Appendix A

Reference List From:

Fatigue Model of Aramid and Polyester Lines

By:

Tension Technology International, Inc.

For:

Naval Civil Engineering Laboratory

Contract N62474-87-C-3073

Circa 1988

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Appendix B

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A thesis submitted for the degree of Doctor of Philosophy

By:

Cesar Jose Moraes Del Vecchio

For:

Department of Engineering

University of Reading

June 1992

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Appendix C

Trip Reports From The Following Technical Visits:

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

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September 2000 & May 2001

APPENDIX C:
TECHNICAL VISITS TO ASSESS STATE OF ART

Introduction

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

Trip To UK September 23-29

As part of this project, Dr. Ray Ayers of SES and Dr. Eric Williamson of the University of Texas visited three locations in thee UK to determine recent advances in the state of art of polyester rope technology, including damaged rope mechanics.

***Trip Objectives*:**

The objectives of the trip were to:

1. Give Dr. Eric Williamson Civil Engineering Professor, University of Texas an orientation in Deepwater Fiber Mooring Technology.
2. Attend a Seminar on Advanced Fiber Rope Technology Theory, Practice and Applications for Offshore Systems at Preston in the UK.

3. Discuss rope design and splice design as they affect damaged rope characteristics with Marlow Ropes.
4. Review damaged rope test results from the BP project with Dr. Neil Casey of the National Engineering Laboratory (NEL). The MMS has purchased data from this project.

Tension Technology International Advanced Rope Design Seminar: September 25 and 26

Presenters: Nick O`Hear, Alan Ractliffe, Chris Leech, Steve Banfield, all of TTI

Major Learnings:

Details of the course are contained in the seminar documentation obtained by Ayers and Williamson (ref). Of a summary basis, following are learnings:

1. Learned the overall state of art based on TTI Presentations.
2. Received an orientation and overview of the computer program "Gen-rope".
3. Learned traditional fiber rope-modeling methods.
4. Learned that Opti-Moor does not currently handle non-symmetrical rope cross-sectional designs, thus, in its current form would not be useful for analyzing rope damage that is not symmetrical. Learned that Gen-rope is being upgraded under UK funding and may not be available to the MMS in the future. This should be evaluated further by the MMS, because Gen-rope was initially developed with NCEL (U.S. Government) funds.

Conclusions:

1. TTI has years of experience with fiber ropes and they tend to rely heavily on these past accomplishments. (O`hear, Flory, & Ratliff)

2. TTI has made many unusual findings that run counter to engineering intuition. We need to more fully evaluate these discoveries to build and enhance a fundamental engineering knowledge base.

Visit to Marlow Ropes: September 27

Ayers and Williamson visited Marlow Ropes, Ltd., a major supplier of deepwater fiber moorings for Petrobras.

Participants: Chris Johnson, Chris Berryman, Neil Schulz of Marlow, Ayers and Williamson.

Learnings:

1. Marlow is still iterating on torque-matched rope design for MODU applications (9/27/00). They expect results within a month or so. Their prototype did achieve balance, but did not achieve high strength efficiency. Their second prototype is under test.
2. Marlow has developed a new splice for "Superline rope, which is the one used for Deepwater FPS applications. This splice is created by overlapping sub-rope pairs at the splice point around the eye.
3. "Superline" (torque-balanced) rope cannot be used with MODUs, if it is desired to combine the fiber rope use with 6-strand wire rope, which is not torque-balanced.
4. Drillers won't use torque-balanced wire rope because it is easily damaged and is very stiff in handling.
5. Marlow has developed a "particle screen" to filter out particles from reaching the rope core. Particles in the rope core increase rope damage during fatigue, and reduces the residual strength of the rope. Petrobras issued a specification to rope manufacturers requiring a 20-micron filter. The filter cloth is a tape wrap, and overlaps for best continuity, even around splices.

6. Marlow believes that damage is either minor, which involves the jacket only, or major, which involves a complete rope severing. They see no in between.

Conclusions:

1. We need to harmonize the BP/SES/NEL damaged rope work (which the MMS is buying) with the first application by BP on the drilling vessel "Ocean Confidence".
2. We need to consider "torque-balanced" polyester rope for MODUs that are equipped to handle six-strand wire rope, and Superline for FPS (not using wire rope) applications.
3. The incorporation of a filter in the rope design under the outer jacket will likely be standard for all polyester ropes.
4. All future Superline ropes will have the new and improved splice design.

Visit to the National Engineering Laboratory: September 28, 2000

Participants: Dr. Neil Casey, NEL, John Hooker, Marlow Ropes, Ayers and Williamson

Learnings:

1. We reviewed the damaged rope test results with Marlow Ropes, explaining to them our findings. BP had given us permission to do this.
2. We found poor repeatability in tests of various numbers of sub-ropes cut.
3. The breaking strains, in addition to breaking loads, look like a good parameter for comparison of results.

4. Jacket tightness (due to load extension) is what seems to keep the rope stiff in bending, after being loaded in tension..
5. We need to compute the radial pressure of the jacket verses the rope elongation, because this is where abnormally high pressures are imposed upon the rope core.
6. Previously strained rope (like the DeepStar rope, deployed for two years) has shown low-tension reeling and unreeling problems. This reeling/unreeling should cause difficulties in the re-bedding of the rope. Residual tension might be reduced due to prior handling loads.
7. Through discussions a key hypothesis was developed: Ropes that we bed-in in a different position from the first bedding-in might exhibit lower overall residual strength. In this re-bedding yarns and sub-ropes- are forced to "nest" in a different nesting alignment than for the first bedding cycle.

Conclusions:

1. The traditional Marlow splices are not effective for damaged rope design as they are for the undamaged condition. Marlow has offered a new and improved design.
2. The jacket/core interactions could induce damage during handling.

Trip to Brazil: May 7-9, 2001

Visitors: **Jerry Williams**, CEAC, **Ray Ayers**, SES

Petrobras: **Cesar del Vecchio**, Head of Materials Technology, Inspection and Corrosion Sector (55-21-3805-6520)

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Introduction – Visit Chronology

Jerry Williams and I were picked up at the hotel by a Petrobras driver and taken to Cenpes, the Petrobras Research Laboratory on the outskirts of Rio, near the airport. At Cenpes we were met by Luis Claudio Costa, who is now in charge of polyester rope applications. Cesar del Vecchio has been promoted to a department manager, now, but keeps interested in the polyester development and applications work as his "hobby". Jerry and I talked with Luis Claudio alone for 90 minutes going down a detailed checklist of technical questions, and then Cesar and Ronaldo Rosa Rossi, Civil Engineer, joined us for two hours. At the beginning of the two hours, I showed viewgraphs of the overall MMS program, the SES work on characterizing Rope Damage, the BP damaged rope program, and then talked about the interest that the MMS has in involving Petrobras in a large scale-testing program that is complementary with the DNV program that Petrobras has joined.

Background on Petrobras Use of Polyester Moorings

For the last 5 to 6 years Petrobras has been a leader in the application of polyester ropes because they needed a small footprint mooring system that cannot be achieved by steel wire rope and chain in deep water.

Petrobras has done research on their deepwater applications in the following format: (a) PROCAP 1000 (production system capabilities in 1000 meters water depth), (b)

PROCAP 2000, and PROCAP 3000. PROCAP 3000 consisted of work in moorings, risers, flow assurance and subsea. Petrobras has determined that the water depth limit where polyester *must* be used is 3,000 meters.

Like other operators, Petrobras started with steel wire rope/chain catenary moorings, and then turned to catenary systems with polyester combinations. After 1996 they went to taut leg moorings with polyester. Most recently they are turning toward use of the DICAS system, which is intended to moor a tanker without using a turret. In the DICAS system a taut line near-single point taut-line mooring is attached where the turret would otherwise be. Then they use pull back moorings to the stern to limit rotation of the tanker with weather forces.

PETROBRAS has developed a new mooring system for production and storage tankers moored in offshore Brazil. The system is denoted DICAS (Differentiated Compliance Anchoring System), and is basically a spread mooring system with different stiffness at the bow and stern of the ship. This difference in stiffness allows the ship to weather vane partially. Due to the characteristics of this system, the design has to take into account the varying direction of the weather and the best lay-out of the production risers and mooring lines.

Concerning anchors, Petrobras installed a few suction anchors with great difficulty, then turned to Vertical Loaded Anchor (VLA) anchors (Vriehof and Bruce). Most recently Petrobras is developing a patented "torpedo" anchor that is installed by dropping it, and allowing it to penetrate the seabed under its weight and velocity. Concurrently they are developing a subsea actuating mooring connector.

Petrobras Testing Capacity

Petrobras has some capacity to test ropes at Cenpes, but the static capacity is limited to 450 tonnes (992 kips). They can do dynamic tests with maximum loads to 450 tonnes and a double-amplitude of 150 tonnes (331 kips).

Of great interest is that Petrobras has gone in partnership with CSL to build a (less than two year old) rope-testing machine at CSL. CSL is a two-hour plane flight from Rio, at the southernmost part of Brazil on the coast. The Petrobras/CSL machine has a 1500 tonne (3,307 kip) static capacity, and a limit of 1000 tonnes (2,205 kips) on dynamic. Details of the machine are included as part of the meeting notes from the CSL visit.

The important thing to us is that Petrobras has a deal with CSL on the machine that allows them 364 testing days at no charge. This deal includes the personnel to do the test, as well as the use of the machine. Petrobras has used less than sixty days so far. If Petrobras wants to test non-CSL ropes in the machine that is OK, except that the other rope-makers might not want CSL to see their test results due to competitive reasons.

Neither Petrobras nor CSL use water baths for the ropes during testing, they only soak the rope for 24 hours before testing. During testing they use a water spray system on the rope in the test machine, only for fatigue tests. CSL uses room temperature that can vary from 10 to 20 ºC on the winter and from 20 to 30 ºC on the summer.

Petrobras Response to MMS/SES Questionnaire

When SES sent out a questionnaire on damaged rope in December of 2000, Petrobras did not respond. I took time to review the questionnaire with del Vecchio, Rossi and Costa, and captured their collective responses. In summary, the Petrobras answers were consistent with those of the other oil companies.

Discussion on Current Joint Industry Projects

1. ***Durability JIP (NEL/TTI)***- We did not discuss this, since SES does not currently have access to this program. Petrobras and the MMS are members, however.
2. ***BP Rope Damage Project*** – I showed the public viewgraphs on this program and offered them the possibility of joining. Rather than make a decision on the spot, I am to e-mail them a request that they respond on joining after I return to Houston.
3. ***DNV Rope Test Program***. Petrobras has joined this program, but knows little about it. They asked the difference between the DNV and MMS programs, and I said that they were intended to be complementary. Then I showed Petrobras the tables concerning the MMS and DNV programs, and discussed that they are to be complementary. After the meeting at Cenpes, and after we visited CSL, the thought hit me that we might be able to make a deal with Petrobras such that they could join the MMS program by agreeing to do damaged rope testing on CSL ropes at CSL. This would involve no cash outlay by Petrobras. It would only use up testing days from the 360-day Petrobras allotment.

4. ***MMS/OTRC/CEAC Damaged Rope Testing*** – I showed the group the tables prepared by Skip ward that describes the MMS Rope Testing Program. I also showed a viewgraph with the five-part MMS program.

5. ***NEL/SES Rope Testing Capabilities*** – I told Petrobras that NEL has decided to scrap their 3,000 tonne (6,614 kip) test machine. I also told them that SES is beginning to test ropes up to 2,000 kips. SES has a dynamic fatigue rating on this machine of 700 kips. The machine is called the L-2000 by SES.
6. ***NEL/ND/SES Modulus JIP***-I advised Petrobras of an upcoming JIP offer to evaluate data held by NEL from the prior NEL/TTI Optimization Program and the Norsk Hydro Program. This data will be removed from confidentiality limits in July. The data can be used to develop a curve fit algorithm for rope stiffness modulus. This algorithm could be used with a mooring design program to determine the safe drilling watch circle when using polyester moorings. Until

now it is only possible to use upper and lower modulus limits, and not the actual modulus.

Technical Discussion Topics

1. ***Merit of Braided vs. Twisted Rope***- Petrobras will use either twisted or braided sub-ropes. They have a slight preference for twisted. But at this point, Petrobras has no concern for long-term fatigue damage, because their wave conditions are benign.

2. ***End Splices (best designs, state of art, standard practice***) - Petrobras has not gotten involved in the detailed design of the splice. They have left this issue to the rope manufacturer. They have found an interesting splice issue for short test samples, though. See the section below on "Marine Growth" for information.

   Petrobras developed a large socket termination to replace the eye splice, but it turned out to be too large (1.5 meters long) and heavy. There was difficulty in passing the socket over the stern roller. In developing this termination they spliced in additional rope material to enlarge the rope diameter at the splice and reduce stress concentrations. This might represent a good way to strengthen eye splices too.

3. ***Safety Factor*** – Petrobras uses a 25% factor on top of the 1.67 factor required in API 2SM. They believe that since polyester moorings are a relatively new technology (even for Petrobras), they do not want to find some unexpected technical problem (like minor installation damage, a poorly constructed splice, marine growth damage effects, problems with torsion, problems with marine finish, etc.}, that would cause them to have to fully replace 16 or 18 legs of a mooring system. If the application for a mooring would allow use of wire rope, and if the operator wanted to pay the increased cost of wire rope, a mooring system would likely be installed without inserts for future testing. Therefore there

would be no need for an additional safety factor. But since the polyester lines would likely be installed with insert sections for testing, if the future testing showed a factor of less than 1.67, the design might not be safe, and changes, including mooring line replacement, might be called for.

4. ***Damaged Rope*** - 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. 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 refer to Appendix D for details on Petrobras' damaged rope information. 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 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.

5. ***Work Wire Twisting Problems*** – Petrobras has had trouble using 6-strand wire as a work wire for installing the anchoring system. These are the same wires that are cutting the polyester. Wire that has locked in twist under low tension will form hockles and break. Petrobras is developing an HMPE rope to use as a work wire. HMPE has a similar diameter to steel, good abrasion resistance and good stiffness, but it has poor creep characteristics (30 %). Petrobras has in progress a JIP with Quintas and Quintas on this objective. It is interesting that the Q & Q

rope is being tested on the CSL/Petrobras machine, because of extreme competition between the rope manufacturers. At present Petrobras is using polyester work wires in place of six-strand, but the rope diameter is too large for a work wire.

Petrobras has also had troubles with hockling of the ground chain, when chain was installed using a six strand work wire and an unsuitable.

6. ***Rope Design - Rope design computer model*** – Petrobras sees no need for a rope design model, unless it is for damaged rope. They rely on the rope manufacturer's designs and the results of test sample testing. Cesar del Vecchio was strong in his opinion on this issue.

7. ***Torque Matched vs. Torque Neutral*** – Petrobras has had no need for torque-matched rope. They have yet to outfit a MODU with polyester rope. They use dynamically positioned vessels, and are confident in their use for the mild conditions of the Campos Basin. Further, they have concerns about forcing a drilling contractor to use a certain mooring system, and the attendant liabilities. There would have to be a need recognized by the drilling contractor before polyester moorings would be used.

8. ***Types of anchoring systems*** – Petrobras has used drag embedment anchors for over 80 % or their installations to date, all mooring system that don't have vertical loads are installed with drag embedment anchors. When vertical loads are required Petrobras uses vertically loaded anchors, suction anchors or torpedo. They struggled with the installation of suction anchors (VLA), and are developing a "torpedo" anchor that is set by a vertical drop at the desired anchor location. Further, Petrobras is starting to use the DICAS anchoring system (patented) that moors a tanker first at the normal turret location, but they use no turret. A second mooring system is applied at the stern of the vessel, and this system is a polyester

catenary, restraining movement of the vessel from the stern against forward, port, and starboard excursions.

9. ***Dropped Rope*** – Petrobras has determined that un-tensioned ropes that are dropped will exhibit a significantly lower break strength than the un-dropped rope. The severity is greater in sand than in mud, but this is not quantified. An interesting new finding is that if the rope has been previously tensioned, the soil ingress does not penetrate like it does in a previously un-tensioned rope. Petrobras has ready for testing a dropped polyester rope segment that they were using as a work wire on P40, and was dropped. I will attempt to learn of their test results. This finding will be helpful for MODU applications, where ropes can be dropped during a drilling location change.

10. ***Marine Growth*** - Petrobras had inspected and tested insert samples from P19 and P27 after one year in service. The inspection showed marine growth between the jacket and the core for the insert sample, which is always located nearest the waters surface. The P19 sample failed at 13.1% below the original average MBL. The P 27 sample failed at 5.3% above the average MBL. At first, they thought that they were seeing some deterioration in performance due to marine growth. But later they found that splices on the insert sample were not made in opposite directions around the eye, as was called for. Problems with the splice in this short sample can cause unbalance in the subrope loadings, and thus cause premature rope failure. Such is not the problem for long rope lengths. Petrobras was relieved to find that marine growth had not prematurely reduced the residual breaking strength of the rope so far. It is premature to say that this will not be a problem in the future, because marine growth between the cover and the core can potentially cause a long-term damage.

Petrobras has decided *not* to use polyester rope within the first 100 meters of the sea surface, where marine growth activity is greatest. It looks like marine growth can be a problem over time, but it may not penetrate the core. This is a good reason to start with a healthy safety factor, as Petrobras chose.

11. ***Mooring System Design*** – Petrobras uses a number of contractors for mooring design/analysis:
    a. Noble Denton DMOOR
    b. SBM
    c. IMODCO
    d. Ariane BV
    e. Petrobras Dynasim (a Cenpes development in partnership with USP-University of São Paulo)

12. ***Rope Handling Damage Column Buckling*** - I described a potential problem with the effect of reeling and unreeling rope between tensioning events like occurs when MODUs change location. They had not seen this effect.

13. ***In-Service Monitoring*** – Petrobras has a program to monitor rope life by removing and testing 15-meter inserts that are placed in each leg of a mooring. They recover rope insert samples at intervals of 1, 2.5,, 7.5, 12.5, 17.5 years, and one entire leg at intervals of 5, 10 and 15 years. They perform residual breaking strength tests after inspecting the samples for damage and any other effects that might reduce performance. We saw the insert sample that was recently removed from P 27 after 2.5 years (at CSL after the visit to Petrobras). Please refer to the report on the visit to CSL for more detailed results of the initial inspection that we made. Two and one-half year samples have now been recovered from P 19, P 26 and P 27.

14. ***Marine Finish Life*** - Petrobras showed no knowledge of the technology of marine finishes. They observed how brand new test rope samples, when placed in water, caused the water to be "milky". They projected that once the rope had been bedded in, the marine finish stayed in the rope.

15. ***Theoretical Rope Strength vs. Splice Strength*** – Petrobras was not concerned about this distinction. I did not push the discussion on this point.

Table 1

POLYESTER ROPES IN PETROBRAS PROJECTS (5/01)

Unit	WD (m)	Supplier	MBL (tonne)	Date	Type	Field	Type	Anchor
P-IX	230	Phylistran	500	1995	FPS	Corvina	Cat.	DE
P-XXII	115	MRL	500	1995	FPS	Moréia	Cat.	DE
FPSO-II	1420	MRL/CSL	711	1998	FPSO	Marlim South	Cat.	DE
FPSO-II	1200	MRL/CSL	711	1999	FPSO	Marlim South	Taut	VLA
P-34	835	MRL	711	1997	FPSO	Barracuda	Cat.	DE
P-19	770	MRL	711	1997	FPS	Marlim	Taut.	SP
IMO-1	420	CSL	494	1997	Buoy	Bijupirá-Salema	Cat.	DE
P-26	990	MRL	711	1997	FPS	Marlim	Taut	SP
IMO-3	830	CSL	494	1999	Buoy	Marlim	Cat.	DE
P-27	530	CSL	630	1998	FPS	Marlim	Taut.	VLA
AVARÉ	550	CSL/MRL	490/630	1998	SSO	Marimbá Leste	DICAS	DE
P-47	850	CSL	711	1999	FSO	Roncador	Cat.	DE
P-36	1360	(1)	1000	2000	FPS	Roncador	Taut	VLA
Espadarte	800	CSL	1000	2000	FPSO	Espadarte	Cat.	DE
P-38	1080	MRL	711	2000	FSO	Marlim South	Cat.	DE
P-40>36	**1360**	**CSL**	**1000**	**(P-36)**	**FPS**	**(Roncador)**	**Taut**	**VLA**
MODU	750	CSL	630	2000	MODU	Bijupirdá-Sal.	Taut	VLA
P-43	800	(2)	1000(3)	2003	FPSO	Barracuda	DICAS	VLA
P-48	1000	(2)	1000(3)	2003	FPSO	Caratinga	DICAS	VLA

Notes:

1. Four different suppliers: MRL, CSL, Q&Q and Le Lys.
2. Not defined yet.
3. Estimated value.
3. Lines with polyester.
4. Poly. connected with combined
5. shackles an thimbles

Buoy: CALM Loading Buoy
DE: Drag Embedment Anchor
VLA: Vertical Loaded Anchor
MRL: Marlow Ropes
MBL: Minimum Break Load
CSL: Cordoada São Leopoldo
Q&Q: Quintas & Quintas

Trip to CSL: May 8, 2001

Visitors: **Jerry Williams**, CEAC, **Luis Claudio Costa**, Petrobras, **Ray Ayers**, SES

CSL: **Felipe Andrian Techeira**, Technical Department (host) (technico@CSLropes.com.br)

Leandro Haach, Quality Control (briefly met) (haach@cslropes.com.br)

Jose (J.T.) Abu-Jamra. President (Beard) (cslropes@pro.via-rs.com.br}

Ivan De Pellegrin, Industrial Director (absent) (cslropes@pro.via-rs.com.br

Topics:

1. CSL Rope Design
2. Splice Design
3. Test Machine
4. Damaged Rope
5. Miscellaneous

CSL Rope Design

CSL uses 7 or 9 separate parallel sub-ropes, with a double braided jacket. Sub-ropes have 12 elements, braided (rather than twisted) with a long lay length. Rope are made with 1,000, 800, 710 and 630 tonne minimum breaking load (MBL). The strands used to make the 12 element braid are composed of several 190 end yarns, i.e., 5 yarns for the 1000 tonne rope. The polyester fibers are supplied by Allied (Honeywell) with SeaGuard marine finish (1W81). See CSL UltraSeven Brochure. See CSL Reference List. The jacket does not have a marine coating. There is a 20-micron filter below the jacket, but does not continue into the splice region.

CSL ships ropes on reels by truck. The reels are approx. 3.2 m in diameter and 4.6 meters in length. Amounts of rope to be stored per reel are:

- 710 tone = 1,300 m
- 1,000 tone = 800 m
- 630 tone = 1,500 m

CSL does not make a torque-matched rope.

Splice Design

CSL splices each sub-rope back to itself in an "S" shape. Like Marlow, they taper the splice over 2 meters by cutting away fiber. Figure 1 shows S shape test link. They peel back the jacket for splicing, and curve the core around the eye from one direction only. They have no filter cloth in the eye, but use three layers of padding to cover the eye below the polyurethane (Hyperlast) jacket. They use a thimble with a flat drum and attempt to get 4 layers on the first layer and 3 on the second, or in the case of 9 sub-ropes, 5 and 4. A simi-circular thimble drum was used first, but this forced six sub-ropes to compress against the bottom sub-rope. See Figure 2 for sketches of thimble and rope lay-up. A short section of jacket is used at back of eye as extra padding. Louis Claudio has seen sub-rope compression buckling at the back of the eye on the inner sub-rope. Splice length at the throat is 2.1 m.

The DNV specification calls for D/d between 2.5 and 6.0, and CSL uses this criterion.

Test Machine:

1. Max Tensile = 15 MN (3,307 kips)
2. Fatigue Tensile Strength = 10 MN (2,205 kips
3. Prototype Rope Length = 10m (32.8 ft) to 16 m (52.5 ft)
4. Stroke = 2.5 meters (8.2 ft) max.

5. Dynamic = 6 cyc/min = 10 sec. period (polyester)
6. For 710 tonne (1,565 kip) rope the cyclic stroke between 20 and 40 % load is 120 mm for 15 m sample length, measured at 2% load. This is a 3.3-inch double amplitude for dynamics.
7. For a 1000 tone rope the double amplitude is 110 mm (4.33 inches double amplitude)
8. CSL has 4 pistons max with 400 mm (15.75-inch) internal diameter, 300 bars pressure (4351 psi) and 325 HP.
9. CSL sprays cold water (10-12 deg C) on the rope while testing in the machine (no bath), but they soak the rope for 24 hours in bath (outside test machine) before testing. See CSL brochure for pictures of testing machine.
10. The control software allows 8 different cycle amplitudes, but does not do stochastic loadings.

Damaged Rope

On this date an insert rope from P 27 arrived to CSL from Petrobras. The insert rope had been in service for 2 ½ years, and was now to be tested for residual break strength.

The rope had a dirty outer cover, and smelled like dead fish. There was marine growth like barnacles between the jacket and the core, but probably not deeper. The plastic coating for the splice taper was broken, and the covers were showing as loose, and it was not difficult to see the core, which was in good shape. See William's photos. CSL indicates that they now use Hyperlast as a protective rather than the plastic used on P-27.

The insert was in place at the top of the mooring leg, so the marine growth might be expected there.

There was another rope to be tested from P40, which was being used as a work line, rather than a mooring, to avoid six-strand wire rope twisting problems. This rope had had tension on it, and then was dropped. Visual inspection showed discoloration on the cover, but the rope core looked fine. This rope was to be break-tested to determine if the residual break strength had been reduced. Petrobras believes that previously un-tensioned rope that has been dropped will be damaged by particle ingress during dropping. But if the rope has been previously tensioned, there is no appreciable effect, other than to the cover. See William's photos.

Miscellaneous

Shell has gotten Lowery Brothers in New Orleans to do some rope testing for them. For six strand work wire you need a swivel. With polyester, Petrobras does not consider that a swivel is needed since the polyester rope can accommodate the rotation.

ROPE DESIGNS

Information discovered from Internet and Brochures:

Large Deepwater Mooring Ropes of Polyester:

1. Quintas and Quintas - 7 subropes parallel lay with a braided jacket
2. Scanrope – Torque Matched Wire Rope design with 12 or 16 subropes or 12 Strand Braided subropes with braided jacket
3. Le Lis – Multiple Parallel subropes (more than 7) that look twisted
4. Marlow – 28 or more twisted 3 part subropes with braided jacket
5. Whitehill – 7 subropes parallel lay with braided jacket
6. CSL – 7 braided parallel subropes with a braided jacket

Appendix D

Detailed Questions Asked and Answers Given Following Our Technical Visit to Petrobras:

Petrobras Damaged Rope Experience:

Follow-Up Questions and Their Responses

By:

Reported By:

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

Staff Consultant

Stress Engineering Services, Inc.

May 2001

Appendix D

Detailed Questions Asked and Answers Given Following Our Technical Visit to Petrobras

Introduction

In reviewing my notes and my memory of our discussions I find that I should have asked some additional questions, specifically concerning rope damage.

Questions and Answers

Here are the questions:

Q1: Of the 7 cases of "cutting damage" that you cited how severe was the damage? Were the ropes fully cut or partly cut?

A1: Two ropes were partly cut and five were fully cut.

Q2: Did you have to replace the entire mooring leg?

A2: On the five ropes that were fully cut we replaced the entire length of polyester rope.

Q3: You told us about line 15 on P 26 that was partly cut, but what about the rest?

A3: This line remained in operation for two years. During these two years we reduced the load on this line until we could assess its loss of strength.

Q4: We understand that the cuts were caused by wire ropes used in installing the anchors?

A4: Not necessary by the wire ropes used in installing anchors. Two ropes were cut during a mooring stiffness test. An AHV was pulling the ship when the tow cable broke and passed over the polyester ropes.

Another one was cut by the wire rope that was being used during a riser Pull-in operation. The winch failed and the wire rope was abandoned by hanging it on stern of the ship. During the night the current and the wind changed direction and because the mooring system acts as a turret, the ship moved and the wire rope passed over the polyester rope, cutting it. A boat that was collecting seismic data cut another rope. The boat had equipment hanged off by a wire rope, and passed over two polyester ropes. For the other three polyester ropes, think that they were cut by a wire rope during an anchor installation, but we aren't sure about it.

Q5: Were the cuts made after mooring line installation , where the rope was fully bedded in, or was it during installation?

A5: All ropes were fully bedded in.

Q6: Are there any examples of other damage to the rope body or to the splice?

A6: Yes, we had ropes damaged on the body and on the splice, mainly on the splice.

Q7: We heard about surface damage to the splice coverings, and we believe that you are not too concerned about that because you are using a large safety factor (SF = 1.25 x 1.67 = 2.09). Is this right?

A6: Not only because of the large safety factor, but because the damage was restricted to the cover alone. I'll try to send you some pictures showing some of their damages.

Q8: What is your best guess of the total number of damaged ropes you have found, including the 7 that you told us about? Were some of the ropes discarded during the installation phase, or were they re-spliced, removing the damaged section?

A8: During installation we had only one rope damaged. It was damage in the spool area during its passage over the stern roller. This rope was cut and re-spliced.

Q9: How many conditions of damage were discovered by ROV inspection, how many were found by a "fully cut hanging rope", and how many damage cases were seen on deck during installation?

A9: Two instance of rope damage were discovered by ROV inspection. The two ropes were partly cut by wire rope. We had already a lot of small damages on the cover of the rope but that didn't compromise their strength. As I told before, only on one rope was it necessary to cut its end and re-splice.

Q10: Since you have seen marine growth in the recovered samples, just below the jacket, what effect do you think that marine growth will have on the residual breaking strength for samples you will recover and test in future years? You told us that currently you will not use polyester in the first 100 meters of water near the surface.

A10: The marine growth that was found between the rope cover and the core had a hard "skin" like a shell. I think that a hard marine growth could cut the core filaments due to movement between the core and the cover. The habitat of the marine growth is in the first 100m, that is the reason that we are installing our polyester ropes bellow 100m.

Q11: Other than recovering samples and mooring legs every 2.5 years, how often, if any, do you use the ROV to monitor the damage conditions of installed mooring legs? Do you have a specification on this?

A11: We use the ROV to monitor the damage conditions of installed mooring legs just after the floater hook up, and then every 2.5 years.