secured to prevent unravelling.

7.6.5 Inspection of Sample Rope Section

The two-meter sample rope section should be weighed to an accuracy of $\pm 1\%$ and the weight divided by 2 to determine the weight per meter.

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

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

The inspector should carefully 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 total number of rope yarns in one strand should be counted and recorded. For strands containing less than 50 yarns, the number and distributions should be the same as given in the manufacturing specification. For strands containing more than 50 yarns the number should be within $\pm 4\%$ of the value given in the manufacturing specification. Extra yarns caused by over runs should be permitted.

The rope manufacturer, in the presence of the inspector, should conduct sufficient testing to confirm the fiber material used in producing the rope. The Fiber Material Identification Tests given in the OCIMF Hawser Guidelines [8] or other suitable test methods should be used.

The inspector should examine all identification marks to ensure they comply with 6.2.7.5.

7.6.6 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 [8]. These tests and calculations should be witnessed and certified by an independent inspector.

During rope manufacturing, the inspector should remove sufficient samples of fiber material from the sample rope section or the finished rope product for wet strength testing using the same procedures as were used with the prototype rope. These samples should be tested in the presence of the inspector. The inspector should verify that the calculated production rope strength, using the same procedures as were used with the prototype rope and the rope strength factor which was determined for the prototype rope.

7.6.7 Inspection of Rope Termination

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

The inspector should 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 this has been done.

7.6.8 Inspection of Finished Rope Assembly

The inspector should 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 should carry out that test in the presence of the inspector to demonstrate the specified length.

7.7 QUALITY CONTROL AND ASSURANCE

7.7.1 Introduction

Appropriate quality assurance procedures are necessary to demonstrate that fiber rope assemblies manufactured against any specific order have the same qualities as the prototypes and so can be expected to have the same properties without requiring further prototype testing.

7.7.2 Quality Assurance Manual

The rope manufacturer should prepare a quality assurance manual which completely and accurately describe the quality control and assurance program used in manufacturing the rope.

7.7.3 Quality Assurance Supervisor

The rope manufacturer should designate a quality assurance supervisor. The quality assurance supervisor and any deputies should not be under the authority or control of the manufacturing or sales branches of the rope manufacturer's company organization. The quality assurance supervisor and any deputies should 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.

7.7.4 Quality Control Checklists

The rope manufacturer should 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 application is to be carried out. The checklists should be followed and completed by the assembler during the assembly of each termination.

7.7.5 Quality Control Report

The rope manufacturer should prepare a quality control report which includes the various quality control checklists for the production and assembly of that rope. This report should 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.

8 Rope Handling and Installation

8.1 GENERAL

This section provides guidance for the development of procedures for handling, installation and recovery (if applicable) of synthetic fiber ropes. General requirements will be given regarding the contents of 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. For additional guidance on handling of fiber ropes, see Appendix G.

8.2 GENERAL STORAGE, HANDLING AND INSTALLATION CONSIDERATIONS

Care should be taken in packing synthetic fiber ropes for storage after manufacture, transportation to site, and during installation. The requirements should be in accordance with the manufacturer's recommendations, and the rope design and properties as found in Section 4.

8.2.1 Ultra-Violet Light and Chemicals

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

In the absence of detailed information from the rope manufacturer, Table 6 can be followed with regard to the typical resistance levels of rope materials to chemical and UV damage [24]:

Table 8.2.1—Resistance to Chemical and UV Weakening

	Polyester	Aramid	HMPE	Nylon	Steel (for comparison)
Chemicals	good ¹	good ¹	excellent	good ¹	varies ²
UV light ³	good	fair	fair	good	excellent

Notes:

¹ Attacked by strong alkalis and acids.

² Corroded by water, acids etc.

³ Protective coatings and jackets can greatly reduce the harmful effects of sunlight on ropes manufactured with high tenacity fibers [24].

8.2.2 End Fittings

Connecting hardware which has sharp and/or protruding edges should be avoided when ropes are stored and/or wrapped onto a spool. If this is not possible, adequate protection should be provided to prevent chafing of the ropes in the storage spools.

As indicated in 4.5.2 of this document, the usage of steel or other terminations may complicate the handling of the terminated ends of the line as care must be taken to ensure that excessive bending is not applied to the fiber rope which might cause compression damage to fibers. Bend restrictors fitted to the end of the fiber rope may be advantageous in avoiding or reducing this problem.

Lighter weight terminations and fittings using materials other than steel, such as composites, may be used if their performance has been proven to be satisfactory.

In the case of very long lines it may be necessary to provide mid-length connections by means of hard connectors such as spliced eyes with thimbles and connection shackles. Special consideration needs to be given to handling of the connection parts of the rope.

8.2.3 Twisting from Unbalanced Torque

As noted in 4.4.1, markings along the rope may be used to assist in monitoring the torsion/twist free rope during deployment. Twisting or unwinding of fiber rope may be a problem for pre-deployed mooring line when connected to a surface buoy. The maximum twist during installation should not exceed the manufacturer's limits based on torque tests as described in 6.3.7.

As discussed in 4.6.9, twist might be induced into components and then transferred between them during installation procedures. This may cause serious operation problems and should be avoided. Work wires of a non-torque balanced type (e.g., six strand wires) should not be used, unless consideration has been made for the effect of any twist induced into the installed mooring components.

8.2.4 Bending Radius

As indicated in 4.4.3, the installation minimum bending radii (MBR) quoted for installation or maximum design conditions (which may be 'one-off' events) may not need to be the same as for storage conditions, since storage is associated with prolonged static bending. The rope manufacturer should establish the limits of drum diameter to rope diameter ratios for installation and handling, taking into account the associated working tensions of the mooring lines.

Deepwater mooring fiber ropes should not be permanently installed around bollards or fairleads. This is because of the limited knowledge of their long term behavior under fatigue tension and bending and the potential for significant wear and

internal fiber damage to occur in the length of rope in contact with the bollard or fairlead.

During deployment rope assemblies will need to be stored and reeled around drums, fairleads and rollers. Failure of the external rope sheath (particularly the extruded polymer type) may result in a local bending stiffness discontinuity. This could become an area for bending fatigue damage to concentrate. Adequate steps should be taken in the design and installation to avoid this type of damage.

8.2.5 Cutting and Abrasion

All handling equipment [25] should not induce any detrimental loading into fiber ropes, such as excessive bending, chaffing, grinding, 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 may result in damage to the rope jacket or core.

8.2.6 Heat Damage

As indicated in 4.6.6, the fiber maximum working temperature should not be exceeded. In this respect ropes should not be located near to heat sources such as 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 or other alternative means should be considered. Heat build-up may also be more severe if fiber ropes are running over surfaces which naturally provide insulation such as painted surfaces.

8.2.7 Foreign Particles

As noted in 4.4.5, the presence of foreign particles such as blasting grit, sand, etc. should be prevented from coming into contact with the ropes. When the installation work is laid up due to weather or other reasons, protective covers should be provided to protect the rope from foreign matters and excessive UV exposure.

8.2.8 Wire Rope/Synthetic Rope Mix

During spooling and re-spooling, wire rope and synthetic rope should not be mixed on the same drum unless some form of segregation such as dividers can be provided.

8.2.9 Fiber Rope Weight

Fiber ropes have significantly lighter weights (both in water and in air) than steel wire rope or chain lines of equivalent strength and this feature makes them particularly attractive for installation of moorings in very deep water.

Rope diameters of fiber ropes (particularly for polyester) are likely to be bigger than steel wire rope and this influences the space required to store the lines prior to deployment.

Ropes that are positively buoyant may present some handling challenges during deployment; however the exact level of buoyancy for a rope depends not only on the fiber density but also on the flooding characteristics of the rope and the density of the jacket.

8.2.10 Salt Crystallisation

Fibers which are alternately wetted with salt water and allowed to dry out can suffer from abrasion damage from the internal formation of salt crystals. For the deepwater mooring lines this will not occur during deployment in a permanent mooring system as the ropes will be completely submerged.

8.3 INSTALLATION DESIGN CONSIDERATIONS

8.3.1 Deployment

Rope spooling tension should be kept consistent with the deployment tension to prevent any detrimental effects on the fiber ropes. Handling equipment usually associated with conventional steel wire or chain moorings should not be used unless it can be shown that the equipment does not adversely affect the rope and jacket design. Deployment techniques of polyester rope from installation vessels may include the use of rotary winches, traction winches, capstan or warping head type winches, or caterpillar type winches or hand-over-hand methods using special grips. Interference type stoppers designed for use with steel wire rope or chain should not be used for handling fiber rope. If necessary several links of chain can be permanently added to the rope termination and the clamp can be used on the chain links.

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 of rope in accordance with the rope manufacturer's recommendations.

During deployment the fiber rope should be separated from the termination hardware by means of split reels or special wrapping of the hardware.

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. This must be avoided by designing the rope reeling tension to be consistent with the tension applied during deployment.

Care should be taken to minimize the time that the rope is stationary on a stern roller, deployment sheave or overboard-

ing fairlead, while the rope is under significant load, in order to prevent rope damage. In case unexpected events cause rope deployment stoppage while contacting the stern roller, procedures should be developed to mitigate the localized abrasion, bending fatigue, and heat build-up damages.

8.3.2 Minimum Tension and Maximum Allowable Low Tension Cycles

07 | This requirement only applies to aramid rope mooring lines.

During the installation a minimum line tension in the synthetic fiber rope should be maintained to prevent lines from possible compressive damage. If the installation method results in excessive number of load cycles of loading in which the line tension goes from the installation tension to below the guideline limit provided in 3, then analysis will be required to demonstrate acceptability. An analysis should demonstrate that the total number of load cycles going below the guideline tension for both the installation phase and the remaining lifetime of the installation does not exceed the limiting value listed in Table 4.6.7.3 of this document.

Activities which might result in such loading include deployment of anchors and anchor proof loading.

For the pre-deployed lines awaiting the arrival of the platform, the environmental loads may induce small tension variations in the synthetic fiber rope. To prevent the rope from possible compressive damage, the pre-deployed line should be maintained at a minimum mean tension of 5 tonnes for polyester ropes and 2% of MBS for higher modulus ropes (Aramid and HMPE). As such, counting of load cycles is not required for pre-deployed lines.

8.3.3 Contact with Seabed During Deployment

During deployment, fiber rope contact with the seabed is undesirable. Where fiber ropes have been accidentally dropped to the seabed, the ingress of foreign particles such as sand will affect the rope's yarn-on-yarn abrasion resistance and hence will adversely affect the rope's fatigue life. Unless it has been demonstrated through testing that the rope jacket is impermeable to damaging ingress of the silt and other particles present on and near the seabed, a rope which 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 9.4.1.

In most instances, it is necessary for the fiber rope to be pre-deployed prior to hook-up with the installation. Any installation proposal involving the pre-deployment of fiber lines on the seabed should for example include: suitable justification through testing or otherwise that the jacket can provide adequate resistance to the ingress of sand; foreign particle ingress protection at rope terminations; bottom stability (if laid on bottom); environmental loading such as waves and current; rope compression fatigue; rope buoyancy con-

siderations (i.e., 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.

8.3.4 Connection to Anchors

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 will depend on the type of connection hardware specified and the power and capability of the available Remote Operation Vehicle (ROV).

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

- Abrasion or fouling of the mooring line with the anchor system, anchor chain, separate anchor lowering lines and bridles, connectors, etc.
- Uncontrolled twisting of the fiber rope and/or adjacent wire ropes due to lack of torque matching between mooring line fiber rope and steel rope segments, and due to lack of torque balance in anchor lowering lines.
- Increased 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 which will be connected to the synthetic fiber mooring lines, a length of chain or wire rope should be used to keep the fiber rope clear of the seabed to avoid damage due to particle ingress, and damage to fiber rope during anchor handling on board the installation vessel. The length of this steel line segment may also depend on the selected preset configuration of the mooring legs.

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 should be specifically designed for such use. The mooring designer 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 RP 21.

8.3.5 Temporary Moored Units

Design should account for the necessary steel wire/chain segments (i.e., for connection to winches, to avoid bending over sheave fatigue, creep elongation, other marine winching operations, etc.) and at the anchors (see 8.3.4 above). Breaking-out of anchors such as drag embedment anchors should be monitored carefully (if fiber ropes remain attached), since there may be some possibility of undesirable fiber rope loading such as compression damage. Where the temporary moorings will require regular handling of fiber ropes due to repeated deployment and recovery, the use of fiber ropes which have high resistance to external abrasion should be considered.

Mooring test load requirements for temporary moorings can be found in API RP 2SK [1], 6.6.5. The mooring test load for fiber ropes in temporary mooring systems should also satisfy the need to achieve an acceptable post installation stiffness of the fiber ropes. 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. During operations, the mooring leg tensions should be monitored regularly, and the mooring line tensions should be adjusted as required to maintain a minimum operating tension specified by the mooring designer.

8.3.6 Permanent Moored Units

Similar to temporary moorings, a suitable length of steel wire or chain should be provided at the top and bottom ends of the synthetic rope mooring leg for permanently moored units. The upper steel line segment can be used for adjustments of the mooring leg tension needed to allow for rope extension and creep. Therefore, suitable equipment for adjusting the length of the upper steel line segment should be provided for each mooring leg. Further, the length of the upper steel line 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.

Mooring test load requirements for permanent moorings can be found in API RP 2SK [1], 6.6.5. The mooring test load for fiber ropes in permanent mooring systems should also satisfy the need to achieve an acceptable post installation stiffness of the fiber ropes. The level of post installation stiffness required for the fiber rope should be verified by the mooring system designer based on the maximum allowable platform/vessel excursions during operating and survival conditions, and be consistent with the rope testing. While in service, the mooring leg tensions should be monitored regularly, and the mooring line tensions should be adjusted as required to main-

tain a minimum operating tension specified by the mooring designer.

8.3.7 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 ropes under tension whether they be steel wire or fiber ropes.

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 minimizing opportunities for the taut line to be abraded or touched by other items of equipment during installation particularly when under tension.

8.3.8 Possible Pre-deployment Techniques

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 [2], the installation schedule and procedures should be established to prevent the fiber ropes from being left unattended that damage may occur while awaiting hook-up to the vessel or platform. The same applies to temporary moorings after the surface vessel has been disconnected and the fiber ropes are left at the location, prior to recovery for re-use at another location.

a. Surface Buoyed Lines (Ref. Figure 8.3.8a)

The minimum tension requirement only applies to aramid rope mooring lines.

Pre-deployed mooring lines should not be left buoyed at the surface awaiting connection to a platform unless the minimum tension requirements of 8.3.2 are met. The possibility of independently buoyed lines being allowed to rotate should also be considered. These requirements are intended to avoid the fibers in the line undergoing compression with the possibility of buckling fatigue and subsequent damage and failure.

Pre-deployed, surface buoyed lines which are tensioned together in groups while awaiting platform arrival can be used to keep lines in tension and avoid multi-turn twisting of mooring lines.

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

b. Bottom Laid Lines

Fiber ropes which lie on the seabed (temporarily or permanently) require a jacket in order to protect them against external abrasion from the seabed, and to prevent ingress of particles that will result in accelerated yarn-on-yarn abrasion (see seabed contact criteria in 8.3.3). Particular care should be

paid to the design of the jacket at the termination to prevent soil ingress at the end of the rope; however, if the jacket does not flood, the implications for submerged weight and cooling of the fibers should be taken into account.

Following careful study it may be possible for lines to be laid on the seabed to await arrival of the platform. The top end of the line will need to be weighted to keep it firmly on the seabed and the actual weight of the fiber rope in water should be carefully considered to ensure that it is not able to lift off under the effects of seabed currents. The HMPE fibers which are positively buoyant may not be suitable for this form of deployment unless 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 should keep the fiber ropes clear of abrasion damage at the touch down locations.

The recovery line required at the top end of the laid down mooring should be suitably tensioned to prevent it from dragging over and damaging the fiber rope. This may require the provision of additional clump weights.

c. Mid Span Suspended Lines

07 | The minimum tension requirement only applies to aramid rope mooring 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 must be capable of surviving movement due to current. The suspension buoy must be large enough to maintain sufficient tension in the line to prevent fiber buckling fatigue (see minimum tension requirements of 8.3.2) and to also hold the end terminations clear of the seabed. This mode of installation may be most feasible for fiber ropes which are inherently positively buoyant; however the method relies heavily on the mid-length buoy which is an added complication during deployment and must be built to withstand significant hydrostatic pressures. Failure of the buoy would result in the fiber rope being dropped in an uncontrolled fashion to the seabed with attendant concerns about what, if any, damage it would have sustained.

8.4 INSTALLATION/ RECOVERY PROCEDURES

Complete and detailed procedures should be developed for the installation and recovery (where applicable) of deepwater moorings incorporating synthetic rope segments. These procedures should define in adequate detail the vessels and equipment to be used for the work and the methods of how the synthetic rope segments will be handled to prevent rope damage and to prevent synthetic rope segments from contacting the seabed. The procedures should 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 should be defined in the procedures. If special rope jacketing is used, which allows seabed contact,

this should be specified in the mooring system specifications and installation procedures.

8.4.1 Installation Planning

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

- Details of rope shipping, shipping reels, rope protection, shipping reel handling, lifting and storage, etc. should be included. If the shipping reels are to be used during installation and/or recovery, their design should be adequate for the intended offshore operation. This may require reinforcements and or modification of typical standard shipping reels, either incorporated by the rope manufacturer, or provided by the installation contractor.
- 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 re-spooling operations should be developed in adequate detail to ensure that these operations are safe, and that the equipment used for this operation is adequate and properly tested.

8.4.2 Installation Operations

Installation operations will depend upon the mooring system being installed, the equipment available for the installation, prevailing weather conditions and sound site decisions. Detailed offshore installation (and recovery if applicable) procedures should therefore include the following critical elements:

- Arrangement of installation machinery/equipment on board the installation vessel.
- Stability assessment of the installation vessel and recommended loading conditions to maintain vessel stability and minimize motions (if applicable).
- Seafastings/tie-downs of installation machinery and equipment. 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 should be adequate for survival of storm conditions offshore in standby mode. If the survival motions of any installation equipment on board the installation vessel is limited, these limits should be specified, and procedures developed for timely return to port of the installation vessel.
- Procedures for the deployment of anchors, which should prevent damage to any mooring leg components, and which should eliminate risk of entanglement between synthetic rope segments and steel mooring line components or any separate anchor deployment

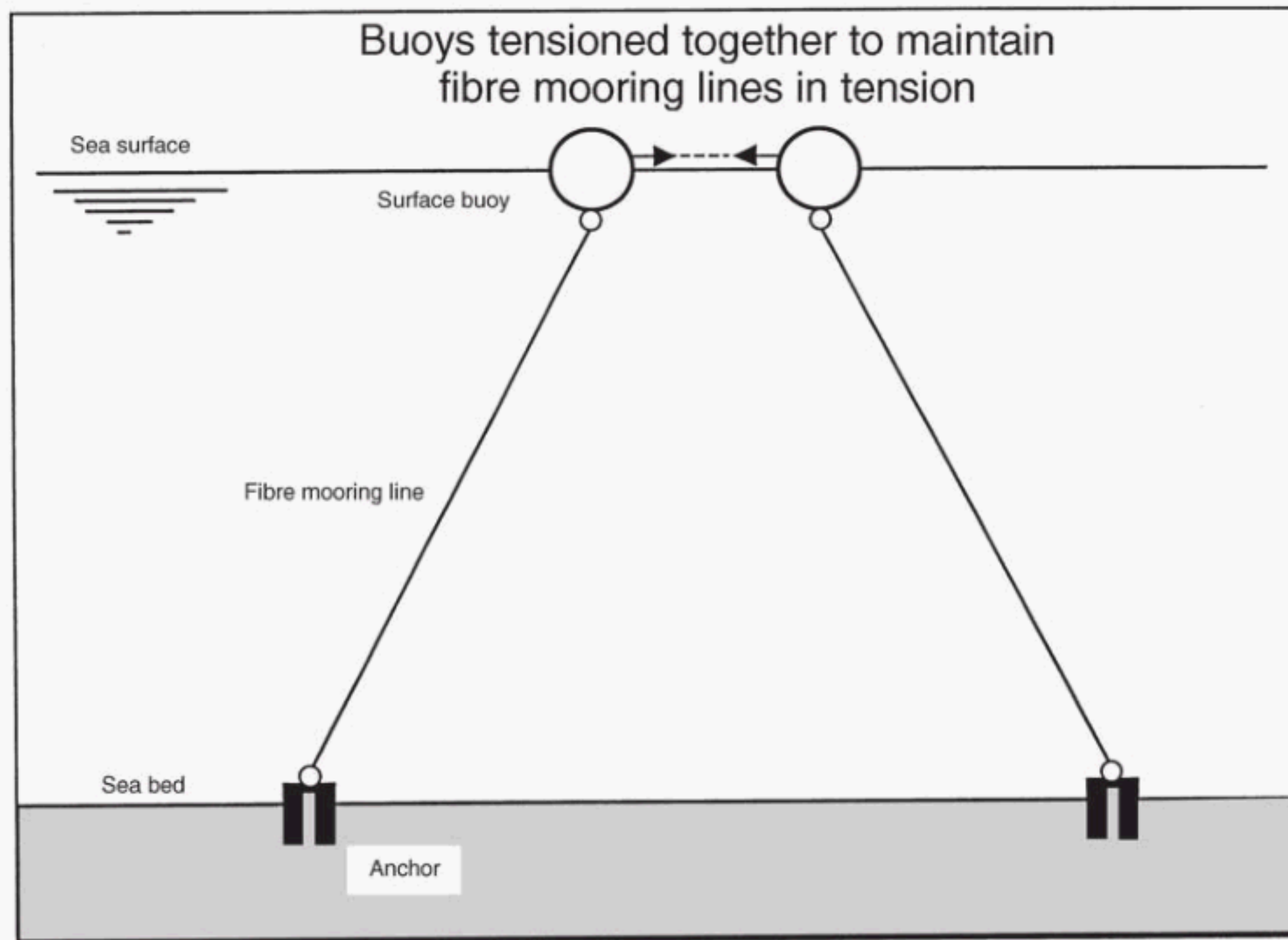


Figure 8.3.8a—Surface Buoys Tensioned Together to Maintain Fiber Rope in Tension

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.

- 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 including details of installation vessel position, heading, movement, etc.
- The procedures should demonstrate that the synthetic rope sections can be safely deployed/recovered by the proposed equipment, without damage to the rope, its jacket (if used) and its terminations. Testing of the synthetic rope handling/installation equipment may be required 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, and left at the site, until the MODU or FPS can be connected to the preset mooring system. The pre-installed configuration of the mooring system should be carefully considered, and fully detailed, in order to minimize damage to the system while left unattended. To minimize low tension

load cycles, special arrangements may be required, which either ensure the minimum tension applicable for the type of synthetic rope, or which limit or minimize load cycling at low tensions.

- If large surface buoys are used to support the preset mooring legs, they should be suitably marked to minimize the risk that such buoys can be overrun by shipping, which may 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 test tensioning of the mooring lines and anchors should be developed. Such test loading could be performed during pre-installation of the moorings, or after hook-up to the MODU or FPS.
- Detailed procedures for the connection and disconnect (if applicable) of the vessel to the preset synthetic mooring system should be developed. These procedures should detail the type of installation vessel and special equipment required, and they should define the towing procedures, towing vessels and connection sequence.
- If there is a significant risk that synthetic rope segments and other mooring line segments can be damaged dur-

ing installation and/or hook-up, a suitable number of spare components should be prepared to replace damaged or dropped mooring line components.

- Suitable means for stopping off synthetic ropes should 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 synthetic ropes, and special equipment may be required.

8.4.3 Contingency and Inspection Plans

Contingency procedures should be developed, detailing what can happen, and what can be done to correct the problem, in case of failure of any of the installation equipment. For example, if the anchor is lowered on a separate line, and this line or the winch deploying it fails, the mooring leg deployment equipment should be capable of handling the increased mooring line load, without significant damage to the mooring line, and without pulling the mooring line deployment equipment off the vessel. The procedures should therefore list all plausible failure scenarios, their impact, and how the impact of such failures can be mitigated or minimized.

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

If the installation/recovery equipment is used on a regular basis, regular inspections of the equipment should be carried out to ensure its integrity. Function testing of hydraulic systems, winch brakes, instrumentation, etc. may be required to ensure the equipment is functioning properly, and loads can be monitored and controlled.

In the case of temporary moorings, where the synthetic mooring ropes are recovered and intended to be moved to another location, the synthetic mooring rope segments should be carefully inspected in order to determine whether they are suitable for re-use. Such inspections can be performed offshore during recovery, or in port. Procedures for the inspection of such ropes, guidelines for rope acceptance/rejection, requirements for testing, and procedures for offshore repair and/or onshore repair should be established and followed in accordance with 9.4 and in collaboration with the rope manufacturer before synthetic ropes are recovered and re-used.

9 In-service Inspection and Maintenance

9.1 GENERAL

This section provides guidance for typical in-service inspection and maintenance. In general, there are very few

industry standards concerning this aspect, unlike for steel components (e.g., API RP 2I [26]).

A plan for the fiber rope inspection and condition assessment should be developed by the operator of the mooring system and the manufacturer of the rope in conjunction with the certifying authority on a case by case basis to provide consistency with the overall safety assessment for a given installation.

An individual log should be kept for each rope which clearly records the history of the rope usage including information such as rope tensions, relevant environmental conditions, and inspection/re-tensioning details on the rope.

9.2 INSPECTION AND TESTING TECHNIQUES

The following provides an overview of the currently available inspection techniques for fiber ropes:

9.2.1 Visual Inspection Techniques

Present visual inspection techniques are generally limited to external visual examination only. Inspection of mooring legs on mobile units can be performed on deck or at dockside during rig moves. Inspection of installed mooring legs can be performed using divers or a Remotely Operated Vehicle (ROV).

The success of such inspection techniques clearly depends upon underwater visibility and extent of marine growth.

9.2.2 Internal Non-destructive Inspection Techniques

Presently, no reliable Non-Destructive Testing methods are available for fiber ropes [27]. When NDT techniques become available, full justification by trials, etc. should be performed to assess their accuracy and suitability for their intended usage.

9.2.3 Destructive Inspection and Testing Techniques

It may be prudent to include short fiber rope inserts which are periodically removed, examined and tested in order to detect internal deterioration, determine residual strength, and establish appropriate replacement and retirement criteria; however, the increase in the number of terminations and the potential risk involved in the insert replacement operation should be considered. Likewise, when a rope is replaced or retired, it may be prudent to examine and test it.

9.3 FIBER ROPE INSPECTION PROCEDURE

Inspection procedure for fiber rope mooring should include a combination of external visual inspection, internal examination and residual strength testing techniques as indicated above. The inspection procedure should be developed and

documented by or in close collaboration with the rope manufacturer, and should address the following subjects:

- Visual inspection requirements for rope core, rope jacket and terminations.
- Training of rope inspectors by rope manufacturer.
- Description of rope strand damage, which will reduce the rope strength to less than the rated MBS of the rope.
- Type of acceptable jacket damage, and description of jacket damage which will require repair.
- Description of termination damage requiring repairs and/or re-splicing of the termination.
- Description of termination hardware damage requiring hardware replacement.
- Description of the type of rope and/or termination damage, which would require the rope to be replaced immediately.

9.3.1 Visual Examination

External visual examinations should be carried out on a regular basis for all fiber rope moorings. Examinations should be performed by a competent experienced inspector, who has a thorough knowledge of the construction of the rope, the possible deterioration modes, and the inspection techniques. If possible, involve a representative from the rope manufacturer. Prior to inspection, it may be necessary to remove any marine growth or otherwise using suitable means which will not damage the rope itself. This type of inspection should be able to detect any jacket defects, twist of rope (axial marking referred in 4.6.9) and any external damage due to fish bite. It may also be able to detect changes in rope diameter and any bacterial effects at the near sea surface segments. All terminations and fiber rope near to the water surface should be examined closely to ensure that no damage has occurred.

9.3.2 Internal Inspection

If external visual examination indicates any uncertainty as to rope integrity, then it may be prudent to remove the rope or section of rope or rope insert (if present) from service. A detailed internal examination of the interior of the removed rope should then be conducted in order to identify developing degradation. The internal inspection may involve removal of sample yarns and/or rope sub-core strands, for splicing and testing for general properties such as elongation and break strength. Yarn extracts may also undergo microscopic examination by specialist laboratories to determine details such as the level of foreign particle ingress.

9.3.3 Fiber Rope Inserts

See API RP 2I for additional discussion on fiber rope inserts.

The use of fiber rope inserts may be more applicable to permanent units. If inserts are to be used, then it is recommended they be used at the near-surface termination for ease of replacement/access, and also because this is the likely region of damage due to fish bite, UV, chemical action, bacterial action, etc. Practically, the uppermost segment is also usually subject to the maximum current velocity, wave motion and maximum line tension. These inserts can be removed and tested at testing laboratories in order to assess damage, by fatigue testing followed by break tests. Test sample preparation and procedures should be in accordance with 6.3. Recovery and replacement of complete lines can be based on residual strength tests of inserts. The lengths of available break test machines may govern the fiber rope insert length.

9.3.4 Inspection of Fiber Ropes for Temporary Moorings

For mobile units (e.g., MODUs) regular inspection of fiber mooring ropes may be feasible, while the fiber rope moorings are recovered before they are re-deployed at a new location. In general, before a fiber rope is re-installed it should be carefully inspected for abrasion of the jacket and rope core, damage to terminations, and termination hardware. Such inspection can be performed during recovery of the moorings on board the recovery vessel, or it can be performed at a base port facility.

It is likely that ropes used in temporary moorings will get damaged more often than their permanent counterparts, and may be subject to additional fatigue damage associated with multiple deployment and recoveries. This additional fatigue may not be detectable through external visual inspections so destructive testing techniques will have to be used. The frequency of conducting the destructive testing should be established based on an accurate log of the rope usage, and in association with the rope manufacturer and the certifying authority. The first destructive test the first time a particular rope is used should be carried out as soon as possible after one year of accumulated service.

9.4 ROPE RETIREMENT CRITERIA

The rope retirement criteria should be based on appropriate testing of rope or rope inserts for residual strength and suitable inspection techniques and procedures as described above.

9.4.1 Damage Assessment

Rope that has been damaged accidentally during installation may be put in service provided certain criteria are met. Procedures for determining whether a damaged rope can be retained in service should be established and approved by the certifying authority. These procedures will depend upon the rope construction and the materials used, and should be developed as follows:

1. A damage assessment should be performed and recorded immediately after damage to the rope is detected. The assessment should include detailed description of the damage and causes, damage measurements such as length and depth of a cut, and photographs of the damaged area.

2. An evaluation of rope strength reduction due to the damage should be carried out. Specific guidelines for such an evaluation have not been developed. The following principles can be used as a general guidance:

- In break test a fiber rope normally fails at the splice, which typically has 20% to 35% lower strength than the rest of the rope. Consequently damage to the splice is more detrimental than damage to other areas.
- If a strand is substantially damaged, it is conservative to assume loss of that strand. The reduction in rope strength can be estimated based on loss of the load carrying fiber area and a factor accounting for the imbalance of load sharing due to the missing strand.
- The cumulative effect of damage along the rope length should be considered as well as individual areas of damage.
- Results of experiments indicate that intrusion of soil particles into the load carrying fiber can significantly reduce rope strength (up to 40%) and fatigue resistance.
- Jacket is not a load carrying component; however, damage to jacket can disturb the load sharing among the strands, allow soil intrusion or buildup of marine growth on load carrying fiber. These adverse effects should be considered in the strength reduction evaluation.

3. If the above evaluation indicates that the rope fails to retain 90% of the required design strength of the mooring line, the rope should be replaced immediately. Otherwise the rope can be temporarily placed in service with or without repair.

4. For the rope that is temporarily placed in service, a test should be conducted to confirm the 90% retained strength. A rope sample of the same fiber material, rope construction, termination, and size should first be prepared. After simulated damage that closely resembles the field damage is imposed on the sample rope, a break test should be performed in accordance with Appendix A. If this test fails to confirm the 90% retained strength, the rope should be replaced immediately. If the test confirms the 90% retained strength, and analyses based on the reduced strength indicate that creep rupture and fatigue criteria are still met, the rope can be permanently retained in service.

5. The rope to be permanently retained in service should be suitably repaired within one year from the date the damage is detected.

9.4.2 Repair Procedures

Rope repairs should be carried out by personnel trained and qualified to a standard approved by the rope manufacturer and the certifying authority. Repairs may be carried out offshore provided adequate facilities are available and detailed procedures for the operation have been documented and approved by the certifying authority.

Repair procedures should include:

- Description of strand repairs, butt or termination splicing techniques which may be employed to restore the rope strength.
- Description of jacket damage repair which can be performed, and type of facilities and equipment required to perform the repairs.
- Log of details of the damaged area.
- Removal of obvious abrasive particles from load bearing part of rope.
- Prevention of further ingress of abrasive particles into the load bearing part of the rope.
- Reinforcement to make rope suitable for subsequent redeployments without further damage.

All strand repairs, butt and re-terminations should be based on the same quality control procedures used in making the new rope.

9.5 MAINTENANCE PROCEDURES FOR PERMANENT MOORINGS

9.5.1 Inspection Following Hook-up

After installation, the mooring line should be inspected for any external damage by an ROV or diver. Twist and torsion can be verified at installation by an ROV/diver monitoring of the marking that runs externally on the jacket. Limiting values on the extent of damage should have been determined by the manufacturer through appropriate testing. Particular attention should be made to the condition of fiber ropes terminations. Other design aspects which should be verified immediately following hook-up are the fiber rope near surface termination position and the installation tension. Actual elongation should be recorded for all lines during the application of installation tension.

9.5.2 Regular Inspection as Maintenance

Regular inspection of the mooring lines should be performed over the service life of the mooring system. The inspection and/or maintenance scheme should include methods and techniques used to verify that the system is operating as designed. The frequencies at which inspections and tests are performed may vary from project to project. In general, the previous inspection would normally provide an indication as to the next inspection date. Reference can be made to API RP 2FP1 [28] for further details. In addition to 2FP1 recommendations, the following is recommended:

- Records of anchor leg re-tensioning caused by creep elongation should be reviewed, and confirmed with the designer that adequate lengths of chain/wire segments are available for further re-tensioning due to creep elongation such that the fiber rope does not come into contact with the fairlead and stays well below the water surface.
- The pre-tensions of mooring lines are within the designer's recommended limits. The measurement of catenary angles may not necessarily be very accurate for Taut Leg Moorings (TLM). Thus other means should be used to determine the mooring line tensions.
- Conditions of the terminations are checked regularly.
- Foreign particles in way of rope body and crevices.
- Marine growth, if affecting the condition of the rope, should be removed on a regular basis, by a method which will not damage the rope.

9.5.3 Removal and Replacement of Inserts

07 | The avoiding compression fatigue recommendation only applies to aramid rope mooring lines.

Where fiber rope inserts have been installed, adequate tension should be maintained in the fiber mooring line during the disconnected period from platform to avoid compression fatigue. Reconnection of the fiber mooring line to the insert can be made after satisfactory condition assessment of rope terminations and steel connectors such as the tri-plates, shackles, connecting links, etc. and appropriate fiber rope insert testing in accordance with 6.3.

9.5.4 Frequency of Fiber Rope Insert Testing

Where fiber rope inserts have been installed, at least one insert rope (e.g., most loaded line) should be removed and tested periodically. Testing may include the fatigue testing of rope in order to show that the mooring line has adequate fatigue resistance to last to the next inspection date. Subsequent break testing of the sample can provide an indication of any strength loss. Recovery and replacement of complete lines can be based on these tests, and this should be included in the maintenance manual.

9.5.5 Inspection after Storm or Unusual Event

An inspection as indicated in 9.5.2 should be carried out after events such as passing of a storm (defined as environmental conditions approaching the design storm conditions), vessel collision, etc. [28].

10 Design Examples

10.1 GENERAL

The design example generally follows the analysis procedures set forth in API RP 2SK [1] for the calculation of offset and maximum line tensions. Departures from these include:

- a. The necessity for employing a dynamic mooring analysis.
- b. The approach to incorporate fiber rope stiffness bounds into the analytical calculation.
- c. The calculation of minimum tensions for fiber rope compression fatigue.
- d. The number of cycles of line tension below recommended minimum allowable tensions.
- e. The clearance of fiber rope off seabed.

The design example is intended to illustrate the principal steps in the analysis of a synthetic mooring system using polyester rope and to demonstrate the unique synthetic mooring design features. The procedures described here are not unique and it may be necessary to combine the recommendations given in API RP 2SK [1] to accommodate specific software. For illustration purpose, only the extreme responses of a permanent mooring system under the intact conditions and the fatigue life of such a system have been analyzed. The analysis focuses on the polyester rope segment.

10.2 MOORING SYSTEM DESCRIPTION

The system to be analyzed is:

- a. A typical 8-column semi-submersible with a 12 point, 25 degree/45 degree/65 degree mooring pattern, as shown in Figure 10.2.
- b. The mooring system is a permanent installation with a 20-year design life.
- c. Each of the mooring lines is identical and consists of three segments: bottom chain, intermediate polyester rope, and top chain. Pretension is selected to be 502 kips.

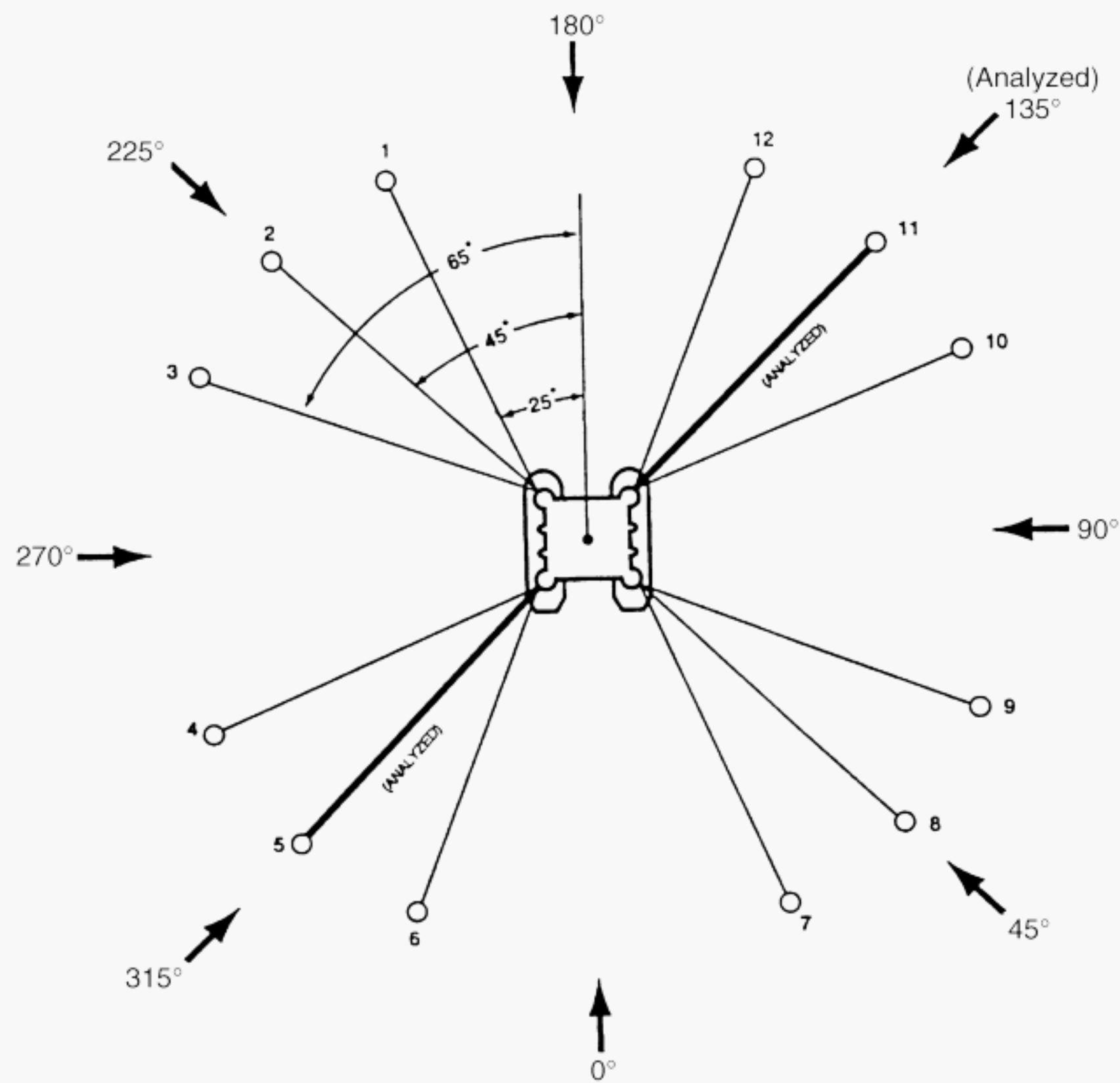


Figure 10.2—Mooring System and Environmental Directions

Mooring line characteristics for the three segments are as follows:

a. Bottom Chain Segment:

Segment type	ORQ + 20% Chain
Diameter	3.875 in. (98.4 mm)
Length	500 ft (152 m)
Line mass	4.612 slugs/foot
Normal added mass	0.600 slugs/foot
Weight in water	129 lbs/ft (192 kg/m)
Nominal drag diameter	0.646 ft (0.196 m)
Stiffness (AE)	180,200 kips
Breaking strength	
New	2,007 kips
4 mm (wear + corrosion)	1854 kips
Normal drag coefficient	1.20
Tangential drag coefficient	0.05
Friction coefficient	1.00

b. Intermediate Polyester Segment:

Segment type	Polyester rope
Diameter	7 in. (178 mm)
Length	3,900 ft (1190 m)
Line mass	0.544 slugs/foot
Normal added mass	0.534 slugs/foot
Weight in water	4.9 lbs/ft (7.3 kg/m)
Nominal drag diameter	0.583 ft (0.178 m)
Post-installation stiffness (AE)	22,481 kips
Storm stiffness (AE)	67,443 kips
Breaking strength	2,200 kips
Normal drag coefficient	1.20
Tangential drag coefficient	0.05
Friction coefficient	0.60

c. Top Chain Segment:

Segment type	ORQ + 20% Chain
Diameter	3.875 in (98.4 mm)
Length	300 feet (91 m)
Line mass	4.612 slugs/foot
Normal added mass	0.600 slugs/foot
Weight in water	129 lbs/ft (192 kg/m)
Nominal drag diameter	0.646 ft (0.196 m)
Stiffness (AE)	180,200 kips
Breaking strength	
New	2,007 kips
4 mm (wear+corrosion)	1854 kips
Normal drag coefficient	1.20
Tangential drag coefficient	0.05
Friction coefficient	1.00

For the polyester segment, two rope stiffness values, namely the post installation stiffness and the storm stiffness as defined in 4.6.4.1, are used in the analysis. The post installation stiffness is used to establish the maximum platform excursion, and the storm stiffness is used to establish the most probable maximum and minimum line tensions. The nominal drag diameter of the chain segments is increased by a factor of 2. For the polyester segment this is not required.

The breaking strength of the chain segments for a permanent mooring installation should be corrected for wear and corrosion allowance. The level of correction depends on the length of the design life. A correction of 4 mm (0.157 in.) is taken off the effective chain diameter for this installation with a 20-year design life when considering breaking strength.

10.3 EXTREME RESPONSE ANALYSIS EXAMPLE

10.3.1 The Environment

The design example environment for the extreme response analysis is as follows:

- Water depth = 3,000 ft (914 m).
- Significant wave height = 41.3 ft (12.6 m).
- Peak spectral period = 14.5 sec.
- JONSWAP spectrum with a peakedness factor 3.3.
- Wind velocity (1 min.) = 91.1 knots.
- Surface current velocity = 2.1 knots.
- Quartering direction at 135 degrees (See Figure 10.2).
- Collinear wind, wave and current.
- Design storm duration = 3 hours.

Wind load is assumed to be applied statically to the vessel, and is computed using the one-minute average wind speed. An alternative way is to incorporate the dynamic effects of wind into the analysis using the one-hour average wind speed plus a fluctuating wind component (See details in API RP 2SK [1]).

It is necessary to account for the current load on the polyester rope segment since the diameter of the polyester rope is usually larger than that of its steel counter part. The current load on the mooring lines, including chain and polyester rope segments, is evaluated assuming a linear current speed profile from the still water level to the sea bottom. The current load on risers should also be included when it is significant compared to the total environmental loading. In this example, the current load on the risers is not evaluated.

10.3.2 Mean Load/Offset Computation

Mean loads can be derived from model test data or they can be directly computed. The vessel mean loads, computed using coefficients calibrated by model test data, are as follows:

Wind (1-minute average)	793	kips
Current on the platform	240	kips
Current on the mooring lines	77	kips
Steady wave drift	84	kips
Total mean load	1,194	kips

The associated mean vessel offset is 60.8 feet (18.5 m) (2.0% water depth) based on the post installation stiffness.

10.3.3 Vessel/Fairlead Motions

In this example, wave frequency vessel motions are calculated based on the response amplitude operators (RAOs) and phases, in the three linear directions (surge, sway, heave), and the three angular directions (roll, pitch, yaw). These RAOs and the associated phases can be derived from hydrodynamic computer programs or model test data. Usually the vessel's center of gravity is used to define the motions. The computed root mean square (RMS) value of the wave frequency motions in the wave direction in quartering seas is 5.94 ft (1.81 m).

Low-frequency vessel motions can be derived from hydrodynamic programs, model test data, or design curves. The computed RMS value of the low-frequency motions in the wave direction is 6.78 ft (2.07 m).

Maximum vessel offset is the mean offset plus appropriately combined wave frequency and low-frequency vessel motions [1]. To establish the dominant responses, the maximum wave frequency motion is compared with the maximum low-frequency motion as follows:

Maximum wave frequency motion:

$$3.72 \times 5.94 = 22.1 \text{ ft (6.74 m)}$$

Maximum low-frequency motion:

$$3.00 \times 6.78 = 20.3 \text{ ft (6.19 m)}$$

where the factors 3.72 and 3.00 represent a 1 in 1,000 and 1 in 100 wave maximum responses, respectively, typical for 3-hour storm conditions. Since the wave frequency motion dominates, the maximum offset is computed as:

$$\text{Mean Offset} + \text{Maximum Wave Frequency Motion} + \text{Significant Low-Frequency Motion} = 60.8 + 22.1 + 2 \times 6.78 = 96.5 \text{ ft (29.4 m) (3.2\% water depth)}$$

The maximum offset is computed with respect to the vessel's center of gravity. To compute line end (fairlead) motions in the frequency domain, the vessel RAOs and phases in the six degrees of freedom must be translated to the fairlead location. In this example, only the motions in the plane of the line are considered. The line end motions in the horizontal and vertical directions in the plane of the line, and the phases between them are computed for each frequency. The complex RAOs of the line end motions of the most-loaded line, in this example No. 11, are given in Table 10.3.3 for each frequency. The standard RAO value of the fairlead is the square root of the sum of the squares of the real and imaginary parts, in the case of each motion.

Line end motions in time domain can be computed by transforming the wave elevation time series into a horizontal and vertical motion time history at the line end, in the plane of the line, through the use of the fairlead motion RAOs of Table 10.3.3. The line end motions are then used to compute the line tensions in time domain. In general, an analysis of a full three-hour time series is required. An alternative method is to perform the analysis in a segment of fairlead motion time history centering about the maximum tangential motion, which is computed from the three-hour line end motions. In this example, the segment is selected to be 120 seconds long. Detailed procedures in computing the line end motion and tension time histories can be found in API RP 2SK [1]

10.3.4 Dynamic Line Tensions

Extreme line tensions including maximum and minimum tensions and their frequency of occurrence are required to check against the axial tension and axial compression fatigue. In the computation of the extreme line tensions, the storm stiffness as defined in 4.6.4.1 for the polyester rope is used.

10.3.4.1 Frequency Domain Analysis

The frequency domain analysis is provided here using line No. 11 for the maximum line tension and line No. 5 for the minimum line tension.

The most loaded line No. 11 is analyzed for the maximum tension. Initially, a quasi-static analysis is performed under mean plus low-frequency tensions. It is found that wave frequency tensions dominate. Hence, the line tension is analyzed under mean plus significant low-frequency conditions as:

$$\text{Mean Tension} = 790 \text{ kips}$$

$$\text{Mean Tension} + \text{Significant Low Frequency Tension} = 875 \text{ kips}$$

Line No. 11 is then analyzed under a 875 kip tension with the specified end motions as described in Table 10.3.3. The computed mean, significant low frequency and maximum wave frequency tensions for each of the three segments of the line are given in Table 10.3.4.1.

The maximum line tensions for both the chain and polyester segments in this example are acceptable in meeting the design tension criteria.

The mooring analysis for the polyester mooring system should also account for additional design criteria (see Table 10.3.4.1).

- Clearance of polyester rope off seabed.
- Minimum line tension.
- Number of cycles of line tension below recommended minimum allowable tension.

These additional design criteria are addressed by analyzing the leeward line, No. 5. The procedure is similar to the one used for line No. 11 except that the line is analyzed under a different top tension as:

$$\text{Mean Tension} = 291 \text{ kips}$$

$$\text{Mean Tension} - \text{Significant Low Frequency Tension} = 254 \text{ kips}$$

The line is analyzed under a 254 kip top tension with the associated end motions. The minimum line tension for the polyester segment is found to be 114.2 kips, which is 5.2% MBS. Since the minimum line tension is above the 5% MBS for polyester rope, there is no need to check the number of cycles of line tension below recommended minimum allowable tension. Had the minimum line tension been below the 5% MBS threshold, the number of cycles should be checked according to Table 4.6.7.3. It is also found that the entire mooring line is suspended under this condition, and therefore the polyester segment is clear from the seabed

10.3.4.2 Time Domain Analysis

The time domain analysis is provided using line No. 11 for the maximum line tension and line No. 5 for the minimum line tension. The procedure is similar to the frequency domain in that the analysis is carried out by combining the mean plus significant low-frequency tension with the applied line end time history motions. The resulting maximum and minimum tensions of the polyester segments and the maximum ground length are as follows:

Table 10.3.3—Fairlead Motion Complex RAO

Wave Freq. (Rad/Sec)	Wave Period (Sec)	X Real (AMP/AMP)	X Imag (AMP/AMP)	Z Real (AMP/AMP)	Z Imag (AMP/AMP)
0.21	30.00	-0.0112	-1.0645	1.1044	-0.1045
0.27	23.61	-0.0071	-0.9161	1.2624	0.4181
0.32	19.46	-0.0065	-0.8234	0.3821	-0.0699
0.38	16.55	-0.0067	-0.7347	0.4640	-0.2898
0.44	14.40	-0.0071	-0.6373	0.4339	-0.3624
0.49	12.74	-0.0073	-0.5312	0.3683	-0.3977
0.55	11.43	-0.0072	-0.4210	0.2891	-0.3932
0.61	10.36	-0.0065	-0.3129	0.2095	-0.3554
0.66	9.47	-0.0055	-0.2144	0.1390	-0.2910
0.72	8.73	-0.0042	-0.1312	0.0824	-0.2145
0.78	8.09	-0.0028	-0.0648	0.0400	-0.1347
0.83	7.54	-0.0019	-0.0332	0.0210	-0.0771
0.89	7.06	-0.0011	-0.0079	0.0062	-0.0234
0.95	6.64	-0.0016	-0.0175	0.0038	-0.0105
1.00	6.26	-0.0022	-0.0323	0.0033	-0.0038
1.06	5.93	-0.0028	-0.0459	0.0025	0.0016
1.12	5.63	-0.0034	-0.0551	0.0008	0.0022
1.17	5.35	-0.0040	-0.0643	-0.0009	0.0028
1.23	5.11	-0.0045	-0.0735	-0.0027	0.0034
1.29	4.88	-0.0044	-0.0703	-0.0031	0.0033
1.34	4.68	-0.0038	-0.0565	-0.0025	0.0027
1.40	4.49	-0.0031	-0.0427	-0.0019	0.0020
1.46	4.31	-0.0025	-0.0289	-0.0012	0.0013
1.51	4.15	-0.0018	-0.0151	-0.0006	0.0007
1.57	4.00	-0.0012	-0.0013	0.0000	0.0000

Note:

Line No. = 11

Line Heading = 315.00 Degrees

Wave Heading From +X = 135.00 Degrees

Line End Motions with X in Line from Fairlead to Anchor and Z Vertical

Location (X = 114.03' Y = 103.03' Z = 1.61')

No. 11 mooring line—

Maximum Tension of the Polyester Segment = 1,117
kips (51% MBS)

No. 5 mooring line—

Minimum Tension of the Polyester Segment = 65 kips
(3.0% MBS)Maximum Ground Length = 81 feet (i.e., Polyester seg-
ment is clear from the seabed).

Table 10.3.4.1—Maximum Tensions of No. 11 Mooring Line

Tension (kips)	Bottom Chain Segment	Intermediate Polyester Segment	Top Chain Segment
Mean	752	765	790
Significant Low-Frequency	85	85	85
Maximum Wave Frequency	208	205	202
Total	1,045	1,055	1,077
% MBS	56	48	58
Allowable as% MBS	60	60	60

These peak quantities are compared to the allowables as before. The maximum line tension of the polyester segment is acceptable (below 60% MBS limit), and the polyester segment is clear from the seabed; however, the minimum tension is unacceptable (below 5% MBS limit). According to design criteria in 5.3.2, it is necessary to investigate the number of tension cycles below 5% MBS for polyester rope.

10.3.5 Maximum Allowable Low Tension Cycles

A minimum line tension in the synthetic fiber rope should be maintained to prevent lines from possible compressive damage. The minimum line tension should maintain at least 5% MBS. Provisional conditions are applied when the minimum line tension drops below 5% MBS. As defined in Section 4.6.7.3, the maximum allowable number of low tension cycles below 5% MBS for polyester ropes shall not exceed 100,000 cycles. In the extreme design example above, the minimum tension for Line No. 5 is 3.0% MBS according to a time-domain dynamic analysis. It is therefore necessary to investigate the number of low tension cycles below 5% MBS.

The starting point of the investigation is a wave scatter diagram relating storms in terms of significant wave height to their probability of occurrence during the design life. In the usual case, a sufficient number of directions are required to define the environment. The example environmental conditions to be analyzed are given in Table 10.3.6. It is conservatively assumed that an omni-directional environmental condition occurs in the direction of the leeward line all the time as in the present example. The worst direction considered is the 135-degree wave direction for the leeward line No. 5.

Design life of the mooring system is assumed to be 20 years. During the design life, there are a total of 58,400 3-hour events. The number of wave cycles per event is determined as a function of the zero-crossing period of the storm.

Analysis of the leeward mooring line, Line No. 5, based on a time domain method shows that when the significant wave height equals 34.0 ft (9.1 m), the minimum line tension is 3.2% MBS. When the significant wave height is reduced to 30.0 ft (9.1 m), the minimum tension increases to 8.0% MBS. By linear interpolation, the significant wave height associated the recommended minimum line tension of 5% MBS is 32.5 ft (9.91 m). Thus for events with the significant wave height of 32.5 ft (9.91 m) or higher, each event has the potential to result in a minimum line tension below 5% recommended tension. Calculation of the number of cycles is given in Table 10.3.5.

It is conservative to calculate the total number of low-tension cycles by including the number of cycles associated significant wave height of 30.0 ft (9.1 m) and above. Over the design life of the mooring system, the number of low-tension cycles is 5,818. This is within the design limit of 100,000 cycles.

Table 10.3.5—Calculation of Number of Cycles

Sig Wave Height ft(m)	Zero-Cross Periods	Probability Occurrence Percent	Number of Wave Cycles	Number of Cycles with Line Tensionless than 5% MBS
2.3(0.7)	3.2	62.005	121,791,033	0
6.0(1.8)	4.0	31.990	50,493,108	0
9.9(3.0)	4.6	4.913	6,681,448	0
13.8(4.2)	5.4	0.868	1,023,435	0
17.8(5.4)	6.2	0.163	166,010	0
21.8(6.6)	7.1	0.042	37,212	0
26.0(7.9)	8.4	0.009	6,548	0
30.0(9.1)	9.1	0.005	3,178	3,178
34.0(10.4)	9.7	0.003	1,751	1,751
37.9(11.6)	10.4	0.001	606	606
42.6(13.0)	11.1	0.001	283	283
Total				5,818

Table 10.4.1—Environmental Condition, Mean Loads and Low-frequency Motions for the Analyzed Direction

Sig. Wave feet(m)	Peak Period sec	Probability percent	Mean Loads kips	Low Freq. RMS feet(m)
2.3(0.7)	4.5	62.005	37.3	0.0(0.0)
6.0(1.8)	5.6	31.990	73.1	0.1(0.03)
9.9(3.0)	6.5	4.913	129.4	0.2(0.06)
13.8(4.2)	7.5	0.868	181.0	0.3(0.09)
17.8(5.4)	8.7	0.163	230.5	0.3(0.09)
21.8(6.6)	10.0	0.042	322.6	0.4(0.12)
26.0(7.9)	11.2	0.009	476.7	0.9(0.27)
30.0(9.1)	12.2	0.005	629.5	1.7(0.52)
34.0(10.4)	13.0	0.003	785.8	2.4(0.73)
37.9(11.6)	13.9	0.001	975.5	2.9(0.88)
42.6(13.0)	14.9	00.001	1116.3	3.3(1.01)

10.3.6 Effect of Rope Stiffness

In the above example, the post installation stiffness and the storm stiffness of the polyester segment are taken as ten and thirty times the breaking strength of a typical 2,200 kip polyester rope, respectively. They represent the minimum and maximum stiffness values of the example rope. Minimum and maximum stiffness values of other polyester ropes with different construction but same breaking strength might be different from the one used. Figure 10.3.6 shows the effect of stiffness (in terms of multiple of MBS) on offset (in terms of percent water depth) and top line tension (in terms of safety factor) of the example mooring system in the stiffness range between the minimum stiffness and maximum stiffness of the example polyester rope. The effect of stiffness variation on the minimum line tension is expected to show a similar trend.

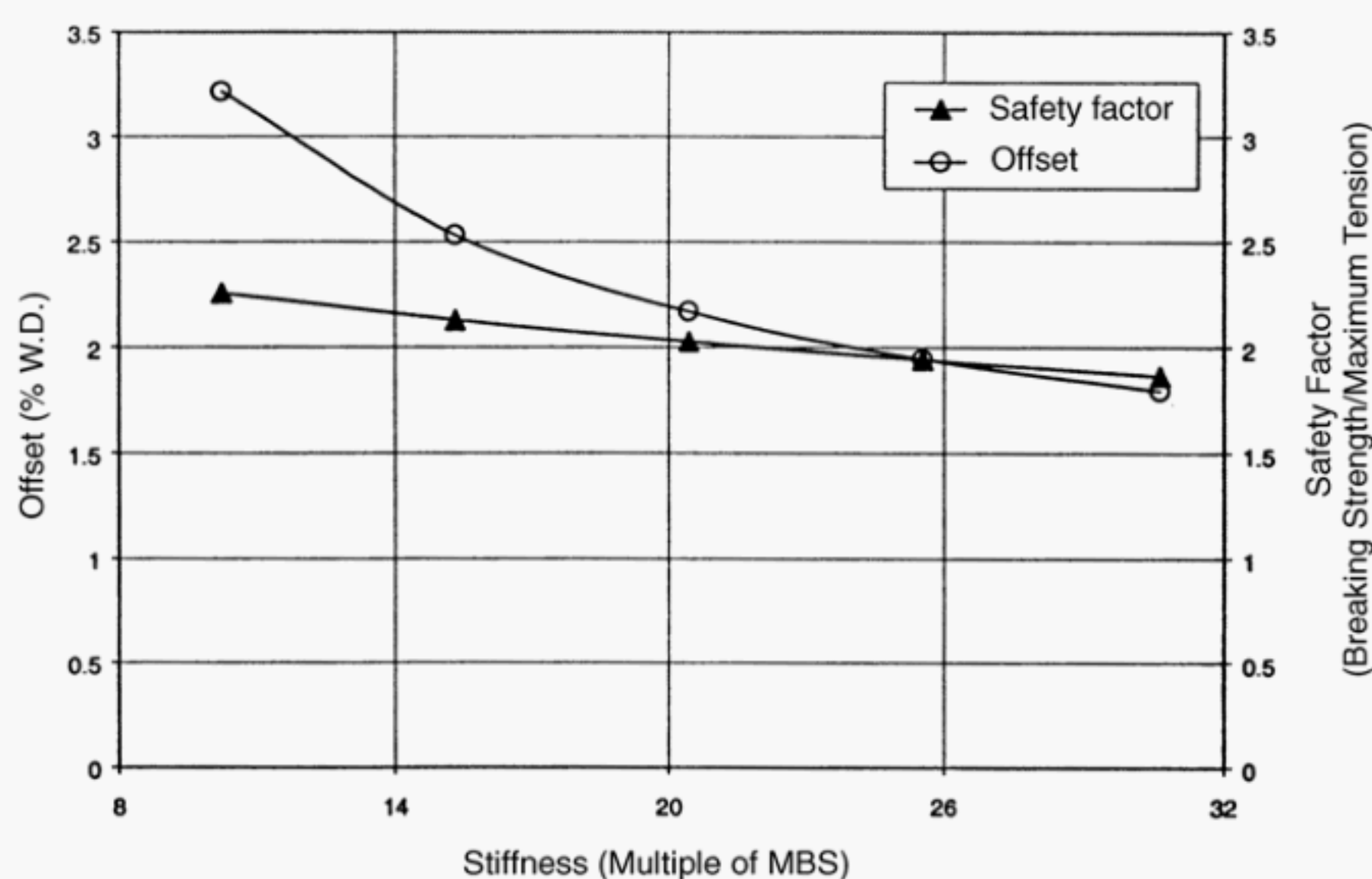


Figure 10.3.6—Effect of Rope Stiffness

10.3.7 Effect of Draft Variation on Pretensions

The mooring system is designed to maintain a sufficient level of pretension in order to provide adequate restoring force to keep the floating structure in position under the storm conditions. The pretension of anchoring leg varies with draft of the floating structure. For ship shape vessel, large variations of draft from ballast to fully loaded condition may cause significant reduction in pretension, especially for taut moorings. Consequently the rope tension may fall to low value and less than 5% MBS under storm conditions. In the design analysis process, it is recommended that all drafts from fully loaded to minimum loaded conditions be considered.

10.4 FATIGUE ANALYSIS EXAMPLE

The following example illustrates the computation of life-time fatigue damage on a mooring line and the estimation of allowable fatigue life. The fatigue computation is performed in accordance with API RP 2SK [1].

The semi-submersible system with a 12-point mooring in the extreme response analysis is considered. Fatigue analysis is provided here for the polyester rope at the top chain/rope intersection.

10.4.1 The Environment

The environment is defined as a set of the following:

- Directions.
- Wind speeds.
- Current speeds.

d. Wave heights, spectral shapes, spectral peak periods or equivalent.

e. Probability of occurrence of the above. The mean forces and the low-frequency and wave frequency motions and tensions associated with each environmental condition can be derived from computer programs, model tests, or design curves in accordance with the general procedures as described in [1], which are also demonstrated in Section 10.3.

In the usual case, a sufficient number of directions are required to define the environment. It is conservatively assumed that omni-directional environmental conditions occur all the time in the direction of the most-loaded line. The most loaded line, as determined in the extreme design analysis, is line No. 11 in the wave direction of 135 degrees. The omni-directional sea-states, cumulative probabilities of occurrence, and mean loads are given in Table 10.4.1. In addition, the following parameters are used:

- Water depth = 3,000 ft (914 m).
- Collinear wind, wave and current.
- Environment is in the analyzed direction 100 percent of the time.

10.4.2 Fatigue Analysis and Damage

The simple summation method for the computation of fatigue damage [1] is used. In this approach, low frequency and wave frequency fatigue damages are calculated independently. The total damage is assumed to be the sum of the two.

The damages are estimated using the RMS values of the low frequency and wave frequency tensions, the polyester rope fatigue characteristics, and the number of wave frequency and low-frequency tension cycles per year.

Although fatigue characteristics of large polyester ropes are not well established, available data and experience indicate that typical polyester ropes have tension/tension fatigue characteristics at least as good as comparable wire ropes in salt water. Further discussions on this subject can be found in 4.6.7.2. For the current design example, the tension/tension fatigue characteristics equivalent to that of the six-strand rope [1] is chosen in the fatigue analysis.

The frequency domain method of dynamic analysis introduced in 10.3 is used. Suitable values of polyester rope stiffness shall be chosen to account for the wave and low frequency tensions. Assuming that fatigue damage is largely dominated by wave, the storm stiffness is used to provide a conservative approach.

A detailed computation of the fatigue damage per year associated with a 135-degree direction (wave heading towards), for line No. 11 is given in Table 10.4.2 for the polyester rope segment. The total annual accumulated fatigue damages is:

$$D = 6.205 \times 10^{-6}$$

The useful fatigue life is computed as:

$$\text{Life} = 1/(10D) \text{ years.}$$

$$= 16,115 \text{ years}$$

The safety factor applied is 10, based on the design criteria given in 5.3.3.

Table 10.4.2—Polyester Rope Segment Fatigue Damage

Sig. Wave Height ft(m)	Mean Tension kips	RMS Tension (Wave) kips	RMS Tension (Low) kips	Number of Cycles (Wave)	Number of Cycles (Low)	Zero Cross\ Period (wave)	Zero Cross Period Wave	Wave Frequency Damage	Low Frequency Damage
2.3(0.7)	484.1	0.3	0.2	3,929,175	253,003	4.98	77.34	3.87E-10	4.75E-12
6.0(1.8)	492.0	0.8	1.3	1,952,665	130,531	5.17	77.34	1.06E-08	5.17E-09
9.9(3.0)	504.5	1.4	2.7	267,776	20,042	5.79	77.36	1.44E-08	1.58E-08
13.8(4.2)	515.4	2.7	3.4	37,066	3,540	7.39	77.37	2.92E-08	7.16E-09
17.8(5.4)	526.1	5.5	3.0	5,525	665	9.31	77.38	7.99E-08	8.05E-10
21.8(6.6)	544.8	10.7	4.1	1,203	171	11.02	77.43	2.64E-07	7.44E-10
26.0(7.9)	578.5	18.1	10.8	229	35	11.97	77.54	4.33E-07	8.09E-09
30.0(9.1)	615.6	27.2	20.0	113	19	12.86	77.65	1.13E-06	5.31E-08
34.0(10.4)	655.3	36.2	28.4	63	11	13.53	77.78	2.02E-06	1.30E-07
37.9(11.6)	705.4	46.0	35.1	22	4	14.33	78.05	1.89E-06	1.15E-07
42.6(13.0)	743.3	59.6	39.8	10	2	15.21	78.31	2.56E-06	9.54E-08

APPENDIX A—TESTING OF ROPE WET STRENGTH

A.1 Test Specimen

Five specimens should be tested.

The specimens should be terminated in the same manner as that which will be used on the rope assembly, including the thimble design as described in 6.2.7.3. The specimen length should be at least 40 times nominal rope diameter between rope ends of terminations.

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.

The entire specimen including terminations should be soaked in fresh water for 22 and 26 hours before testing. The specimen should 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 is to be soaked again 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 should be maintained between 15° and 25° C (59° and 77° F).

A.2 Test Machine

The test machine should have sufficient bed length, stroke, rate of loading, and force producing capacity to carry out the test as described in one pull without pause. The test machine should be equipped with a force measuring and indicating/recording device which is accurate to within $\pm 1\%$ of the estimated breaking force for the rope specimen. The force measuring and indication/recording device should be calibrated by a recognized independent calibration agency, using a reference load cell traceable to applicable national standards. This calibration should have been done within the previous year. An original calibration certificate should be available for examination, and a copy of this certificate should be attached to the test report.

A.3 Test Procedure

The specimen should be tested for wet break strength in accordance with “Determination of Cycled Strength” from the latest edition of CI 1500 “Standard Test Methods for Fiber Rope” [23] as follows:

1. Cycle the rope ten times from 1% of estimated MBS (initial tension) to 50% of estimated MBS at the rate described below.
2. On the eleventh cycle, apply force to the rope at the rate described below until it breaks.
3. Record the breaking force (maximum force applied to the rope). Record the point 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. The rate of travel of the pulling head during the break test should be such that the rope is loaded to 20% of its estimated MBS in not less than 2 sec. nor more than 30 sec. The crosshead should then continue moving without pause at approximately that rate of travel until the rope breaks.

A.4 Data Reporting

The breaking tension and the location and nature of break should be reported for each specimen. The average wet break strength and the standard deviation of wet break strength are to be calculated, using the data from all five tests, and reported. Standard deviation should be computed by the $n-1$ formula. The minimum wet break strength, defined as the average wet break strength minus two times the standard deviation of wet break strength, should be calculated and reported.

APPENDIX B—TESTING OF ROPE ELONGATION AND MODULUS

B.0 General

The mooring system designer and the rope manufacturer should specify and execute a rope test program which provides adequate information on and gives adequate assurances of rope performance characteristics.

B.1 Testing of Rope Wet Extension and Creep Properties

The extension data are intended to be used in mooring line pretension calculations and platform offset calculations. The shapes of the load-extension curves at 6 min., 60 min., 600 min. and 6000 min. may be extrapolated on a semi-log basis (elongation point on normal scale vs. time on log scale) to longer times.

The creep data is intended to be used in mooring line creep take-up calculations. The percent creep at 6 min., 60 min., 600 min. and 6000 min. may be extrapolated on a semi-log basis (creep on normal scale vs. time on log scale) to longer times.

B.1.1 TEST SPECIMEN

One specimen should be tested.

It is not necessary that the terminations used in this test be the same as those which will be used on the rope in service; however, the terminations should be of sufficient strength to safely withstand at least 70% of the MBS.

The length of the specimen should be sufficient to accommodate a gage length determined as follows:

The gage length over which elongation is measured should be sufficient to achieve $\pm 10\%$ accuracy for the expected extension [17, Attachment 6/B]. This criterion should be judged by the accuracy to which the extension measuring system can measure the difference between rope length (over gage length) at trough load and at peak load for the intended cyclic load range.

The gage marks should be no closer than 5 times rope diameter from the rope ends of termination. Thus the specimen length should be sufficient to accommodate the gage length, as determined above, plus at least 10 times nominal rope diameter between rope ends of terminations.

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

The specimen should be conditioned in water as described in A.1.

B.1.2 TEST MACHINE AND APPARATUS

The test machine should be as described in A.2.

In addition, the test machine should be equipped with an elongation measuring device and data collection system capable of measuring and recording the elongation over the gage length determined above. The data collection system should be capable of recording sufficient data points during a load cycle to accurately determine the secant tangent between tensions separated by no more than 5% of the breaking strength of the specimen.

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

$$WR = 0.0004 \times WL \times D^2$$

where

WR = rate of water application, liter/min,

WL = length of rope over which water is applied, meters,

D = rope diameter, mm.

The water temperature should be maintained at between 5° and 10°C (41° and 50°F).

B.1.3 TEST PROCEDURE

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

1. Tension the rope to 1% of MBS (initial tension). Measure and record the original initial length between gage marks.

2. Tension the rope to 30% of MBS while recording elongation vs. tension. This tensioning should be done at the rate of crosshead travel established in A.3 (Appendix A).

3. Hold tension at 30% of MBS for 30 minutes.

4. Reduce tension to 25% of MBS. Maintain this tension for 6 minutes and then record the elongation of the rope at this tension.

5. Lower rope tension to 1% of MBS. Measure and record immediate initial length between gage marks. With minimal delay, retention it to 30% of MBS while recording elongation vs. tension. This lowering and retensioning should be done at the rate of crosshead travel used in Step 2. Then lower tension to 25% of MBS and maintain this tension.

6. Maintain the rope at 25% of MBS tension for a total of 1 hour (54 additional minutes), adjusting tension as necessary to maintain it at $25\% \pm 2\%$ of MBS. At the end of 1 hour record elongation at 25% of MBS.

7. Repeat Step 5.

8. Maintain the rope at 25% of MBS tension for a total of 10 hours (9 additional hours), adjusting tension as necessary to maintain it at $25\% \pm 2\%$ of MBS. At the end of 10 hours record elongation at 25% of MBS.

9. Repeat Step 5.

10. Maintain the rope at 25% of MBS tension for a total of 100 hours (90 additional hours), adjusting tension as necessary to maintain it at $25\% \pm 2\%$ of MBS. At the end of 100 hours record elongation at 25% of MBS.

11. Repeat Step 5, then lower tension to zero to complete the test.

B.1.4 DATA REPORTING

Tabulate the elongation at 5% of MBS load increments from 5% to 30% of MBS for the first tensioning and for the retensionings after 0.1 hr (6 min.), 1, 10 and 100 hours by the following formula:

$$Elg = L_L - L_i$$

where

L_L = Length of gaged portion of rope at designated load,

L_i = Immediate initial length of gaged portion of rope at initial tension before application of designated tension (Step 5).

For each elongation, calculate the percent extension by the following equation:

$$Ext = 100\% \times (Elg)/L_i$$

where

Ext = Extension

Determine the extension at 25% of MBS tension after relaxing from the 30% of MBS tension and waiting for 6 minutes (Step 4). Report this value as the lower postinstallation stiffness.

Plot extension vs. tension on the 1st tensioning and the retensionings after 0.1 hr (6 min.), 1, 10 and 100 hours. Report the load-extension plots.

Calculate the rope creep at 25% of MBS (as recorded before relaxing rope) after 0.1 hr (6 min.), 1, 10 and 100 hours as percent of initial length by the following formula:

$$C = 100\% \times (L_L - L_O)/L_O$$

where

L_O = Original initial length of gaged portion of rope at initial tension before application of any higher tension (Step 1).

Plot the rope creep after 0.1 hr (6 min.), 1, 10 and 100 hours on semi-log graph paper 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 later 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).

Report the creep vs. log time plot and the percent creep per log cycle.

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.

B.2 Testing of Rope Wet Modulus Properties

B.2.1 TEST SPECIMEN

One specimen should be tested.

The specimen should be terminated as described in B.1.1.

The length of the specimen should be sufficient to accommodate a gage length determined as described in B.1.1.

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

The specimen should be conditioned in water as described in A.1.

B.2.2 TEST MACHINE AND APPARATUS

The test machine should be as described in A.2 and B.1.2.

The entire rope section including terminations is preferably to be immersed in fresh water during the test. Alternatively, the entire length of rope between ends of terminations can be sprayed with fresh water at the rate described in B.1.2.

The water temperature should be maintained between 5°C and 10°C (41° and 50°F).

B.2.3 TEST PROCEDURE

The specimen should be tested for wet dynamic elongation and extension properties in accordance with Section 12 "Determination of Cycled Elongation and Extension" of CI 1500-97 "Standard Test Methods for Fiber Rope" [23], modified as follows:

1. Tension the rope to 1% of MBS (initial tension). Measure and record the original initial length between gage marks.

2. Tension the rope to 55% of MBS while recording elongation vs. tension. This tensioning should be done at the rate of crosshead travel established in A.3 (Appendix A).

3. Hold tension at 55% of MBS for 30 minutes. Then reduce tension to 25% of MBS.

4. Maintain tension on the rope at 25% of MBS for 6 minutes and then record the elongation at this tension.

5. Lower rope tension to 1% of MBS. Measure and record the immediate initial length. With minimal delay, retension it to 55% of MBS while recording elongation vs. tension. This lowering and retensioning should be done at the rate of crosshead travel used in Step 2. Then lower tension to 25% of MBS.

6. Cycle the rope about 25% of MBS mean tension with a tension amplitude of 5% of MBS at a rate of 5 ± 1 cycles per minute (0.083 Hz). Record the rope elongation on the 1st, 10th, 100th, and 1000th cycle while maintaining the same cycling rate.

7. After the 10th and 100th cycle, repeat Step 5. After the 1000th cycle, proceed as follows.

8. Lower rope tension to 1% of MBS. Measure and record the immediate initial length. With minimal delay, retension it to 55% of MBS while recording elongation vs. tension. This lowering and retensioning should be done at the rate of crosshead travel used in Step 2. Then lower tension to 40% of MBS.

9. Cycle the rope about 40% of MBS mean tension with a tension amplitude of 15% of MBS at a period of not less than 1 cycle per minute. Record the rope elongation on the 1,010th, 1100th and the 2000th cycle while maintaining the same cycling rate.

10. After the 1,010th and 1,100th cycle, repeat Step 8.

11. After the 2000th cycle, lower rope tension to 1% of MBS. Measure and record the immediate initial length. With minimal delay, retension it to 55% of MBS while recording elongation vs. tension. This lowering and retensioning should be done at the rate of crosshead travel used in Step 2. Then reduce tension to zero to complete the test.

These cycles should be applied without significant pauses or interruptions.

B.2.4 DATA REPORTING

Calculate extension, as described in B.1.4.

Determine the extension at 25% of MBS tension after relaxing from the 55% of MBS tension and waiting for 6 minutes (Step 4).

Plot and report installation extension vs. tension on the 1st cycle. Report this value as the higher post installation stiffness.

Plot and report dynamic extension vs. tension on the 1st, 10th, 100th, and 1000th cycle.

Plot and report dynamic extension vs. tension on the 1010th, 1100th, and 2000th cycle.

On a semi-log graph, plot the extensions at 5% of MBS (on normal scale ordinate) against number of cycles (on log scale abscissa). Repeat for extensions at 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, and 55% of MBS.

For the purpose of calculating modulus, the stress in the rope is calculated by dividing tension by the rope fiber area. Calculate the rope fiber area by the following formula:

$$rfA = 1,000 \times Wf/Df$$

where

rfA = rope fiber area, mm,

Wf = mass of fiber per unit length of rope, kg/m,

Df = mass density of fiber material, g/cc.

For the purpose of calculating modulus, the strain in the rope is calculated by dividing elongation (change in length) by gage length. Strain can also be determined by dividing extension by 100%.

For the purpose of calculating dynamic modulus, use the secant slope (slope of the line joining the trough (lower) and peak (upper) cyclic loads. Secant modulus is determined instead of tangent modulus because it can be determined more uniformly and accurately.

Calculate the secant modulus between the extensions at 20% of MBS tension and 30% of MBS tension on the 1000th cycle. Report this as the intermediate modulus.

Calculate the secant modulus between the extensions at 25% of MBS tension and 55% of MBS tension on the 2000th cycle. Report this as the storm modulus.

The dynamic moduli are intended to be used in dynamic mooring analysis. The dynamic moduli at 10th, 100th, and 1000th cycle can be extrapolated on a semi-log basis (modulus on normal scale vs. cycles on log scale) to more cycles.

APPENDIX C—TESTING OF ROPE TENSION-TENSION FATIGUE QUALIFICATION

This test is intended to demonstrate that the synthetic rope has a fatigue equivalence represented by one of the design curves listed in 4.6.7.2, and the design equation can subsequently be applied in the fatigue design of the rope. As specified in 6.3.6, the following testing parameters should be utilized for this purpose:

Design Curve	Minimum Number of Cycles	Mean Tension (% MBS)	Tension Amplitude (%MBS)
Polyester Rope	380,000	30	15
Spiral Strand Equivalent	80,000	30	15
Six/Multiple Strand Equivalent	30,000	30	15

C.1 Test Specimen

One specimen should be tested.

The specimen should be terminated in the same manner as intended for production ropes. The specimen length should be a minimum of 50 times nominal rope diameter between rope ends of terminations.

The specimen should be conditioned in water as described in A.1.

C.2 Test Machine and Apparatus

The rope should 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.

The entire rope section including terminations is preferably to be immersed in fresh water during the test. Alternatively, the entire length of rope between ends of terminations can be sprayed with fresh water at the rate described in B.1.2.

The water temperature should be maintained at between 5° and 10°C (41° and 50°F).

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

C.3 Test Procedure

The cyclic load test should be conducted as follows:

1. Cycle the rope about a mean tension of 30% of MBS with a tension amplitude of 15% of MBS 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 while the water bath continues until its surface temperature falls to within 10°C of the temperature of the water bath.
3. Continue cycling for at least 30,000 cycles to qualify for the six/multi-strand-rope design curve; or at least 80,000 cycles to qualify for the spiral-strand-rope design curve; or at least 380,000 cycles to qualify for the polyester rope design curve.

C.4 Rope Post Test Examination

After cycling, examine the entire length of the rope including termination in detail for any pending failure. A break test may also be conducted to determine the residual strength of the rope.

C.5 Data Reporting

Record the number of applied cycles and signs of deterioration, if any.

Synthetic ropes which pass the 30,000-cycle test may apply the six/multi-strand-rope design curve equation as described in API RP 2SK [1].

Synthetic ropes which pass the 80,000-cycle test may apply the spiral-strand-rope design curve equation as described in API RP 2SK [1].

Synthetic ropes which pass the 380,000-cycle test may

APPENDIX D—TESTING OF ROPE AXIAL COMPRESSION PERFORMANCE

07 | This test only applies to aramid rope fiber ropes. This test for axial compression performance should be carried out if the low tension design criteria in 5.3.2 are to be deviated from.

D.1 Test Specimen

One specimen should be tested.

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

The specimen should be conditioned in water as described in A.1.

D.2 Test Machine and Apparatus

The rope should 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.

The entire rope section including terminations is preferably to be immersed in fresh water during the test. Alternatively, the entire length of rope between ends of terminations can be sprayed with fresh water at the rate described in B.1.2.

The water temperature should be maintained at between 5° and 10°C (41° and 50°F).

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

D.3 Test Procedure

The cyclic load test should be conducted as follows:

1. Cycle the rope from a trough tension of 1% of MBS to a peak tension of 25% of MBS 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 while the water bath continues until its surface temperature falls to within 10°C of the temperature of the water bath.

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

4. Tension the rope to break, using the test procedure of A.3, to determine residual strength.

D.4 Data Reporting

Report the residual strength, both in absolute terms and as a percent of new MBS.

Report the number of applied cycles.

If there is no reduction in MBS, then the rope may be classed to endure the demonstrated axial compression fatigue cycles.

APPENDIX E—COMMENTARY ON MARINE FINISH

E.1 Commentary to 4.2.3.1

Addressing the characteristics, use and specification of marine finishes for deepwater moorings is complicated by a number of factors:

- 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.

As an alternative to the testing called out in 4.2.3, prototype rope certification fatigue testing may be done without the marine finish (but with the normal spin finish) applied to the fibers. Performing fatigue tests without the marine finish does not lessen the importance of the marine finish, but avoids short-term fatigue results being skewed by a marine finish which may not be effective for the entire field deployment duration; however, results of such testing may or may not be conservative because of the compounding effect of marine finish on the relative breaking strength (and thus reference test loads) of the ropes.

E.2 Commentary to 4.2.3.2

Demonstrating the long-term durability and effectiveness of marine finishes can be a complex undertaking. The methods used to measure effectiveness may be quite different than those methods used to measure durability. In addition, the most appropriate measures for durability may be material dependent, so that a method that works well for one finish type is not effective for a second finish type. Methods of accelerated testing can also skew finish comparisons by triggering chemical mechanisms in one finish technology not present in others.

The simplest measure of finish effectiveness is whether it enhances the yarn-on-yarn abrasion resistance of the yarn. This metric can be monitored after long-term seawater expo-

sure to indirectly observe physical or chemical changes in the finish or the yarn-finish interface caused by the seawater environment. This is a performance-based test that is much less open to interpretation as compared to chemical measurements.

Another simple measure of finish effectiveness is whether it stays on the yarn over time (durability). Solvent extraction methods can be used after seawater exposure if the assumption is made that the solvent(s) used in the extraction process remove all the marine finish components from the fiber or rope sample. In this case comparing the weight of the control and extracted samples gives the amount of marine finish remaining on the yarn. More complex chemical techniques such as FTIR, GC-MS or X-ray spectroscopy will provide more accurate measures of finish level but require elaborate analytical facilities and higher testing budgets. Many of these methods also presume a prior knowledge of the chemistry of the finish being analyzed.

Several pitfalls should be avoided with strictly chemical analyses.

Note: Solvents can be finish-specific, i.e., solvents that are effective removing one type of finish or finish component may be poor at removing other types or components. The fibers themselves may react with certain solvents and release polymeric compounds that will be misinterpreted as finish components.

Also, some finishes may contain components that are sacrificial or act as carriers for more active components. In such cases the abrasion resistance of the fibers will remain high even as the total amount of extractable material is observed to decrease over time.

The chemistry of marine finish dissolution or removal by seawater will not be linear in time. Like most chemical processes, reaction rate is determined by activation energy and will proceed logarithmically. For this reason, long-term (>20 year) marine finish stability will most likely be determined by the reaction in the first 5% of the design life (one year). Testing beyond this timeline is unlikely to produce any further reaction in the material.

Accelerated testing methods need further development for use in finish analysis. Simply using warm seawater may produce changes in the seawater, the finish, or the finish/fiber interface that could skew test results. Other methods for accelerating finish removal such as ultrasonics or thermochemical should be viewed with caution until their effectiveness as compared with more traditional methods is established.

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APPENDIX G—STRATEGY FOR MINIMIZING FIBER ROPE DAMAGE DURING INSTALLATION

07

G.0 General

Installation of fiber rope begins with staging. While stored prior to deployment, load-bearing cores of fiber ropes should be protected from dust, UV rays, and moisture if possible. This protection can be accomplished by storing fiber ropes on reels within an enclosed structure or providing adequate tarps or covers to protect the ropes.

During any handling of fiber ropes, efforts should be taken to limit the amount of oil and grease exposure.

G.1 Installation Using Anchor Handling Vessel

G.1.1 INSTALLATION VESSEL

Installation vessels must also be prepared or inspected prior to loading and deployment of fiber ropes. There are several key areas on conventional installation vessels that should be prepared. The stern roller should be inspected for any sharp areas or potential areas where the fiber rope or jacket could get snagged or cut. The stern roller should also be checked to see that it is operating properly and rolls under minimal load. The vessel work deck should be cleaned and inspected for any sharp objects or snag points. (One particular item to watch for is old sea fastenings, which may not have been fully removed from the deck.) All winch or deployment drums should be inspected for sharp objects or snag points, including storage reels if they are to be used during any step of the installation. The level winds should be inspected to see that they are working properly and have no sharp surfaces.

G.1.2 LOADING FIBER ONTO VESSEL DRUMS

Once the vessel has been inspected and prepared, the fiber rope can be loaded. Proper guides should be utilized to load the fiber rope from the shipping or storage reels onto the vessel drums. If any fiber rope transfers will take place offshore, properly designed rollers should be utilized to maintain minimum bend radii specified by the rope manufacturer and API RP 2SM. During loading, the installer should conduct a visual inspection of the rope to ensure that the rope is in good condition. (Inspect any jacket or terminations for visible damage.) All termination and connecting hardware should be inspected for sharp corners or snag points during loading.

Any terminations or sections of the fiber rope which have polyurethane coatings should be visually inspected to ensure that the coatings are intact and fit for purpose. A visual inspection should be conducted to check for any visible sign of splice damage.

During loading onto the vessel drums, it is important to load the fiber rope with sufficient back tension and as densely

as possible to protect against the rope “cutting in” on itself during deployment.

G.1.3 ROPE STOPPING TECHNIQUE

With an installation plan in place, check any fiber rope stopping devices or methods for suitability and proper operation. Also check any interfaces these devices or methods have with connecting hardware. The objective is to ensure the safety of personnel while using proven stoppering techniques that do not damage the fiber rope.

G.1.4 ROPE DEPLOYMENT

For most fiber rope installation, the load the fiber rope will see during the deployment should not exceed 10% of the design minimum break load (MBL) of the rope; this is especially true for new rope. If installation requires loading beyond 10% of the rope’s MBL, a higher density and back tension should be used when loading the rope on the installation drums. To reduce the installation loading, use of subsea mooring connectors may be needed to limit the load on the fiber rope during deployment. During deployment, the rope should be monitored at the stern roller to check if the stern roller is operating properly and causing no damage to the rope.

G.1.5 CONTACT WITH SEAFLOOR

Provided that adequate documentation exists for the performance of the filter barrier, fiber ropes may be laid on the seabed prior to hookup to the vessel. The area should be surveyed for rock outcroppings and other geohazards that may make this option ill-advised.

Upon each recovery of a fiber rope laid on the seabed, the rope should be visually inspected for any signs of jacket damage and filter barrier damage. If the jacket has been damaged, the rope should be further inspected to see if the filter barrier is intact. If the filter barrier is not intact, then the rope should be removed from service and inspected in closer detail to determine if soil or other particles have moved into the load bearing fiber cores. If the load bearing fiber cores have not been affected by soil or other particle ingress, then the rope filter barrier and jacket may be repaired and returned to service. If the rope has experienced ingress of particles at the damaged location, additional sections of rope at least 5 diameters on each side of the damaged location shall be inspected. If this inspection reveals no particle ingress beyond this area, then that length shall be removed. If inspection reveals particle ingress on one or both ends of the rope, additional inspection will be performed, at 5 diameter intervals away from the end where particle ingress is found, until no particle ingress is

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found. This inspection will determine the affected area that must be removed and then the rope may be re-terminated for further use.

For hard seabed conditions that may result in damage or abrasion of the jacket, fiber ropes should not be allowed to contact the seabed.

G.1.6 CONNECTING THE PRESET MOORING

For preset fiber rope connection operations, rope tensions should be actively managed to minimize high stress being placed on any ropes over tight bending radii.

Extra attention should be paid to ropes near boat rudders or other low hanging parts of the installation vessel. (This can be accomplished through calculations and knowledge of the vessel architecture below the waterline.)

G.2 Installation Using Deepwater Construction Vessel

While Anchor Handling Vessels (AHVs) account for a large number of fiber rope deployments, Deepwater Construction Vessels (DCVs) are sometimes utilized to install larger diameter fiber ropes for permanent facilities. Use of DCV requires many of the measures recommended for AHVs to protect against fiber rope damage.

G.2.1 CONTACT WITH PROBLEM AREAS

The same precautions taken for AHVs should also be taken for DCVs. These include inspection and removal or mitigation of any sharp or snag points that may damage the fiber rope during any stage of installation. Extra precautions should be taken to reduce the chance of fiber rope damage in welding areas or during other activities that can cause fiber rope damage. Protective layers or barriers could be utilized to keep the fiber rope from coming into direct contact with problem areas. As with AHV deployment, the use of fiber work ropes should also be considered for handling of the fiber rope on the DCV where there can be direct work rope to fiber mooring rope contact.

G.2.2 DEPLOYMENT WITH LARGE WINCH

The major difference is the size of a DCV deployment winch, which commonly holds a much larger quantity of fiber rope compared to an AHV winch. This means that the length can be greater than that utilized for an AHV deployment. Care should be taken to select a suitable fiber rope length such that use of the planned installation vessel is most efficient, but also allows for safe transportation and spooling of the fiber rope to the deployment winch. Since at least some of the fiber rope reels will have to be spooled onto the deployment winch offshore, special consideration should be taken in the transportation reel. The transportation reels may have to meet certain dimensional requirements to interface with the

DCV's on-board spooling units and conform to particular deck arrangements. Sea-fastening considerations for the transportation reels should also consider the use of bolt-style clips to reduce the requirement and risk of welded sea-fastenings in close proximity to the fiber rope.

As with AHV installation, fiber rope packing on the DCV winch is another important consideration.

G.3 Additional Considerations

G.3.1 ROPE STIFFNESS AND LENGTH

Fiber rope stiffness and elongation during the deployment process must also be considered. It is important to get accurate elongation and stiffness data from the rope manufacturer in order to properly plan the installation operation.

The shipping reels should be clearly and correctly labeled to allow for easy identification of rope segments and lengths to reduce the chance of improper installation.

G.3.2 ROPE TWIST

Fiber ropes utilized in permanent moorings may have twist monitoring stripes. These stripes should be visible on the deployed section of the fiber rope and should be monitored during spooling operations to ensure acceptable twist is maintained.

G.3.3 TERMINATION HARDWARE AND COATING

It is common to coat the splice region of the rope with polyurethane to protect it from handling/installation damage. These coatings should be adequately applied and inspected such that connection activities between fiber rope segments can be executed with minimal risk of damage. Care must be taken when applying the coating to make sure the build up does not hinder installing the spool. Using a mold may be desirable so that the polyurethane is consistent and fits properly in the spool.

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