Final Report

CHARACTERIZING POLYESTER ROPE MOORING INSTALLATION DAMAGE

Prepared For
MINERALS MANAGEMENT SERVICE
Herndon, VA

And For
THE OFFSHORE TECHNOLOGY
RESEARCH CENTER
College Station Texas

November 2001

Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041

A final Report

CHARACTERIZING POLYESTER ROPE MOORING INSTALLATION DAMAGE

PN 7141-RRA

Prepared For
THE MINERALS MANAGEMENT SERVICE
Herndon, VA

And For
THE OFFSHORE TECHNOLOGY RESEARCH CENTER
College Station, Texas

Ray R. Ayers

By:
Ray R. Ayers, Ph.D., P.E.

Reviewed By:

Matthew J. Stahl, D. Eng., P.E.

November 2001

Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041

TABLE OF CONTENTS

Page No.

TABLE OF CONTENTS

Page No.

APPENDICIES

APPENDIX A:	Reference List From: Fatigue Model Of Aramid And Polyester Lines
APPENDIX B:	Reference List From: Light Weight Material For Deep Water Moorings
APPENDIX C:	Trip Report From Technical Visits
APPENDIX D:	Detailed Questions Asked And Answers Given Following Technical Visit to Petrobras: Follow-Up Questions and Their Responses

INTRODUCTION

Mooring systems utilizing polyester rope are now being installed for MODUs and are being actively considered by operators for deepwater floating production systems in the Gulf of Mexico. The Minerals Management Service (MMS) has initiated a program with the Offshore Technology Research Center (OTRC) to assess the significance of damage to the polyester mooring lines during installation and appropriate mitigation measures. The MMS/OTRC program includes the following five studies:

1. Characterize rope damage
2. Develop a model to predict the impact of damage on rope performance.
3. Conduct small-scale tests to provide data to calibrate the rope model.
4. Conduct large-scale experiments on damaged rope to validate the rope model.
5. Develop guidelines for dealing with installation damage.

On behalf of the MMS, the OTRC has requested that Stress Engineering Services (SES) perform the first study cited above, namely to characterize polyester rope installation damage. The OTRC requested that the study be based on discussions with operators, contractors, and manufacturers who have interests and experience in this area, as well as available literature. The study focuses on mechanical damage due to handling, installation equipment, and procedures that have the potential to impair long-term rope performance.

Such mechanical damage is assumed to be surface damage and could include cuts, nicks, abrasion, chafing, distortion, etc. The study includes how the damage was observed or detected and whether the damage was observed during or after installation. The damage should be characterized in a manner that is consistent with its use in modeling effort, item 2 above, which is being conducted by Dr. Eric Williamson, OTRC, University of Texas. Information and data describing the impact of damage to rope performance is considered as particularly valuable. Such information includes observations related to a progression of initial damage or tests of rope with observed damage.

While the principal focus of this study is on mechanical damage during installation, information characterizing other types of potential installation and in service damage will be addressed. These damages include potential damage caused by rope contact with the seafloor during installation. Dropping the rope can lead to sand particles being introduced into the rope body, which could in turn lead to progressive damage through internal abrasion, wear, or cutting mechanisms. The growth of small marine organisms within the rope body has also been observed. The shells of such organisms could potentially create a similar progressive damage mechanism.

The potential impact of damage on rope performance may be related to the construction or configuration of the rope. This study should include information on the rope construction(s) that are likely to be preferred for deepwater mooring systems.

Recent experiences with polyester mooring lines have already shown the some susceptibility of polyester rope to installation damage and service damage. Manufacturers and contractors have begun to respond to these observations and are developing installation methods and practices, mooring system designs, and rope construction details to mitigate such damage. The study described herein assesses these trends and activities to provide information on the likely state of practice or preferences for deepwater polyester mooring lines for early Gulf of Mexico installations.

PROJECT OBJECTIVE/SCOPE

The objective of this project is for SES to perform a study to characterize key types of polyester rope damage that might affect the performance of a deepwater taut line mooring system. This work will serve as input for studies 2 through 5 above. This study is primarily a “paper study”, but includes some limited qualitative damage experiments with two types of 450,000 lb. ropes, recovered from the DeepStar Test Mooring. SES has performed the study using advice and assistance from its working relationships with the National Engineering Laboratory in East Kilbride, Scotland and Tension Technology International near London.

CONCLUSIONS

The following major conclusions are drawn from this work:

1. ***We have found from all industry sources and the literature that there is ample design and test data and industry knowledge to support the safe application of polyester taut line mooring systems for floating production systems (FPS) and mobile offshore drilling units (MODU) in the Gulf of Mexico***. Recommended practices, like API RP 2SM, are already in place to assure the safe design of such systems. As with any new technology, there remain technical issues, summarized later (Part A: Recommendations for Further Work), that need further study in order to further reduce cost and technical risk

2. Based on survey results, the industry expects 5-7 MODU applications in the Gulf of Mexico in the next 5 years, and perhaps 1 to 3 FPS applications. FPS mooring systems are more critical because 20-year lives are often projected for the mooring system, and industry does not currently have that length of experience. But fortunately there are ways to monitor the strength of the mooring system during operation over time, and insure safe operations in the process.

3. The most common design of polyester rope assemblies is to jacket together 7 to 30 or more parallel subropes (smaller-diameter ropes) into one rope. At each end of the assembly the subropes are fashioned into an eye for termination and connection to other assemblies, using chain and other standard mooring hardware. Worldwide there are over a half-dozen large mooring rope manufacturers to supply large (say 700 tonne) polyester mooring ropes.

4. Petrobras has been the pioneer in the application of polyester rope technology, having installed and operated over twenty polyester mooring systems for FPS since 1997. They have been able to use dynamically-positioned MODUs for drilling, without mooring lines.

5. Based on Petrobras experience, they have experienced 7 damaged lines, and 5 were completely severed. This damage was due to interference with work wires during normal operations, and was not due to normal operational loads. Since ropes that have experienced seafloor contact during installation have been found to have a reduced residual breaking strength over non-dropped rope, they have called for use of a filter cloth to protect the rope body against this kind of damage. After 2 ½ years of service, they have found that marine growth, like barnacles, tend to grow between the rope body and jacket. These sharp growths could lead to a future problem with loss of rope strength, but further study is needed.

6. This study has found that the general effect of external damage to the midline rope body is to reduce the residual breaking strength of the rope assembly, when compared with an undamaged rope. A given damage level, like a certain depth of knife cut, can produce different levels of residual strength from testing, depending on the rope design, the splice design, and their interaction.

7. Generally the splice region of a polyester rope assembly is weaker than the rope body away from the end splices. We have found that cutting the mid-rope region first produces slack subropes, and cyclic loading causes slack to progress to the splice due to effects of normal tension cycling during operations. This is certainly true for short rope assemblies, and is believed to be true for longer rope assemblies.

8. This study has found that a “butcher” knife cut is sufficiently representative of many kinds of cutting and abrading damage that can be occur offshore (See Part B, Applying Damage to Rope Test Samples. The key strength loss factor is caused by the loss of cross-section of the rope body, which represents the effect of the knife cut severing various subropes in the cross-section to various degrees. If the undamaged splices were structurally immune to the effect of mid-rope cutting damage, the design implications would be simple to deal with: the loss of rope strength would be proportional to the loss in cross-sectional area. But we project

from testing and studies that mid-rope damage translates to the splice, and has an additive effect on weakening the splice even further.

These main conclusions are supported by information in the body of this report, which follows in two parts:

Part A: State of Art of Polyester Rope Technology, Rope Damage, Experience and Studies
Part B: Externally Induced Mechanical Damage Characteristics

PART A

STATE OF ART OF POLYESTER ROPE TECHNOLOGY, ROPE DAMAGE EXPERIENCE AND STUDIES

SUMMARY OF LITERATURE SOURCES

Floating drilling and production systems are moving to deeper water, where conventional steel wire and chain catenary mooring systems become too heavy and have poor restoring forces for effective station-keeping. Mooring ropes made from polyester fibers are less expensive and are a more effective rope component for deepwater mooring systems than steel wire rope. Since polyester ropes are only slightly heavier than water, taut-line, rather than catenary, systems are possible. Taut-line systems rely on the axial elasticity of the mooring ropes for restoring forces, rather than the catenary weight restoring forces of the chain and steel wire systems.

The literature available on fiber rope moorings has become vast. Of course the history of the use of various types of fiber ropes for marine applications is legion. It is difficult to pick a starting place for the birth of deepwater mooring technology, but a convenient starting place is with the U.S. Naval Civil Engineering Laboratory effort to develop synthetic mooring systems to anchor a floating structure, using very close allowable excursion tolerances, in offshore California starting around 1987. NCEL contracted a company called Tension Technology International to help F. C. Liu of NCEL to develop the application of Aramid and polyester rope constructions. A literature study in the final report "Fatigue Model of Aramid and Polyester Lines" is what we would refer to as the first major synthetic fiber literature study, which cites a large number of 1989 and prior references. Their reference list is found in Appendix A.

A 1992 Ph.D. Thesis by Cesar Del Vecchio "Light Weight Materials for Deepwater Moorings" has been an excellent state-of-the-art reference for "modern" higher-technology synthetic fibers, and most of this work, validated over time, is still referred to as fundamental. Its reference list is included herein as Appendix B. A still more current rendering of the state-of the art is the "Engineers Design Guide and Commentary for Deepwater Fiber Moorings, 1999. Two of the most recent literature searches and state of the art assessment can be found in the DeepStar IV Project 4406: " An Evaluation of Deepwater Polyester Rope Mooring Technology", and in the HSE Report "Review of Fibre Rope for Offshore Mooring Applications[32].

A number of laboratory type rope testing programs have been conducted on various sizes of polyester rope, for instance, the NCEL tests in 1988, the Fiber Tethers 2000 project in 1995, the NFR project, "High Technology Fibers for Deepwater Tethers in 1996-1998, the JIP "Testing and Optimization of Full-Scale Fiber FPS mooring lines in 1999 and the JIP "The Durability of Polyester Mooring Ropes", 1999 to present.

In 1995 Petrobras installed two separate trial legs of polyester line in offshore Brazil. Since 1997 over 20 polyester mooring systems have been designed installed and operated by Petrobras in the Campos Basin[2]. All of these systems have been for FPS in water depths to 1100 m. There has been no need for polyester moorings for their contracted MODUs because all are dynamically positioned and the environment is mild.

In contrast, the first applications in the GOM will be for MODUs, with FPS applications following 3-5 years later[3]. Industry has unanimously responded to the MMS that polyester mooring technology is suitably mature for deepwater mooring applications, and BP is one of those respondents. BP is a pioneer in this area with the Ocean Confidence deployment.

The literature now contains a number of guidelines and specifications for deepwater polyester rope mooring systems. The 1999 NDE/TTI Engineers Design Guide (EDG) for Deepwater Fiber Moorings[11] is recognized as the technical foundation for recommended practice documents developed by certification societies such as API[15], ABS[12], BV[14] and DnV[13]. The EDG was not written to provide restrictive guidelines, and is more of an encyclopedia of fiber mooring technology. The API and ABS guidelines are very similar, having some of the same authors. BV was the first classification society to issue guidelines and they still use their 1977 revision.

The API guidelines call for use of a 1.67 factor of safety for undamaged conditions, which is the same recommendation given for steel moorings in API RP 2SK. We would recommend using an additional safety factor to cover "material unknowns" with polyester, because the history of polyester applications is short. The additional factors that have been used and recommended vary from 10% to 25%. The key for each oil company and drilling contractor is to apply appropriate safety factors to reflect their willingness to the accept the economic consequences of mooring system component replacements for their polyester mooring projects because of uncertainties over the various aspects of long term durability.

In summary, It is clear from our assessment of the many sources of public and private data that polyester rope technology can be applied to design safe polyester rope taut line mooring systems for FPS and MODUs in the Gulf of Mexico and worldwide.

LITERATURE ON ROPE SEAFLOOR CONTACT

Two separate and independent studies have reported reductions in breaking strength of test rope assemblies after being exposed to seabed particles. The Norwegian Deepwater Program[28] reported on nine tests being run after the samples were exposed to varying conditions of seabed clay. After exposure, and then after 100,000 fatigue cycles, reductions in breaking strength of 13 to 40 % were reported. In other tests conducted for Petrobras[7], reductions in breaking strength of 20 and 31 % were reported after exposure to seabed sediments (representative of those in Brazil) and cycling of only 300 cycles.

This raises a clear issue of the ability to re-use ropes that have contacted the seafloor. We do not yet understand the mechanisms for particle ingression and how marine finishes and differential pressures might play a role in the phenomenon. Until this issue is better understood, one should exercise caution in re-using fiber ropes that have touched the seabed. Petrobras has determined that by using a particle ingression filter of 20 micron just under the protective jacket, larger particles can be prevented from reaching the rope core and reducing the rope residual strength. More recently we learned from Petrobras that a rope that has been previously installed and maintained at pretension for a period of time, appears to be resistant to particle penetration, if dropped (after being tensioned).

SURVEY RESULTS

Introduction

The MMS asked SES to assist them in collecting information from key oil and gas operators, contractors, consultants and manufacturers regarding the advancement of technology for taut line fiber rope moorings for deepwater oil and gas drilling and production systems. SES requested opinions concerning how to handle rope damage issues. The MMS will use this information from the industry to properly plan and schedule their regulatory activities, principally for Gulf of Mexico.

Respondents to Survey

Rope Manufacturers

CSL Ropes
Quintas & Quintas (2)
Whitehill Manufacturing
Le Lis
Marlow

Designers/Installers

Diamond Offshore
Aker Maritime (2)
SBM IMODCO
Delmar
FMC

Consultants

Tension Technology International
National Engineering Laboratory
Stress Engineering Services

Fiber Manufacturers

Acordis

Classification Societies

Bureau Veritas
DNV
ABS

Oil/Gas Companies

Petrobras
Shell
Exxon Mobil
BP (2)
Chevron
Texaco
Norsk Hydro

Questions and Summarized Responses

Following are the survey questions asked to industry, along with a summary of the responses offered:

1. ***What is your role with respect to fiber rope mooring systems (Manufacturer, Oil/Gas Company, Consultant, Designer, Installer, Fiber Manufacturer)?***

   Answer: Responding were 7 Oil Companies, 6 Rope Manufacturers, 5 Installers, 3 Consultants and 1 Fiber Manufacturer

2. ***Does your involvement include Gulf of Mexico applications of fiber rope?***

   Answer: All groups answered yes except Petrobras, Norsk Hydro and BV

3. ***Fiber Rope Applications***

   - ***Do you think that fiber rope mooring technology is sufficiently mature for use in the GOM?***

     Answer: All groups said yes, but qualifiers from some respondents were that (1) MODU applications are more mature than FPS ones, and (2) torque neutral, parallel strand ropes were mature (using chain and no steel 6-strand wire rope), but fiber rope technology is not mature for torque-matched rope (using 6-strand wire rope).

   - ***Over the next 5 years, how many deepwater FPS Fiber Mooring Systems do you think that your company might be installing in the GOM, and in what design water depths and years?***

Answer: This depends on decisions by oil companies operating in the GOM, and their combined responses are: perhaps 5-7 MODU applications in the next 5 years.

- ***Over the same period, how many MODU Fiber Mooring Systems will your company be purchasing or leasing in the GOM, and in what design water depths and years?***

  Answer: On the same basis as above. Perhaps 1 to 3 FPS applications are possible.

4. *Rope Design/Materials*

- ***Will all of the above mooring systems use polyester fibers? If not polyester, what?***

  Answer: A resounding vote on polyester by all groups, with numerous mentioning of HMPE for the future.

- ***Will you want to use torque-neutral rope designs, compatible with chains, or torque-matched rope designs, compatible with six-strand wire rope?***

  Answer: Oil companies in GOM say that they could use either TN or TM. The rope manufacturers have mixed responses on TN vs. TM. Some offer either upon request, others warn of technical issues with TM. Consultants and classifying societies generally are less comfortable with TM applications.

- ***What aspects of rope taut line mooring system design/development do you think needs further refinement or development (like terminations, marine coatings, etc.)?***

Answer: Among oil companies, rope manufacturers and consultants/societies the most frequently mentioned need is for improved terminations. Other items, mentioned less often, were marine coatings, rope handling, rope stiffness and dropped ropes, all of equal intensity.

- ***How do you think that rope designs will change in the next 5 years***?

  Answer: A recurring answer from operators, manufacturers and societies/consultants is the new stronger fibers will be used. Most groups see little changes except improvements in splices, introduction of torque matched designs and improved jackets/filters.

5. Mooring Design/Analysis

- ***Do you think that current mooring analysis methods for steel systems are adequate for fiber rope systems?***

  Answer: All but one mooring designer/installer said yes, but almost all operators, consultants and societies said that improvements to handle viscoelastic behavior are needed**.**

- ***What factor of safety would you consider using in FPS/MODU design? As called for in API RP 2SM or higher, and why?***

  Answer: The operators were half and half on using API RP 2SM factor of 1.67, and the other half would use an additional factor of 10 to 25 percent. Rope manufacturers were mostly "silent" on this issue. Consultants and Society groups vary in response. DNV is issuing a new standard (OS-E301) using same factor for all materials. Responses from designers/installers varied.

- ***What Criteria would you use for fatigue design?***

Answer: Most respondents suggest using API RP 2SM. The currently running Durability JIP (by NEL/TTI) may shed new light on this.

- ***What criteria would you use the design of damaged ropes?***

  Answer: Most of all respondents suggested using a reduced capacity based on loss of cross-section.

- ***What kind of damage do you expect? Where?***

  Answer: Damage from handling and wire rope cuts. Also dropped rope. Damage locations: splice and main body.

6. Rope Specification and Testing

- ***How would you deal with the nonlinear stiffness characteristics of fiber ropes? Is it necessary to know the actual stiffness during storms and loop current events, or will upper and lower bounds be sufficient?***

  Answer: The answer from all groups split between using upper and lower bound stiffnesses, and needing a nonlinear rope model.

- ***A relatively new technical concern is tension and torque interactions, requiring that torques for cables and fiber ropes be matched. Do you see this to be an important issue?***

  Answer: Most of all respondents indicate that tension and torque is a concern. Usually failures occur in chain and wire rope, rather than polyester line**.**

- ***Studies have shown that dropped ropes can fail prematurely due to particle ingression. How would your company handle this issue? Use a filter barrier? What about the splice area?***

  Answer: Most respondents rely on a filter barrier or improved jacket. Mooring designs call for keeping the polyester rope off of the seafloor.

- ***How would you determine the remaining strength of damaged rope?***

  Answer: Most respondents suggest break testing of damaged sections. Answers were varied on this. The need for a guideline is recognized.

7. Rope Manufacture and Quality Assurance

- ***Fiber Rope Mooring Systems have many rope end splices and connections with other mooring elements. How comfortable are you with the maturity of quality assurance methods, particularly for the rope splice fabrication.***

  Answer: Most operators are concerned with this issue. The rope manufacturers are not. Consultants and societies have concern**.**

8. Rope Handling, Installation and Recovery

- ***Based on your knowledge of mooring rope installation experience, how comfortable are you with the level of maturity of our mooring installers in installing fiber ropes?***

  Answer: The majority of all respondents indicate a need of more experience, and the remainder are confident.

- ***What do you think is the greatest concern in affecting a successful mooring installation?***

  Answer: Making sure that the process is well planned.

- ***What kinds of rope damage do you think we should be most concerned about?***

  Answer: Of greatest concern is surface damage to the rope or dropping it.

9. In-Service Inspection and Maintenance

- ***How would your company or your contractor deal with in-service inspection of installed fiber ropes in MODUs and FPS? How would you quantify damage and determine remaining life?***

  Answer: Many respondents cited using ROV inspections and designing in inserts for later removal and testing.

TECHNICAL VISITS TO ASSESS STATE OF ART

The MMS sponsored visits to the following organizations for purposes of determining the current state of art:

- Rope technology education and discussion Tension Technology International Seminar, UK.
- Rope Testing discussions, National Engineering Laboratory, UK
- Rope Manufacturing discussions with Marlow Ropes, UK, and CSL Ropes, Brazil
- Polyester Mooring Development and Operations experience, Petrobras, Brazil

MMS-sponsored participants were the author and Dr. Eric Williamson (UK trip) and Mr. Jerry Williams (Brazil trip).

From our participation in the TTI Seminar we were brought up to date on what the various people in TTI have done to advance the state of art, and this is a broad body of work. From our visit to Petrobras we learned of their experience with being a pioneer in polyester deepwater mooring applications, we have some early information on their operational experiences and their experience with damaged rope. The Table 1 summarizes Petrobras current polyester moored FPS. Because they contract dynamically positioned MODUs, they have no experience with mooring them. From our visit with rope manufacturers Marlow and CSL we have developed an understanding of rope-making and splicing techniques. A summary of the more detailed learnings from these trips is included in Appendix C.

RECOMMENDATIONS FOR FURTHER WORK

Discard Criteria for Damaged Ropes

There is an industry need to develop guidelines for the use or disposal of polyester mooring ropes, depending on the degree of damage. These guidelines should be based on full-scale validation of the damage process and the effect of externally caused damage on the residual breaking strength of the rope. This report is intended as a starting point for planned model and full scale testing, leading to industry guidelines.

Rope Mechanics Modeling

There are currently no industry accepted rope strength analysis models for determining the strength axial stiffness of fiber ropes, both in the undamaged and damaged conditions. The MMS project, described in the introduction, is intended to address this need.

Long-Term Durability

The largest area of uncertainty for rope design is in predicting long-term durability of mooring systems, both for FPS and MODU applications. Indications are clear that polyester ropes (if the splice is well made) will out-perform steel wire rope in short to medium cycle fatigue. But the fatigue laws that govern polyester rope fatigue have not yet been established. It is believed that yarn abrasion is the failure mechanism for high cycle (20 year rope life) fatigue, but less is known for high cycle fatigue. Recent technical papers [4,7,15 and 23] are impressive additions to the state of art.

Marine Finishes

The role of marine finishes in extending rope fatigue life and overall durability is unclear to most offshore designers. The rope manufacturers guard their proprietary knowledge in this area very carefully, and little is known in the rope user community. Also the process by which silt, clay and sand particles reduce the residual strength of ropes is not well understood. Does the marine finish material used on a rope affect the rate of particle ingression into ropes, and is the process affected by hydrostatic pressure differences between the submerged rope core and the ambient pressure outside the jacket?

Effect of Marine Growth on Rope Integrity

While visiting Petrobras and CSL we had the opportunity to see a rope insert that had been recovered after 2 ½ years of service. Preliminary visual inspections found marine organisms lodged between the rope jacket and core. Some of these items were hard and sharp like barnacles. There was no immediate indication of rope cutting damage yet due to these organisms, but the possibility exists that after 5 or 7 ½ years these organisms could cause problems with reducing rope residual strength. How different will the organisms be in the Gulf of Mexico, and what impact, if any, will they have on rope strength? This is a topic for further study.

Rope Contact With The Seafloor

There is always a possibility that a polyester rope can be dropped during installation or dropped due to a mooring leg failure, and it is desirable to be able to recover and re-use these dropped rope segments. Research in Norway and by Petrobras has confirmed that soil particle ingression into the rope core creates internal rope abrasion, that has the effect of significantly reducing rope fatigue life and rope breaking strength. Petrobras has found that a particle filter jacket can be used just below the protective jacket of the rope to prevent particle migration to the rope core, and hence avoid the deleterious effects on rope strength of particle ingression. More fundamental work needs to be done to better understand this process and how to protect the ropes. Recently Petrobras has learned that particles do not invade previously tensioned ropes as they do in previously un-tensioned ropes.

Torque Matched vs. Torque Neutral Rope Designs

The “Rope Club” at Reading University[34] has done some initial work on the interaction of torque and tension in torque-matched rope designs. Such designs are new for the mooring rope industry and achieving sound designs is difficult. Torque-matched ropes are the key for joining polyester rope with 6-strand (torque-sensitive) wire rope. Solutions to this technical problem will enable older drilling rigs, equipped with wire rope handling systems to be outfitted with polyester ropes to make them capable of mooring in deep water.

Rope Handling Damage (MODUs)

There are indications from informal testing that polyester rope that has had service in a mooring spread (is fully bedded in), and is recovered for re-use (relocation of the drilling vessel), and subsequently handled by recovery and deployment winches, has a different condition of bedding in the second and subsequent deployments. Bedding in, handling, then re-bedding in could result in reducing the rope strength. This hypothesis has not yet been confirmed, and the financial and technical success of using polyester moorings in MODU applications depends upon confirming that handling between installations is not a problem. Resolution of this issue is needed.

Creep Rupture

The creep behavior of synthetic fiber ropes is difficult to predict because the influence of rope construction and terminations complicates the creep behavior of the fiber. Several important questions remain. Research findings on the creep rupture behavior of polyester ropes do not agree. Recent work on the subject by Whitehill[4] does not confirm earlier findings by Del Vecchio[5,] who measured higher creep rates in the rope than in the fibers under comparable loads.

As termination techniques improve, ropes will be loaded to higher portions of their potential strength, aggregate strength, or whatever the most appropriate basis for creep and creep rupture turns out to be. Will creep and creep rupture behavior suffer to the point that a safety factor based on breaking strength is inadequate? Can we predict creep in ropes made from other fibers based on data for polyester fiber rope? In large-scale rope, what role does cyclic loading (compared to constant loading) play? Is there a simple, accurate qualification test for creep rupture that would prevent potentially undesirable combinations of fiber, construction, and termination from entering service?

Rope Modulus Determination

Industry has a currently accepted practice for the design of taut-line polyester rope mooring systems. Based on API RP 2SM[1] and the Engineers Design Guide[2], for instance, the designer can use the post installation modulus and the storm modulus, both determined by rope testing as upper and lower bounds. These modulii, intended to be conservative, vary by 50%. This practice was established because determining an accurate modulus of a complex and viscoelastic material like polyester rope has been found to be quite difficult. This practice poses two issues: (1) We use a design factor of safety, like the API RP 2SM recommended factor of 1.67 on force – two decimal places, while the assumed modulus, used in determining the force can easily vary by 20 % from actual, depending on rope loading history. (2) Since we are using upper and lower bound modulii, we do not know what vessel displacement “watch circles” will result in actual operations, and we cannot accurately determine drilling downtimes for MODUs. Further, in production systems, riser design is significantly affected by the choice of rope modulus. Needed is an algorithm to express the nonlinear, viscoelastic load-deflection characteristics of polyester ropes.

Rope End Termination Quality Assurance

Although ropes are machine made, and splices are handmade. We recognize that the splice is generally less efficient than the potential rope strength (strength of the rope body, as if the splice were 100% efficient). Thus the polyester splice terminations, perhaps 70 to 100 per mooring spread, are the weakest links in the mooring system. It is not sufficient to call for eye splices and move on. Eye splice designs vary from one manufacturer to another. Furthermore, configurations and manufacturing techniques that work well for one rope construction, fiber, and finish are not necessarily appropriate for another.

So, even a good eye splice is a potential weak link that requires close attention, but there is no recognized standard for qualifying either their design or manufacture. For many applications, this is acceptable; ropes have been used for centuries without the sort of standard we are calling for. However, the details of splice development and manufacture are just as important as other aspects of rope construction for both qualification and acceptance. For this application, involving very large ropes in novel constructions and having a high consequence of failure, we assert that a standard of some sort is essential.

In-Situ Inspection

This area of technology development is a practical one. How will industry insure that their polyester moorings are damage-free? And if damage is indicated or found, how can the degree of damage be assessed? Petrobras used the video systems on ROVs to make the initial assessment, and then processed the videotapes to determine the degree of damage, when found. Is this sufficient? Probably not, especially when the amount of rope damage determined has a major impact on the structural capacity of the rope. Improved methods are needed.

Closure on Recommendations

The recommendations listed above have been developed as the author has worked in the field for the last four to five years. These items seem to be the most critical of the needs, but other experts will vary in their advice.

PART B

EXTERNALLY INDUCED MECHANICAL DAMAGE CHARACTERISTICS

INTRODUCTION

The purpose of this part is to provide a starting point for future testing of the effects of externally applied damage to polyester mooring ropes. To our knowledge, there has been no formal technical work in this area. Referring back to the MMS damaged rope program in the Introduction, this work is input to items 2 through 5 of the program: developing a rope model, conducting small-scale tests, conducting large scale tests and developing guidelines for dealing with installation damage. The best starting point is to look at available operational experience with polyester rope damage.

PETROBRAS ROPE DAMAGE EXPERIENCE

Petrobras sees the biggest issue in rope damage to be external damage by six-strand wire rope. They have had 7 occurrences of cutting damage with no evidence of fusion, which is melting of the fibers that is caused by heat buildup from sudden energy release. In addition, they see some limited splice damage, due to handling (over the stern roller, etc.). Other damage could be due to marine growth or dropped rope (see paragraph on dropped rope), but they have no major concerns on this due to the 25% added safety factor. (Please see Appendix D for details of Petrobras' experience with damaged rope.) To avoid their major source of damage problems Petrobras is now developing HMPE ropes for work wires in mooring system installation (See next section). They have even used polyester work wires, but they want the smaller diameter line that HMPE will provide.

On P-26 Petrobras found from an ROV inspection that line number 15, in a polyester section, was "necked down", indicating damage. Because of the jacket pressure on the core, the rope 50 rope diameters from the damage had "healed" to the full cross-section. They used some German image processing software to process the damaged rope image and determine the cross-sectional dimensions for determining % loss of cross-section.

Petrobras thought that a ROV-supported device to measure the rope cross-section would be useful.

ROPE RETIREMENT CRITERIA FROM API RP 2SM

This RP[1] requires that the damaged rope have a retained breaking strength of 90% of the required design strength of the mooring line. First a damage assessment is called for. Then principles are provided for evaluating the rope strength reduction. If the evaluation indicates that the rope would fail to retain 90 % of the required design strength, “the rope should be replaced immediately.” Otherwise, the rope can be temporarily placed in service with or without repair. For the rope that is temporarily placed in service, a test should be conducted to confirm the 90% retained strength. To do this, a rope sample of the same fiber material, rope construction, termination and size should be prepared. Then the damage can be simulated on the test sample. If break testing of this sample is successful, then it the rope segment in question, with minor damage, may be permanently retained in service.

This information was placed in API RP 2SM based on the best judgment of the committee writing the RP, and is not based on test experience with damaged rope.

ROPE CUTTING EXPERIMENTS

To better understand how susceptible polyester rope is to damage, we performed some simple external damage experiments on a short specimen of 450,000 lb rope. For ease of cutting we placed the rope in a wooden miter box to constrain rotation. The cutting devices we experimented with included a crosscut handsaw, butcher knife, fish filleting knife with serrated edge, a piece of steel reinforcing bar and a hacksaw, all shown in Figure 1. But our technician used his machete for cutting a test length from the reel of 4-inch diameter rope, as shown in Figure 2.

Figures 3, 4, and 5 show us cutting with the butcher knife, reinforcement bar and hacksaw, respectively. The easiest cutting was using the fish knife with the serrated edge, followed by the sharp butcher knife. The hacksaw and the handsaw could

eventually cut the material, but cutting was of an abrasive nature, rather than slicing. The abrasion of the rope by the piece of reinforcement bar, simulating rubbing by a crossing wire rope was slow.
Figure 6 shows us trying to puncture the jacket of the rope with the rough edge of a piece of steel channel section. It was difficult to inflict much damage in this case. Cutting the jacket was relatively easy.

As we experimented with cutting the rope it became clear that slicing would cause the greatest penetration for the same pressure on the rope. In the samples we had, there was no rope tension, and thus the cut ends would not "open" and friction from the slice initiation would make slicing deeper more difficult. This would not be the case for the slicing of actual installed mooring lines, because the tension on the rope would cause the cut ends of the rope elements to separate from each other. Figure 7 is a sketch of the deformation and change of force distribution due to a transverse slice.

The more the nature of the cut is by rubbing or abrasion, the more difficult it is to make the cut deeper (because the fibers melt and cause a hard spot), but it seems unlikely that rapid rubbing of an abrasive device could generate sufficient heat while for this to occur.

Comparing our experiments with the cutting of a real mooring rope, one can see that a rubbing or slicing action on the surface of a long rope under tension might cause sufficient transverse cutting force to cause the rope core being cut to rotate in a torsional mode. This suggests that when a transverse cut or abrasion occurs, the slice would be as shown in Figure 8a, rather than as shown in Figure 8b. This twisting effect means that more subropes would be subjected to the damage than if the cut were being made with the rope core being restrained from rotating.

THIRD-SCALE DAMAGED ROPE TEST LEARNINGS

The MMS has purchased data from a BP-sponsored project to perform cyclic then residual break strength tests on some 450 kip parallel subrope polyester rope manufactured by Marlow Ropes, Ltd. This size of rope might be called 1/3 or ¼ scale, with reference to full scale. This test program includes 3 tests of undamaged rope for reference, 3 tests of one damage level (0.70 inch), and three more tests of a level of damage to be determined.

The testing plan includes (a) inflicting external damage (of predetermined knife-cut depth) to the rope mid-span, (b) exposing the rope sample to 20,000 fatigue cycles, to be explained and (c) pulling the rope to failure, thus obtaining the residual break strength and elongation to break.

Inflicting the external damage is done by knife cutting to a predetermined depth, as shown in Figure 9. The first level of damage was to a depth of 0.70 inches, and the second level of damage was to 0.5 inches

Rationale for Cyclic Loadings

The approach initially taken in developing a test procedure for damaged rope testing was based on a recent paper by Hooker and Bosman[31]: "Recent Investigations into the Physical properties of Superline Polyester Rope".

They proposed that ropes could be exposed to a number of Gulf of Mexico hurricanes, depending on the degree of safety desired. This loading assumption is based on the belief that the majority of rope damage accumulation in cyclic fatigue occurs during hurricanes, and that normal Gulf of Mexico weather conditions are relatively benign.

Specifically, a set of their tests (in water) each simulating one hurricane consisted of:

Test Sequence	**Mean Load (%BS[1])**	**Load Amplitude (%BS[1])**	**Load Range (%BS[1])**	**Cyclic Period (Seconds)**	**Number of Cycles**
1	20	10	20	10	4000
2	40	15	30	10	1000
3	20	10	20	10	4000
4	15*****	10	20	10	1000

[1] BS = average breaking strength

***** Changed from Ref. 31 to facilitate testing at low loads.

The first 4000 cycles was to bed in and condition the rope. Then the 1000 cycles at 40% mean load +/- 15% amplitude was considered the maximum hurricane loading on the most loaded windward line. After another 4000 cycles of normal conditions, 1000 cycles at 15% mean load +/- 10% were applied to simulate the leeward line in a hurricane. We increased the mean load to 15% from the Hooker & Bosman paper because controlling the load was difficult, and we did not want to unintentionally induce compression loadings in this simulated hurricane condition.

Since BP wished to have “interim” damaged rope criteria for MODUs that might come into service before an industry recommended practice could be developed, SES decided that exposing polyester MODU moorings to two hurricanes would ensure that a MODU, having experienced one hurricane, could withstand a second while replacement lines are being manufactured.

BP was aware that work in planning by DNV and MMS would soon result in industry accepted recommended practice, so the 2 hurricane tests would be sufficient for the near term.

Final Test Plan

Just before testing began, we recognized that the rope should be capable of more hurricane cycles than originally proposed, without changing the cost of testing for 20,000 cycles. This would be a more conservative approach. As a result the hurricane cycles were raised from 1000 to 3000, three times more severe. As a result the “non-hurricane” cycles were reduced to from 4000 to 2000.

This change assured us that the results from the damaged rope tests that we conducted would be conservative, with each of the 2 hurricanes lasting 3 times their normal duration.

The final test matrix for one hurricane is as follows:

Test Sequence	Mean Load (%BS[1])	Load Amplitude (%BS[1])	Load Range (%BS[1])	Cyclic Period (Seconds)	Number of Cycles
1	20	10	20	10	2000
2	40	15	30	10	3000
3	20	10	20	10	2000
4	15	10	20	10	3000

1 BS = average breaking strength

The above test matrix is being conducted with the test machine operating under load control.

Interim Findings on Rope Damage

Although testing is still in progress, and test results cannot be published herein, here are some general findings that apply to the residual strength of damaged polyester rope:

1. Breaking strength tests are normally performed on 10 to 15 meter test strops with eye splices on each end. This is what we call the rope assembly. There are two potential weak areas in the rope assembly that has been damaged. One is at the damage location, midway between splices, and the other is at both of the splices. If the theoretical (calculated) breaking strength of the new undamaged rope body is 100%, the splices typically have an approximate breaking strength between 70 to 90% of the theoretical breaking strength. Based on our current knowledge, external damage applied to the midspan of a rope assembly will directly affect – reduce - the efficiency of the splice. We have tested 10-meter ropes, and longer ropes could potentially behave differently, but we do not believe so. No tests have been conducted to explore the effect of sample length, and the conservative assumption is to assume that results on 10-meter samples will be like those for longer lengths of this rope design An end splice that has either (a) each subrope spliced back to itself on each end, or (b) have pairs of subropes that are spliced to each other at each end will restrict the loss of strength to single subropes (as in a) or to pairs of subropes (as in b). If a splice is made in which the subropes are not "matched" for splicing, damage at the mid-span can propagate to the end splice, affect other undamaged subropes to which the damaged subrope is attached, and

propagate to other subropes over time and cyclic loading. Thus, the damage could (at least theoretically) propagate to other subropes.

2. Current thinking by those dealing with damaged rope mechanics is assume that the effect of mid-rope damage on a rope cross-section is to reduce the "effective" cross-sectional area, and thus the stress on the reduced cross section for a constant load will be higher by the ratio of the undamaged area carrying the load to the remaining area after damage (cutting). This can only be true if the splice design is not affected by the damage (other than the area loss). In practice each splice design is different, so one must determine by testing the ability of the splice to handle subrope damage, before assumptions are made on the basis of area loss. There is additionally a question concerning the effect of rope sample length on results.

3. Depending on the splice design, the failure location after break testing will be found either near the mid-span damage location or at one of the spliced ends, depending on the relative efficiency of the splice vs. the efficiency at the damage location, the load path design of the splice and the damage tolerance of the splice design.

CAUSES OF ROPE DAMAGE

Rope external damage can occur due to a number of key causes:

1. Cutting or abrading of the rope body, away from the end splices, often caused by the rope rubbing against objects on deck, or by the abrading of wire rope and polyester rope segments during installation or workover operations.
2. Cutting or abrading of the end splice, either on the outer tangent of the eye or near the tail of the splice region.
3. Particle Ingression into the core of the rope body or splice.
4. Handling, where parallel subropes are forced to bend around a winch drum, and fibers and subropes on the "drum side" of the subrope must "buckle" to

conform to geometric constraints. This buckling effect may be temporary and non-degrading to the rope residual strength, but we have one example (DeepStar used rope) that failed prematurely. Further study is required.

5. Damage due to marine growth cutting the rope. Over time marine organisms can grow between the rope body and the core, and the barnacle-like structures can cut the rope body.
6. Damage from hot slag from the steel welding process falling on the rope and causing local melting.

Although the purpose was not to test damaged rope, Reference 9 indicates that during rope testing of the recovered DeepStar rope, screws (believed to be ¾ inch wood screws) were used on the rope body to attach measurement devices. One rope broke at about 25 percent below the average break load without screws. The significance in this case is that a small screw would affect only a very small part of the entire rope cross section, yet it could reduce the break load by 25%.

APPLYING DAMAGE TO ROPE TEST SAMPLES

Method of Applying Damage:

With all of the possible types of damage, what should one choose as a damage inducing means to inflict damage on rope test samples? Experience from Petrobras suggests that 70 % of the damage events they have experienced have resulted in fully cutting the mooring rope – 100% damage. For the 30% of the cases with partial damage, they used ROV video to determine the reduction in cross-section.

Our earlier described cutting and abrading experiments showed the only difference between a knife cut and a saw cut was the smooth profile of the knife cut and the jagged profile of the hacksaw cut. Rubbing of an abrasive tool over the rope jacket did not cause an easy penetration of the jacket. Damage to the rope, once installed, involves cutting or abrading in the presence of water, so the melting process does not appear to come into play. Further, a wide cutting width versus a narrow one does not change the nature of the cut strands, other than they are shorter by the blade thickness.

For this reason we would advise that knife cuts with a sharp butcher knife are sufficient to inflict damage that is representative of other cutting and abrading tools, or rubbing of steel wire rope. Figure 9 shows a knife assembly that we have used to inflict damage in rope testing for BP.

We have used a “straight” knife cut, but in an underwater cutting scenario, whatever is the cutting tool striking the rope could cause the rope to twist due to the tangential frictional force of the cutting operation on the circumference of the rope. Hence the rope could easily rotate due to the cutting, and cause the cut to be other than straight as shown in Figure 8.

Another problem is that a certain knife cut depth can will not always cut the underlying subropes the same way each time a cut is made on the same rope. This means that there is variability in which strands are cut and the depth of these cuts, depending on the cut location chosen. In testing, we achieved very similar cuts by first making a cut, then counting and documenting all the subropes, elements and strands that are cut. For the next test sample, rather than make the knife cut, we will open up the rope in the cut location, and then (surgically) duplicate the cuts that we counted and documented. Since the effect of a knife cut in reducing the residual strength of the rope is dependent on the location of the damaged subropes with respect to the splices, this also, must be completely duplicated.

Also, recognizing that torsion of the rope during cutting could make the damage more severe, the key to determining damage is to determine the reduced cross-sectional area at the damage location. In general, the splice design and fabrication determines the extent to which one could use the assumption that the reduction of the load-carrying capacity of the rope will be proportional to the reduction in cross-sectional area of the rope due to the damage. Only if the specific splice design is not weakened by damaged elements can the above assumption be valid.

In summary, we recommend that a knife cut be the damage causing mechanism that would represent a variety of externally and mechanically applied cutting and abrading devices. Rope damage due to handling effects (if any), marine organisms and soil ingression must be treated separately. Further, the first order of testing business should be with damage applied to the rope body, rather than to the end splices. Damage to the end splices is complicated by complex loading patterns in the splice region, and should be a subject for future work.

When to Apply the Damage

One must choose the damage condition that is to be simulated for test. If in the field application the damage occurs before the rope is tensioned for the first time (installed), then the damage would be applied to the un-bedded-in rope that has experienced negligible tension since fabrication. If it is desired to simulate the field condition of having a fully installed mooring line that is damaged in place, then the rope should be bedded in first, at least to the pre-tensioned condition. By adding some cyclic loading, like that caused by weather, the rope has then been “conditioned”. In testing, rather than make the cut in the tensioned case, we would (for safety) slack the rope to 2% of minimum breaking strength, and then make the cut.

LOAD-CARRYING CHARACTERISTICS OF UNDAMAGED ROPE ASSEMBLIES

Potential Rope Strength Concept

Before covering the damaged rope case, it is instructive to understand the mechanical behavior of an undamaged rope assembly. A rope assembly is made up of the main body of the rope between the terminations, usually machine made, and the hand-made eye splices (or other end terminations at each end of the rope). Such a rope assembly has a length of rope between terminations, and the end terminations for transferring loads to adjacent mooring hardware. See figure 10 for an example of a short rope assembly for testing.

The concept of *potential rope strength* was introduced in a recent paper by Whitehill[4]. It is explained as follows: A perfect rope would utilize the full potential of fibers when aligned in the axial direction. But when the fibers are cabled or braided into all of the elements of a rope, the strength is reduced because the yarns, the building elements of a rope, no longer have an axial orientation. In this way the yarns, as constructed, might have only 90% of the potential strength of the fibers making up the yarn. Further reductions can take place when the yarns are made into the final rope configuration. One way to think of this effect is that the price that you pay for making all the fibers act together as a compact, load-carrying rope is the reduction in overall rope strength, when compared with the sum of the fiber strengths. The strength reduction is small if the helix angles used in the yarn and rope construction are small.

If one were to perform a series of breaking strength tests on a rope design of a given configuration (wire rope construction, or parallel sub-rope construction), and if the rope had structurally perfect terminations, one would be able to determine the potential rope strength. But when the ropes are terminated, say with eye splices, the terminations can only approach the potential rope strength. In fact, terminations tend to be perhaps 10 to 30 percent weaker than that of the rope potential rope strength. The efficiency of terminations will vary between both rope designs and between termination designs.

The important learning from the Whitehill[4] is that if comparisons are made between the creep of yarn and that of rope, the comparisons should be made using the potential rope strength as a basis. Comparisons should not be made on the breaking strength of the rope assembly, which is impacted by the weakness of the termination. A further implication of this learning is that scaling of rope properties, such as modulus, elongation, and creep, should be done on the basis of rope potential strength and not rope assembly (including terminations) breaking strength.

The next problem to be addressed is that the potential rope strength is difficult to determine, because it must be a calculated value for the particular rope construction. An alternative to using potential rope strength might be to use the sum of the yarn strengths, which is readily available from the fiber manufacturer.

Much of the rope tests reported in the literature provide results by normalizing the data to the *rope breaking strength*, and not to the *potential rope strength*, and consequently, the results should be interpreted with care.

Eye Splice Load Patterns

Particularly in large mooring ropes, tests through the years have proven that the “weak link” to the undamaged rope assembly (rope body plus end splices) is in the splice region.

More specifically, in the conventional rope eye-splice, the two areas of concern are (1) the tapered transition of the splice tail to the rope body and (2) wear areas of the rope-to eye-region (called the tangent locations by NEL). If one looks at the eye splice as a clock on the wall, with the rope section hanging down at 6 o-clock, the high abrasion damage areas are at the 9 and 3 o-clock positions, where the rope rubs against the eye during cycling. The 12-o-clock position has no relative movement in a good splice, but high bearing loads exist there.

A completely efficient splice would have the breaking strength of the rope assembly (rope body plus splices) equal to the rope body “theoretical” strength. But splices will only be approximately 70 to 90 percent efficient in practice. The larger the rope, in general, the less efficient the eye splice.

A new, and much simpler, end splice design has been introduced by Whitehill Manufacturing, which features seven large subropes being individually looped and spliced around a wide-bodied metal shackle, and we do not yet know about the long-term performance of this product, although the manufacturer has done some initial testing.

THE EFFECT OF EXTERNALLY APPLIED ROPE DAMAGE TO THE ROPE BODY

Externally applied rope damage produces another region of inefficiency, in addition to the undamaged splice region described above. Cutting or abrading damage to the main rope body will cause the jacket to be partially severed and then numbers of subrope below the jacket to be either fully or partially severed.

Severing of subropes will cause the load on the full rope to transfer to the remaining adjacent intact subropes. The center of loading changes from the intact rope center to the center of forces of the remaining subropes. Since the elongation of polyester is great when compared to steel, the rope body will slightly change shape to preserve an in-line center of load. Numerically if a rope has 20 subropes and 5 are severed; the load on the remaining intact subropes in the damaged region could be greater by a factor of as much as 20/15, or 33 %, depending on if the splice design will permit maximum splice efficiency.

But will this damage migrate into the end terminations, or remain localized? The answer to this is more complex. In general, if there is no outer jacket, the damage, or loss of strength in the severed subrope will migrate to the terminations as a result of cyclic loadings applied to the rope during testing. The jacket, having been at least partially severed, is not as strong in load carrying capacity, and is less capable of “squeezing” the subropes together in an effort to “bind” the damaged subropes to the undamaged ones, and limit the migration effects of the damage prior to reaching the end splices.

A sound and conservative assumption to make is that the damage effects completely migrate to the splice regions, so that you will have some subropes in the splice which have no load-carrying capacity. Thus, the effect of mid-rope damage is to potentially further weaken the splice region.

But what about partially severed subropes? In this case, if one member of a 3-part twisted subrope is severed, the force balance between the three parts is changed. The symmetrical force balance of the helix configuration is lost, and you end up with two parts in parallel with some residual twist, because that is the lowest energy configuration for two parts. The two remaining parts are made effectively longer, because the helix angle effect (load times cosine theta) is lost. As a result these remaining " longer" subropes are not loaded as highly as the intact subropes, so that the intact subropes will reach their breaking elongation before the two remaining parts of the subrope. The effect of this mechanism is to cause an imbalance in the force carried in each subrope as the subrope body enters the splice region.

EFFECTS OF ROPE BODY DAMAGE ON SPLICE EFFICIENCY.

The most efficient splice design will convert "balanced" forces in the subropes of the rope body to balanced forces in the subropes of the splice. The second generation Marlow splice is intended to do just this, and there is test evidence that it is effective, because the splice fails "explosively" or "instantaneously", and not by subropes failing in series, and less instantaneously. This new Marlow splice fails at a load somewhat higher than the former splice design.

If the subropes coming from the rope body into the splice region have unequal loadings due to damage effects, this should make the splice less efficient than for undamaged rope. The amount of efficiency loss will be a function of the damaged region location with respect to the end splice location. Unloaded (severed) subropes entering one side of the splice region can be near the outside of the splice, where the force imbalance may transfer around the outside of the splice to the other side of the rope body. Or the subrope may be firmly held in place near the eye by other subropes wrapped around the eye above it.

If a damaged subrope is spliced to itself, as in the Whitehill splice, the loss of load-carrying capacity of only one subrope is affected. In the new Marlow splice, if subrope A on one side of the splice is spliced to subrope B on the other (for both ends of the rope assembly), then the maximum effect of damage to single subropes A or B is to lose the load-carrying capacity of two subropes, A and B. As in the former Marlow splice, if the subropes are spliced together without matching the subropes with each other and on each end, one can achieve a progressive failure starting with one subrope, and then propagating to other subropes to which it is joined, from subrope to subrope as cyclic loading progresses.

ROPE DAMAGE DUE TO MARINE GROWTH

At this point we have very little knowledge and experience with rope damage due to marine organisms. Barnacle-like marine organisms have been found previously by Flory on the DeepStar polyester test mooring (in the water for 2 years before recovery) in the Gulf of Mexico[9]. More recently Petrobras has found marine organisms between the jacket and core of an insert rope that had been recovered after 2 ½ years of service in offshore Brazil. Petrobras has now taken a decision not to use polyester in the first 100 meters from the surface of mooring legs they design and install. Their initial findings are that marine growth is much more severe near the water's surface. The presumed damage mechanism is cutting of the rope core fibers by the sharp edges of the barnacle-like organisms. Of course cyclic fatigue loadings on the rope could cause a sawing action of the barnacle against the fibers.

SUMMARY OF DAMAGED ROPE BODY EFFECTS

The effect of rope body damage is to cause the remaining undamaged subropes to carry the additional force not carried by the severed ropes. Further the damage effect on the rope body causes unbalanced forces to be applied to the splice region. Imbalances in loadings in the splice will cause the higher loaded subropes to fail first, and then the others in rapid succession. The end splice will then become even more inefficient than for undamaged rope. Depending on how the splice design can internally achieve efficient load transfer and minimize uneven force effects on the splice load-carrying capacity, the actual failure could conceivably be outside of the splice region. The more logical failure location would be in the splice region, however, just where the splice tapers to the main body diameter.

The effect of damage to the splice region is to reduce the efficiency of the splice. This can best be determined by test. The splice-rope body transition region and the outer boundaries of the rope around the eye are the most critical regions.

The mechanical effect of Particle Ingression (say due to dropped ropes) is to cause fiber and strand abrasion, as translating internal rope surfaces are made rougher by particles serving as "sandpaper". This can even affect the residual break strength of a rope sample that has not been cycled prior to breaking. We do not yet know exactly how the particles migrate from the rope jacket surface to the subropes within the rope core to cause the damage.

A final rope damage mechanism is the following: Damage is caused by a mooring rope being first installed and used to moor a MODU, then the MODU and moorings are recovered and re-installed at another location. The rope experiences bedding in and operational loads during the first installation. Then the rope is recovered (un-tensioned) and then handled by spooling it up and un-spooling it from winches and storage drums. During this handling process the previously bedded in parallel subropes are forced to buckle around the winch drum, and perhaps transferred to other drums before re-installation. Then the re-installed rope might not be as strong as it was during the first installation. We do not have firm proof that such handling loads on the previously installed ropes will cause damage to the rope core sufficient to reduce the residual breaking strength of the rope. This damage mechanism can be simulated as part of a test plan for rope testing.

DETECTION OF DAMAGE

In order to develop guidelines for retaining or discarding damaged rope, it is necessary to determine the degree of damage found. If the damaged rope is on the deck of the installation vessel this can be quite straightforward. However if the mooring leg containing the damaged segment is already installed, the currently most practical approach is to employ a Remotely Operated Vessel (ROV) to inspect the damage, using a video camera. Petrobras employed software to convert the 3-d video picture into a cross section of the rope, which could be measured to calculate the minimum area.

Figure 11 depicts a concept for a ROV-handled tool to make measurements. Alternatively, one can use a material that sets up underwater to make a “mold” of the damaged rope cross-section. In any case, there is a need to compute the reduced cross-sectional area of the damaged section. More work is called for in this area of technology.

ADVICE FOR SMALL SCALE AND FULL SCALE TESTING

The most significant insight gained from this work is that the affect of mid-span rope damage is a function of the splice design. Each different splice design will accommodate mid-span rope damage differently, depending on the load paths of the subropes (damaged and undamaged) in the splice, and the sensitivity of the splice to the effects of un-tensioned subropes and elements.

This means that splice design should be tested first to determine how severed subropes or elements are accommodated in the load transfer. If the splice efficiency is not reduced more than the area reduction of the cut would cause, then the splice is competent enough to permit using the area reduction method for determining residual strength of the rope. Otherwise, the area reduction method is not valid.

SELECTED REFERENCES

1. American Petroleum Institute; *Recommended Practice 2SM* – 3rd "yellow page" Draft, 5 November 1999.

2. National Engineering Laboratory, *Fiber Rope Testing – Phases 1 & 2 (A Study into the Mechanical Properties and Heat Build-Up Characteristics of Small Scale and Full Scale Polyester and Aramid Rope);* prepared for the Norsk Hydro JIP, December 1996.

3. Noble Denton, National Engineering Laboratory, Tension Technology International; *Fiber Tethers 2000 – High Technology Fibers for Deepwater Tethers,* 1995.

4. Huntley, E. and Whitehill, S.; *Creep Rupture Models and Experimental Results for Polyester Rope;* MTS; 1999.

5. Del Vecchio, C.; *Light Weight Materials for Deep Water Moorings;* Ph.D. Thesis; University of Reading, UK; 1992.

6. Cordage Institute Standard CI-1500-97; *Standard Test Methods for Fiber Ropes;* 1997.

7. Rossi, R.; *Recent Developments in the Technical Specification, Design, and Installation of Synthetic Rope Mooring Systems: An Update from Brazil;* Petrobras, 1998.

8. Oil Companies International Marine Forum; *Prototype Rope Testing;* OCIMF, 1987.

9. Devlin, P.; Flory, J.; Fulton, T.; Homer, S.; *DeepStar's Polyester Taut Leg Mooring System Test;* ISOPE-99; 1999.

10. Noble Denton, Tension Technology International; *Engineers Design Guide – Deepwater Fiber Moorings*, 1998.

11. Lo, K. and Xu, H.; *Polyester Rope Mooring Design Considerations;* ISOPE-99; 1999.

12. Mandell, J; Steckel, M.; Chung, S.; and Kenney, M.; *Fatigue and Environmental Resistance of Polyester and Nylon Fibers;* Polymer Engineering and Science; 1987.

13. National Engineering Laboratory; *Testing and Optimization of Full Scale Fiber FPS Mooring Lines,* 1998.

14. Banfield, S.; *Pathological studies, yarn residual strength and temperature measurements of full scale FPS mooring ropes;* Tension Technology International Report Number TTI-SJB-99-109-R Issue 1; 1999.

15. Hooker, J., Bosman, R.; *The Elastic Modulus Characteristics of Polyester Mooring Ropes;* Offshore Technology Conference #10779; 1999.

16. Overington, M and Leech, C.; *Modeling Heat Build-Up in Large polyester Ropes;* ISOPE 1996.

17. Bosman, R.; *On the Origin of Heat Build-Up in Polyester Ropes;* Akzo Nobel Fibers B.V.; no date.

18. Casey, N. and Banfield, S.; Evaluation of Fiber Rope Properties for Offshore Mooring; Floating Production Systems – 97; 1997.

19. Karnoski, S. and Liu, F.; *Tension and Bending Fatigue Test Results of Synthetic Ropes;* Offshore Technology Conference, 1988.

20. Schaap, A. and Driessen-Meijer, Y.; *Mechanical Evaluation of Mooring Ropes with "z-kinks";* Akzo Nobel; 1999.

21. Riewald, P.; *Performance Analysis of an Aramid Mooring Line;* Offshore Technology Conference, 1986.

22. Cordage Institute Standard CI-1503-98 Draft #4; *Test Method Yarn-on-Yarn Abrasion Wet and Dry;* 1998.

23. Karayaka, M., Srinivasan, S., and Wang, S.; *Advanced Design Methodology of Synthetic Moorings;* Offshore Technology Conference #10912, 1999.

24. ABS Guide, American Bureau of Shipping; *Guide for Synthetic Ropes in Offshore Mooring Applications*; March 1999.

25. National Engineering Laboratory; *Testing and Optimization of Full Scale Fiber FPS Mooring Lines,* 1998.

26. Fernandes, A., Del Vecchio, C., Castro, C.; *Mechanical Properties of Polyester Mooring Cables;* ISOPE - Montreal; 1998

27. Van Den Heuvel C.J.M., et al. (1993); *Molecular Changes of PET Yarns During Stretching, Measured with Rheo-optical Infrared Spectroscopy and Other Techniques*; J., Applied Polymer Science, vol. 49.

28. Hydro NFR (1999); *Summary NFR Project Seminar 09-10*; February 1999, Hydro E&P Research Center.

29. Parsey M. (1982); *Fatigue of SPM Mooring Hawsers*; OTC 4307, Offshore Technology Conference Proceedings, May, Houston.

30. NEL/TTI (1999); *The Durability of Polyester Ropes*; A NEL/TTI Joint Industry Proposal.

31. Hooker J. and Bosman R., *Recent investigations into the Physical Properties of Superline*
Polyester Rope; Moorings and Anchors “Deepwater and Ultra Deepwater Fields, 1999

32. CI-1503 (1998), *Test Method; Yarn-On-Yarn Abrasion*, Wet and Dry, Cordage Institute.

32. National Engineering Laboratory; *A Review of Offshore Mooring Applications;* A Report for the Health and Safety Executive Offshore Safety Division, 1999.

33. Tension Technology International, Inc.; *Fatigue Model of Aramid and Polyester Lines*; Final Report to the U.S. Naval Civil Engineering Laboratory, Contract N62474-87-C-3073. Undated (circa 1988).

34. Chaplin, C. R. et al; *Tension/Torsion Interaction in Multi-Component Mooring Lines*, OTC 12173, 2000.

Figure 1. Cutting devices used.

Figure 2. Machete was used for major cuts.

Figure 3. Cutting with butcher knife.

Figure 4. Cutting with piece of reinforcement bar.

Figure 5. Cutting with hacksaw.

Figure 6. Puncture test with raw edge of steel angle.

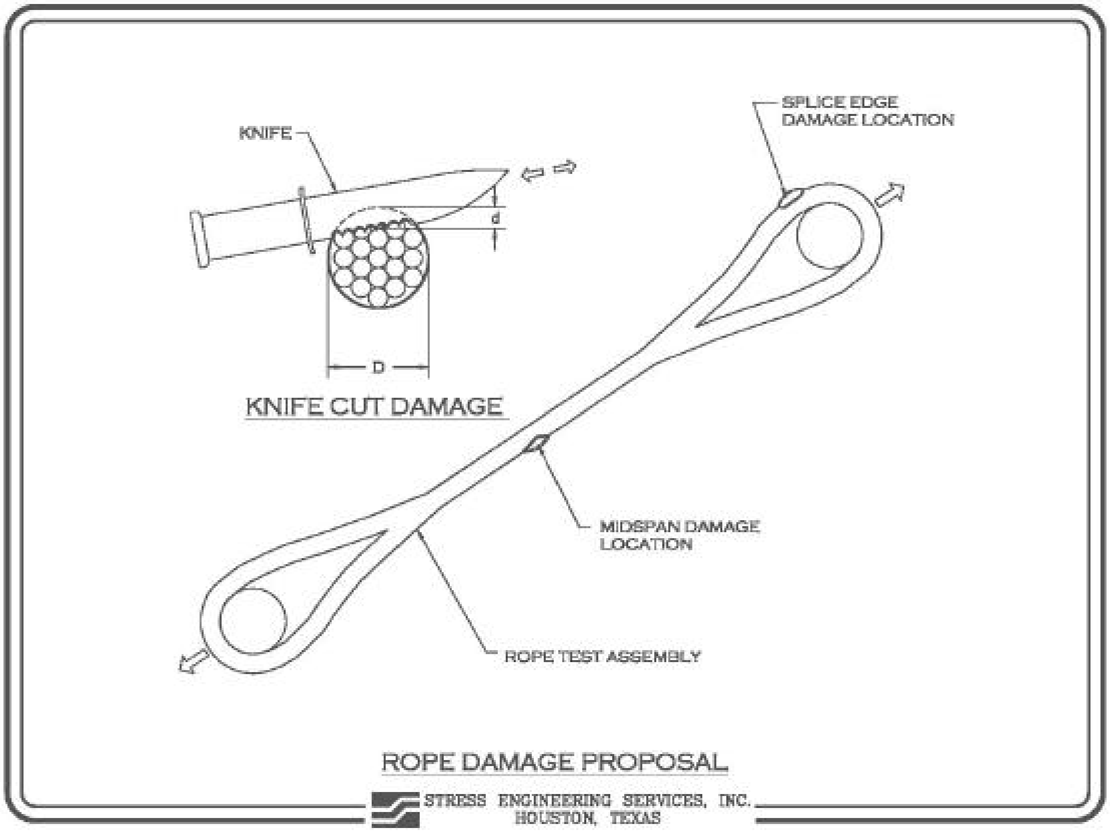

Figure 7. Sketch of knife cut on rope test assembly.

Figure 8. Photograph of using a knife to cut rope assembly.

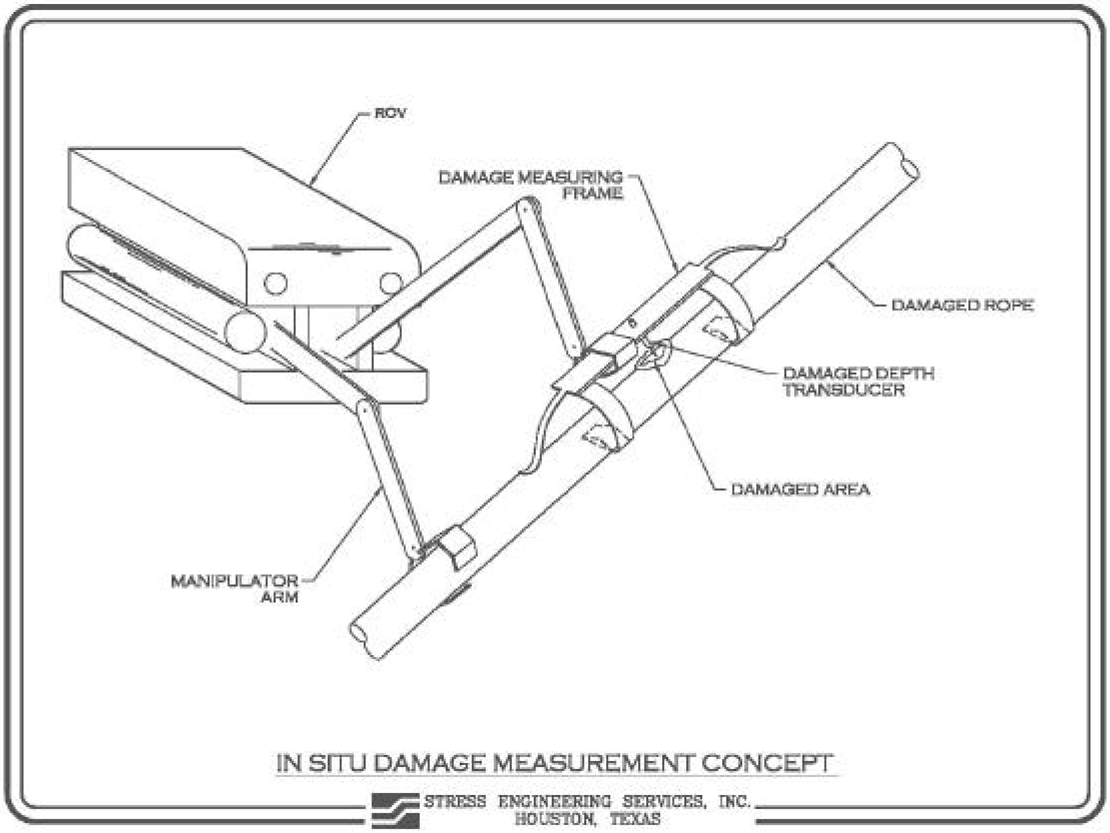

Figure 9. Concept of ROV-supported tool for damaged rope measurement in situ.