PURCHASED REPORT BY MMS:

FINAL REPORT TO BP EXPLORATION FOR DETERMINING INTERIM CRITERIA FOR REPLACING DAMAGED POLYESTER MOORING ROPE

Prepared For
BP America, Inc.
Upstream Technology Group
Deepwater Technology Unit

December 13, 2001

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The MMS will be free to use the purchased data for the normal conduct of their business. Normal confidentiality restrictions will apply for 2 years from the purchase date. The MMS is encouraged to request from BP disclosure of data to others as special cases arise. BP, as sponsor of the work, retains the right to use the data as they see fit, without approval of the MMS or other data purchasers.

The rope manufacturer, Marlow Ropes, considers details of their rope and splice designs as proprietary product information. This part of the report should not be provided to their competitors for any reason. Please contact Dave Petruska of BP if there are any questions.

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

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PN 6941-RRA

Prepared For
BP America, Inc.
Upstream Technology Group
Deepwater Technology Unit

By

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

Reviewed by Matthew J. Stahl D. Eng., P.E.
Approved by Joe R. Fowler, Ph.D., P.E.

December 13, 2001

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13800 Westfair East Drive
Houston, Texas 77041

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FINAL REPORT TO BP FOR DETERMINING INTERIM CRITERIA FOR REPLACING DAMAGED POLYESTER MOORING ROPE

Summary

The BP Upstream Technology Group, first represented by Uel Taggart, Deepwater Consultant, and later represented by David Petruska, Floating Systems Engineer, requested that Stress Engineering Services (SES) perform tests and analyses to develop an interim criteria for replacing damaged polyester mooring rope. BP and SES recognized that the Offshore Technology Research Center (OTRC) is developing a more thorough, longer-term project on the same subject, funded in part by the Minerals Management Service (MMS), and that a JIP is in progress by DNV on damaged rope, but neither of these projects was expected to have results before BP would be accomplishing the installation of a polyester mooring system on the Ocean Confidence (2001). BP was concerned that they would have Gulf of Mexico applications for polyester rope taut line mooring systems before a criterion would be available. Toward this end, BP asked SES to perform a limited number of tests of damaged smaller-scale rope in order to develop a criterion that can be used with confidence prior to the availability of the OTRC and DNV efforts described above.

SES initially proposed that we, with testing assistance from the National Engineering Laboratory in the UK (NEL), collaborate to provide BP with the interim criteria they need. During the testing NEL incurred damage to their test machine, and final tests were run in a test fixture converted for rope testing at Stress in Houston.

After this project was underway, with BP's agreement, the MMS purchased the data included in this final report as input for their ongoing work on polyester ropes.

Also, the MMS made available to BP the work in progress they were doing on characterizing polyester rope mooring installation damage[1]. The objective of the MMS-sponsored project was 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 served as input for the studies reported herein. The MMS study was primarily a "paper study", but it included some limited qualitative damage experiments with two types of 450,000 lb. ropes, recovered from the

DeepStar Test Mooring[5]. The MMS study and this BP study became synergistic because SES was performing both projects concurrently, and we believe that both sponsors benefited from the synergies.

A prior study by SES[2] for DeepStar, evaluating deepwater polyester rope mooring technology, gave us an excellent background for conducting this study. In fact, results from the API 2SM committee work[3] in which SES was a participant, and the DeepStar study led to the SES proposal to BP to perform this work.

An excellent summary of polyester rope technology in general is contained in the report[4] “Deployment Readiness Plan for Deepwater Polyester Moorings for FPS”, September 2001 was prepared by the Upstream Technology Group, Deepwater Technology Unit of BP America. SES was a major contributor to the report.

Project Objectives

The initial objectives of this project were to:

1. Characterize the form of most likely rope damage and perform a limited number of tests (9 damaged rope tests) on samples of 400 kip Marlow Superline rope, a 1/4th scale model of a 1500 kip (700 tone) prototype rope. These tests would serve as a basis for developing an interim damaged rope replacement criteria.

2. Develop an interim damaged rope replacement criteria for BP use until the OTRC/DNV projects were complete and available to the industry.

The project plan changed when Marlow decided to provide a new splice design for their rope after we had tested 6 samples with their traditional splice design. Marlow took a company decision to change their splice design for all large deepwater mooring ropes, and thus, the spliced design that we were testing was then obsolete, and (we were told) would not be available in the future.

Manufacturer's Properties of Two Kinds of Rope Tested

(Rope Body is the Same)

ROPE WITH TRADITIONAL SPLICE		ROPE WITH NEW SPLICE
Property	***Value***	***Value***
Rope Diameter	2.686 in	2.686 in
44000 dtex Yarn Breaking Strength	7089 lb	7089 lb
3x9x44000 dtex Subrope Break Strength	17300 lb	17300 lb
(assuming 100% splice efficiency)		
Theoretical Rope Strength (28 subropes)	484,000 lb	484,000 lb
(excluding cover)		
Cover Theoretical Strength	60,200 lb	58,400 lb
Effective Cover Strength at 65%	39,000 lb	37,960 lb
Effective Rope Strength at 0.81 w/ cover*	**424,000 lb**	-
Effective Rope Strength at 0.81 w/o cover*	392,000 lb	-
Effective Rope Strength at 0.90 w/ cover*	-	**470,000 lb**
Effective Rope Strength at 0.90 w/o cover*	-	436,000 lb

*0.81 and 0.90 are assumed splice efficiencies

Conclusions Regarding Discard Criteria For Damaged Rope

API RP 2SM[3] states that "a damage assessment should be performed and recorded immediately after damage to the rope is detected." It states additionally "specific guidelines for …an evaluation have not been developed." Further, 2SM states that if the evaluation indicates that "the rope fails to retain 90% of the required design strength of the mooring rope, the rope should be replaced immediately."

Our recommendations from testing and analysis suggest the following criteria be used by BP (with agreement from the MMS) until further testing by DNV and the MMS has been completed and evaluated:

1. For the Marlow Superline Rope with the "New" splice, which we have tested, any main body damage to the (28 – 32) subropes below the outer jacket should require immediate discard. This recommendation is made because we have performed tests with as little 6% of the cross sectional area cut, and found a 16 % variation in residual breaking strength, and the lowest breaking strength was 29% lower than what one would obtain by assuming that a 6% area loss causes a 6% loss in breaking strength. This

recommendation applies only for the Marlow Superline rope with the "new" splice design. All Marlow Rope test results showed a large amount of scatter. In the tests of the traditional spliced samples the scatter is likely due to the arbitrary way subropes are joined to each other. In the tests of the new spliced samples, the scatter is believed due to the variability in how a constant depth knife cut will affect different subropes, as they are randomly located under the jacket, and the variability in the torsional alignment of the rope.

2. BP has considered the Whitehill rope as an alternative to the Marlow rope used on the Ocean Confidence Project. For the Whitehill Rope, a relatively new design with seven parallel subropes, and a rope which we have NOT tested under damaged conditions, we recommend that, for the time being, any partial damage to one of the seven subropes under the outer jacket should be considered as total damage to that subrope. Also, until further testing is done, partial or total damage to one subrope would result in having 6 subropes holding the load. Since the six are separately spliced, they would act together as an undamaged subrope with 6/7 of the total rope strength. The difference in splice design makes this recommendation different for Whitehill. Further testing is underway with DNV and planned by the MMS that will likely result in more detailed and less conservative advice for the Whitehill rope. Testing of identical samples, if the need arises, will show how well damage is accommodated by the Whitehill splice design. Our interim recommendation means that 1/7, or 14.3% of the rope residual breaking strength would be conservatively assumed lost for one subrope being partially to totally damaged.

3. For rope designs by other manufacturers, the following recommendations should be considered:

   a. Most commercially available deepwater mooring ropes consist of anywhere between 7 and 32 parallel subropes enclosed in an outer jacket. If each individual subrope is spliced to itself, like the Whitehill, use the recommendations given for Whitehill in (2).

   b. If the subropes are doubly spliced to mating subropes in pairs, like the Marlow, or if the subropes are spliced to arbitrary subropes without matching (like in the old Marlow splice), use the recommendations in (1) above.

4. If damage occurs in the splice region, do not use the rope. If approved, it could be re-spliced. Note that damage can be severe enough along the rope length that re-splicing would be impractical, because equal load sharing could not be assured. The above recommendations are made assuming that inspection of the rope damage is possible either on deck prior to installation, with ROV inspection in situ, or by recovering the rope segment for on-deck inspection.

5. One should use the general recommendations in API RP 2SM[3] Sections 9.4 and 9.5 for rope retirement criteria and maintenance procedures, except that we are concerned about subsections 9.4.1.3 and 9.4.1.4. These two subsections allow use of a damaged line as long as 90% of the design strength (9.4.1.3), or 90% of the residual breaking strength (9.4.1.4) is maintained. One concern is that if 10% of the cross section is found by inspection to be damaged, it is possible for the actual retained breaking strength to be less than 90%, because of the specifics of the way different splice designs resist damage in the rope body. Another concern is that in recommendation 2 above, one partially damaged subrope of 7 total subropes will result in a loss of 14.3 % of the residual breaking strength, 85.7% retained breaking strength, but the rope would otherwise be safe to use if the mooring pre-tensions were adjusted to accommodate the 6- rather than 7-subrope rope.

6. Of course, differences between these recommendations and those of API RP 2SM[3] should be negotiated with the MMS prior to BP making a decision on damaged rope retirement based on these recommendations.

Recommendations for Further Work

We recommend that the MMS Damaged Rope Project (in planning) and DNV Damaged Rope Project (underway) be finished in order to develop a recommended practice for damaged rope.

Project Tasks

The project was accomplished by completing the following tasks, except that two sets of rope splice designs were tested instead of one.

1. Develop a detailed project plan based on the proposal.

2. Characterize the form and magnitude of external rope damage to be tested, and develop a preliminary test plan, including loadings and measurements. Use advice/feedback from experts external to SES/ NEL in this task.

3. Procure the rope samples. The samples were of the DeepStar Polyester Rope Test Mooring Design[5] (a test mooring installed and recovered from near the Shell Auger TLP). The test samples had a nominal breaking strength of 400 kips. A "full scale" rope might have a breaking strength from 1000 to 1500 kips.

4. Test the damaged rope samples by first applying the damage, second subjecting the rope sample to a set of cyclic loadings, and then performing residual breaking strength tests. Although a preliminary test plan was developed, decisions on how to damage each new sample were made only after evaluating the results of the preceding test. In this way we were able to extract the maximum amount of information by using the minimum number of tests, and thus, minimize the cost of this program.

5. Develop a draft document for establishing damaged rope criteria in parallel with the testing effort, so that a clear results focus is maintained as decisions are made on what type of damage to test next.

6. Conduct a one-day workshop with participants chosen by BP to evaluate/validate the draft recommendations. *This was accomplished by participating in a Polyester Rope Technology Peer Review at BP's Houston offices (including teleconference with UK participants) on October 3, 2001*. Interact with the MMS as requested by BP. *This was accomplished by allowing the MMS to learn from our work in progress and purchase the data in this final report.*

7. Deliver to BP a final report describing the criteria and recommending methods to assess damage in the field, and determine the character and severity of rope damage that might be encountered in a typical installation project. *This report fulfills this requirement.*

Project Staff

The project staff from SES includes Ray Ayers, Ph.D., P.E., project manager, and Mr. Brett Hormberg, who performed the detailed testing at SES. Dr. Neil Casey was the test program manager for tests conducted at NEL, and he was assisted in testing by Mr. Bob Belshaw.

Reporting Format

We have divided the remainder of this report in three parts:

A. Original tests at National Engineering Laboratory (NEL) with rope samples having the traditional splice.

B. Additional tests at NEL, and then tests at Stress Engineering Services (SES), all using the new splice design.

C. A discussion of splice effects on damaged rope residual breaking strength.

PART A: NEL TESTS WITH TRADITIONAL SPLICE DESIGN

Summary

The purpose of the work described in this report, is to obtain some base data on the strength loss associated with the introduction of simulated mechanical damage into polyester rope, with a view to generating some provisional discard information for BP to use.

Rope samples were subjected to simulated storm conditions using sinusoidal loading before being subjected to retained break strength tests. Some of the ropes had purposefully induced damage and others did not. Nine Marlow polyester Superline rope samples, with "traditional" splices, were originally delivered to NEL for testing. The rope from which the test samples were made consisted of 28 subropes and had a theoretical break strength, calculated before testing, of 424.0 kips (1 886 kN).

For this first series of tests the damage was introduced by "surgically" cutting individual subropes. After six tests were conducted it became apparent that, as a result of the splicing design, the induced damage had a tendency to "migrate" to the splices and influence the break test by reducing the efficiency of the splices. As a possible consequence of this there does not appear to be an obvious correlation between either loss in residual strength or extension to break with induced damage.

As a result of this significant finding, Marlow Ropes Limited took the decision to change their traditional splice design (for large mooring ropes only) to what we call in this report the "new" splice design. The final test series (MQIQ) produced results for this new splice design. Although the ropes were of the same construction as the original samples the new splices raised the tested break strength from 421.5 to 461.0 kips, a 9.4% improvement. For the second series of tests the damage was introduced by cutting the rope to a predetermined depth using a knife slice.

In addition to the samples with the new splices, Marlow (at the request of Stress Engineering Services) also delivered two DeepStar[5] rope samples that were previously in service in a Gulf of Mexico test. These two tests would have formed the basis of a small extension to the study that

was never performed, however, one of the DeepStar ropes was inadvertently used for a rope handling test (described in Appendix AA), which was added to the test program.

Part way through the second series of tests the 6,740 kip (30 MN) test machine (after suffering a major failure) was permanently taken out of service, which meant that the test program was terminated at NEL. Stress Engineering Services completed the work and Appendix AA provided sufficient detail to continue the testing at SES.

Introduction

The objective of the study reported here was to provide some provisional information on damaged rope discard criteria. This was to be achieved by evaluating the effect of externally induced mechanical damage upon retained strength of polyester rope after the rope sample is subjected to simulated storm runs. The study originally called for nine ropes to be tested. After six tests were conducted Marlow Ropes revised the splice design, therefore new samples were supplied. However, part way through the revised test program the NEL 6,740 kip (30 MN) machine (after suffering a major failure) was permanently taken out of service, which meant that the test program could not be completed at NEL.

This part of the report provides a description of the test equipment, procedures and results of the study for the traditional splice

Conclusions From Part A Tests

Conclusions from tests of rope samples with the traditional splice are as follows:

1. Damage at mid-span can propagate into the splice region. Our rope samples were about 33 feet long. Longer samples might show different results, but we believe that the effect would be the same, but the time to propagate will be longer.
2. The residual load capacity of a damaged rope is not just a function of the per cent area cut. It is also a function of the way the splice design transfers loads under damaged conditions.
3. The key to determining damaged rope load-carrying capability is to understand force transfer in the splice as affected by induced damage.
4. Damage to the Marlow Rope with a traditional splice results in complicated force paths in the splice region, which produces variability in residual breaking strength test results.

Rope Samples

The original program called for nine tests to be conducted. Nine Marlow polyester Superline rope samples, with Marlow traditional splices, were therefore delivered to NEL for testing. The ropes were made up of 28 subropes and had calculated break strength of 424.0 kips.

During the course of the work, after 6 tests had been run, it became clear that, as a result of the splicing, the damage (although induced at mid length) effectively had a tendency to migrate to the splices and influence the break test by reducing the splice efficiency.

To overcome the problem Marlow supplied new samples with revised splices intended to minimize the effect of 'damage migration'. Although the ropes were of the same construction as the original samples the improved splices raised the theoretical break strength from 424.0 to 470 kips.

NEL 6,740 kip (30 MN) Test Machine

Operation of the 6,740 kip test machine is servo-hydraulic, normally through eight hydraulic actuators providing for a maximum static load capacity of 6,740 kips and a cyclic load capability of 4,496 kips. The static load capability is provided by a 119 gpm supply of oil at 4786 psi, whereas the cyclic load capability is provided by an oil supply of 792 gpm at 3046 psi. The tension end of the machine is 59 foot long, and a working stroke of up to 16.4 ft can be applied. Crosshead movement is monitored by four non-contacting temposonic displacement transducers positioned at the four corners of the moving crosshead.

The forces generated by the 6,740 kip test machine are measured and controlled by a balanced pressure system integral with the actuators that drive the crosshead. The standard force measurement system, which is based on differential pressure, has recently been supplemented by a 4,496 kip strain-gauged load cell. This load cell is attached directly to the moving crosshead and the force output from this load cell has been used to generate the results presented in this report.

In order to meet the required combinations of load range and cyclic frequency provided in the test matrix, the machine was reconfigured to maximize the velocity of the moving crosshead. This involved disconnecting the four inner load actuators from the moving crosshead and hydraulically isolating them. The effect of this operation was to reduce the maximum cyclic load capacity of the machine from 4,496 kips to 2248 kips but at the same time increase the maximum crosshead velocity from 2 to 4 inches/sec.

A requirement of the project was to test the ropes (with the exception of the break tests) fully immersed in ordinary tap water. In order to achieve this a flexible tank was produced which fitted inside the machine. The arrangement was such that both of the machine's clevis assemblies, to which the rope was attached, were contained within the tank. This meant that the entire rope sample was surrounded by water.

Test Procedures

Table A-1 below provides the cyclic loading test matrix that was agreed between NEL and SES at the start of the study. For each rope the test matrix was conducted twice. After that the ropes were subject to break testing. Test sequences 2 and 4 are simulated windward and leeward hurricanes respectively. Test sequences 1 and 3 were periods of relative calm to allow the rope to allow bedding in and recovery.

Table A-1
Rope Test Matrix

Test sequence	*Mean load (%Nominal strength)*	*Load amplitude (%Nominal strength)*	*Load range (%Nominal strength)*	*Cyclic period (Seconds)*	*Number of cycles*
1	**20**	**10**	**20**	**10**	**3000**
2	**40**	**15**	**30**	**10**	**2000**
3	**20**	**10**	**20**	**10**	**3000**
4	**15**	**10**	**20**	**10**	**2000**

Upon receipt of the test samples they were each given a unique test mark. These unique test marks have been used throughout the report: MQDE series for the ropes with traditional splices, MQIQ series for the ropes with new splices, discussed in Part B. Care was taken to ensure that the sample was not damaged during installation of the sample into the test machine.

For the MQDE series of tests (standard splice design), the ropes were loaded directly around 7-inch-diameter pins, using no thimble. For the later MQIQ series of tests (revised splice design), the ropes were placed around (10.87-inch diameter by 5.04-inch wide) spools provided by Marlow. The spools were fitted to the 7-inch-diameter pins. Later in the Part B testing, the spools were changed to 6.3-inch diameter by 3.62-inch wide.

Rope Damage

The damage in this part of the testing program was introduced to the rope after it had been fitted into the test machine, but before any loading. The degree of damage introduced was in accordance with instructions from Stress Engineering Services. Specifically, the damage was introduced by surgically cutting individual subropes, taking extreme care not to cut adjacent ones.

The damage conditions imposed were:

1. MQDE 2 No cutting (reference case)
2. MQDE 5 No cutting (reference case)
3. MQDE 1 Three subropes of 28 surgically cut - removing 10.7 % of the area
4. MQDE 3 Three subropes of 28 surgically cut - removing 10.7 % of the area
5. MQDE 6 One part of 9 three-part subropes cut -removing10.7% of the area, but from partial cuts of more subropes.
6. MQDE 4 Five subropes of 28 surgically cut – removing 17.9 % of the area

Shown in Figures A-1 through A-10 are photographic records of the procedures adopted to induce damage in all of the MQDE samples.. In the case of MQDE 1, where only 3 subropes were cut, the jacket was partially removed. However, for MQDE 6 where one strand was cut from 9 subropes (equivalent to 3 cut subropes) the entire jacket had to be removed locally for access.

After the damage was introduced (or after the rope was fitted into the test machine if no damage was required) the rope was fully submerged in tap water. The rope was then loaded to an indicated 2% reference tension and the pin-to-pin length taken as the reference length.

After the test matrix was completed, the load was reduced to a nominal value, the water was drained from the tank and the rope loaded to failure at a loading rate of 0.10 to 0.15 in/sec.

During the cyclic load testing, machine load and crosshead displacement data was recorded on a regular basis to provide information on modulus and rope length. For the break test, load and displacement data was recorded on a continuous basis. After the rope had failed, the provisional location of failure was recorded.

Upon completion of the break test, the sample was removed from the machine, laid out on the floor of the laboratory, and the location of failure confirmed. Relevant photographs were taken during the test program. The process was repeated for each rope.

Test Results

Table A-2 gives the results of the retained break strength tests, which include maximum load, %extension to break and failure location. The % extension to break values are based on the reference rope length taken at approximately 2% of theoretical break load prior to the start of the entire test matrix. These reference rope lengths are also included in the table.

Table A-2
Test Results from Rope Samples with Traditional Splices

Sample	*Condition*	*Break Strain %*	*Break Load Kips*	*% Cut*	*Load Based on % Area*	*% Diff.*
MQDE 2	**Reference**	**7.05**	**410**	**0**	421.5	-2.7
MQDE 5	**Reference**	**7.10**	**433**	**0**	421.5	2.7
MQDE 1	**3 Subropes Cut**	**6.44**	**380**	**10.7**	376.3	1.0
MQDE 3	**3 Subropes Cut**	**4.91**	**340**	**10.7**	376.3	-9.7
MQDE 6	**1 Part of 9 Cut**	**6.16**	**367**	**10.7**	376.3	-2.5
MQDE 4	**5 Subropes Cut**	**5.86**	**364**	**17.8**	346.2	5.1

The associated load-extension plots for the break tests are given in Figures A11 through A16. It can be seen from the plots (and from Table A-2) that the undamaged ropes (MQDE 2 and 5) yielded the highest loads and %extensions to break values. It is worth pointing out however, that with a theoretical break strength of 424 kips, only one of the ropes (MQDE 5) exceeded this value and only just with a load of 433.2 kips. There is around a 5.6% difference between the two break strength values. MQDE 2 yielded a break load value of 410 kips. Once damage has been induced, the load and extension to break values both also are reduced.

For undamaged rope, the jacket accounts for about 8 % of the theoretical strength. For damaged rope where the jacket has been cut to inflict damage to the rope core, we assume that the jacket does not carry force.

Referring to the data in Table A-2 there does not appear to be an obvious correlation between either loss in strength or extension to break with induced damage. In fact the average breaking load of the four tests with damage (MQDE 1 and 3 with 3 cut subropes, MQDE 4 with 5 cut subropes and MQDE 6 with 9 partially cut subropes) is 363.0 +/-17 kips with a relatively low coefficient of variation of 4.7%. The average breaking strength of the two undamaged ropes is 421.7 +/-16.4 kips. This gives a coefficient of variation of 3.9%, 17% lower than the damaged ropes. It is somewhat surprising that different degrees of damage result in similar break strength values. It was this finding, together with the failure locations of the damaged samples (with the exception of MQDE 6, all failed within the splice region) that led to the belief that the induced damage was propagating to the terminations an adversely affecting splice efficiency. This issue is addressed more fully in Part B of this report, but this finding resulted in the MQDE series of tests being halted after 6 of the 9 samples were tested.

Table A-3 shows the failure locations of the six ropes tested.

Table A-3
Type of Test and Failure Locations

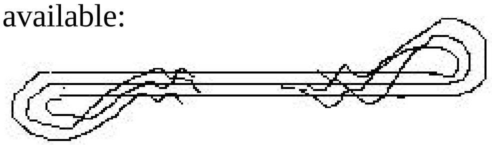
NEL test mark	*Type of test*	*Failure location*
MQDE 1	3 cut subropes	At/around tail of splice.
MQDE 2	Reference test	At/around tail of splice.
MQDE 3	3 cut subropes	At/around tail of splice.
MQDE 4	5 cut subropes	At damage site.
MQDE 5	Reference test	At/around tail of splice.
MQDE 6	9 partially cut subropes	Clear length – probably at damage site.

Interpretation of Test Results

A popular assumption that has been considered by those involved with polyester rope technology is that damage to the rope mid-section can be accounted for by assuming that the residual breaking strength of a damaged rope is proportionally reduced by determining the area of the cross-section of the rope that remains undamaged and dividing that area by the original area. For surgically cut subrope damage, one can then use the ratio of the cut subropes divided by the total number of subropes (in this case, 28). Such a comparison is shown in Table A-2.

Table A-2 shows that the reference load (no damage, thus 100% area resisting) is an average of 421.5 kips, based on only two samples. When 3 subropes are cut, the resisting area is 100 minus 10.7, or 89.3 % of the undamaged area, but the results for the two tests are by test 380 kips for MQDE 1 and 340 Kips for MQDE 3. Test MQDE 1 shows close agreement to the theoretical value (using the area ratio) of 376.3, but MQDE 3 is substantially lower – 9.66% below the average theoretical. Notice also that the breaking strain is 4.91 % for MQDE 3, substantially lower than the 6.44 % value for MQDE 1, while the breaking elongation for the reference tests are around 7%. Why would MQDE 3 fail at a substantially lower breaking strength?

The exact answer is yet unknown. But here is our hypothesis: When the traditional rope splice is made, the subropes are curved around the thimble in one direction and subrope ends are attached to the subropes in the main body, without attention to which end is attached to which subrope in the main body. This is a simplified sketch of how the traditional splice looks using only 3 subropes of the 28 available:



Please note that if the subropes are not color-coded or marked, the structural connections can be made to virtually any subrope not already spliced. It is possible, then that an undamaged (uncut) subrope end can be attached to a damaged (fully cut) subrope in the body, thus making both subropes act as if they are damaged. At the opposite splice there is no assurance of which subrope end is attached to which subrope in the main body, so a similar result can occur, but with totally different subropes involved. Thus, it is possible for multiple subropes to be affected by the damage in only one subrope. Thus, based on “chance” connections of subropes in MQDE 1 and 3, the break tests results can be markedly different. It should be stated that the traditional splice design used by Marlow was not designed based on damaged rope considerations. Matching all of 28 subropes is not trivial, and adds to the cost of the product. This hypothesis could account for the reduction in breaking strength and elongation that occurred in MQDE 3. Another possible hypothesis is that the splice in MQDE 3 was defective in some way, but we doubt that, based on Marlow's excellent track record for providing quality rope splices.

Moving to the results of MQDE 6, although 9 subropes were affected by cutting one of three elements of each of the 9 subropes, test results generally agree with the reduction in area assumption, falling only 2.5 % below. Based on our hypothesis, this condition, where only single elements of the three part subrope are affected, would not necessarily produce a low test result, based on the area assumption.

For MQDE 4, where 5 of 28 subropes were cut, the area loss is 17.8 and the test results are 5% above the theoretical based on area retained. Since the subrope attachments are arbitrary, a variety of results are possible.

One result is significant from this set of tests. From data evaluations and comparisons of retained breaking strengths of the first six samples (MQDE series), we find that the subrope cutting (damage application) in the middle of the test sample has the effect of further reducing the splice efficiency. Also, there is only a limited correlation between severity of damage and residual strength, and there was poor repeatability between tests with the same damage severity.

As a result of this finding, Marlow Ropes Limited took the decision to change their traditional splice design (for large mooring ropes only) to an improved design. Marlow informed us (by e-mail) that:

- The change in splice design that they have made will only be relevant to Superline ropes used for offshore tether applications.
- The existing splice and rope design has been used for over 20 years in general marine applications without problems. In these applications we advise that if the sub-ropes are

severed then the rope should be cut and re-spliced. This generally does not cause operational problems so we shall carry on giving the same advice.

- To date Marlow have only supplied Superline Polyester tethers to Petrobras. During the Petrobras prototype rope approval stage it is required that the certifying authority review and witness splicing procedures. Marlow Ropes have also trained Petrobras personnel to perform the Superline splice. We will ensure that the details of any new splice are communicated to Petrobras so that re-training can take place.

- With regard to a general communication of our discovery to the industry, including other rope manufacturers, they would suggest something like this – "Results from the SES/BP test program have highlighted an important issue regarding the inspection and assessment of damaged parallel sub-rope rope constructions. If a sub-rope is severed it may affect the load holding capacity of other sub-ropes that it is spliced into. This must be taken into account when performing damage assessments on these ropes. This can be easily done provided splicing methods are understood."

- The SES/NEL test program has highlighted an important issue that Marlow believe warrants a re-design of the splice. Marlow agrees that changing the splice design will affect the validity of prior test results and it would be preferable to conduct further tests using the new splice design.

- Spiraline ropes are still undergoing further development.

Marlow provided, free of charge, new samples to be tested in Part B of the program, which follows.

Figure A1. Removing Jacket

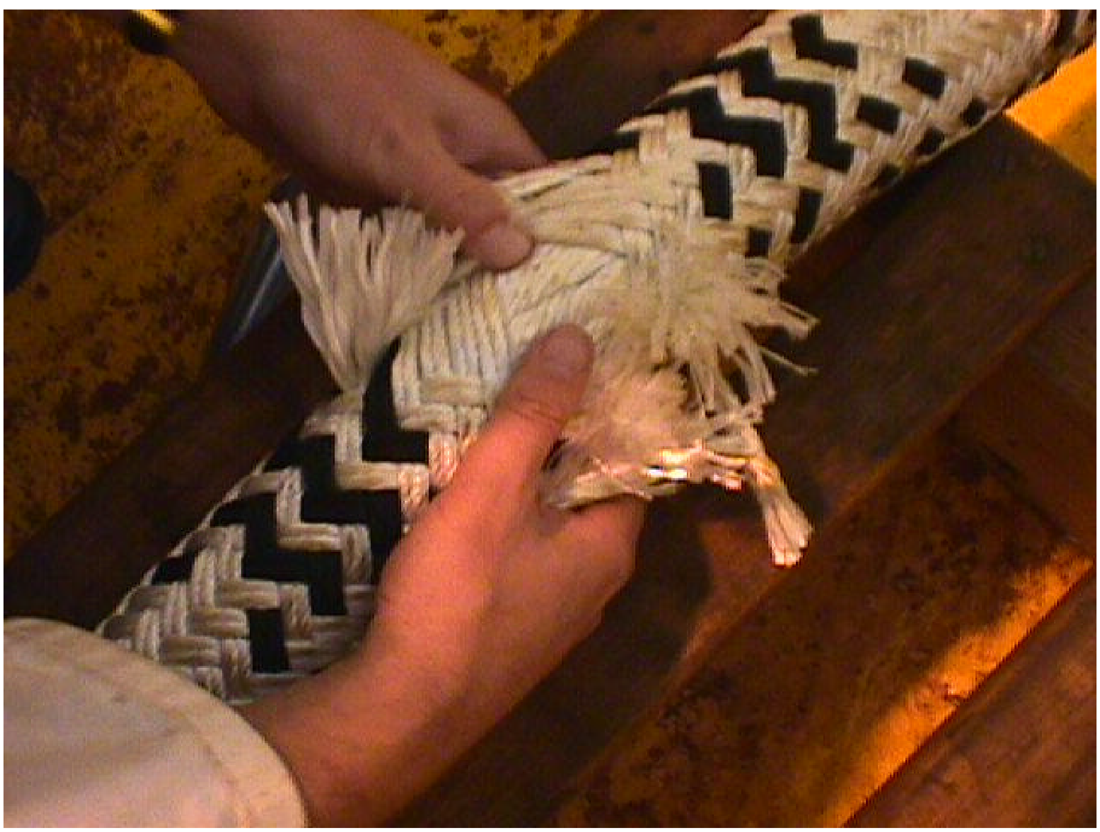


Figure A2. Further Removal of Jacket

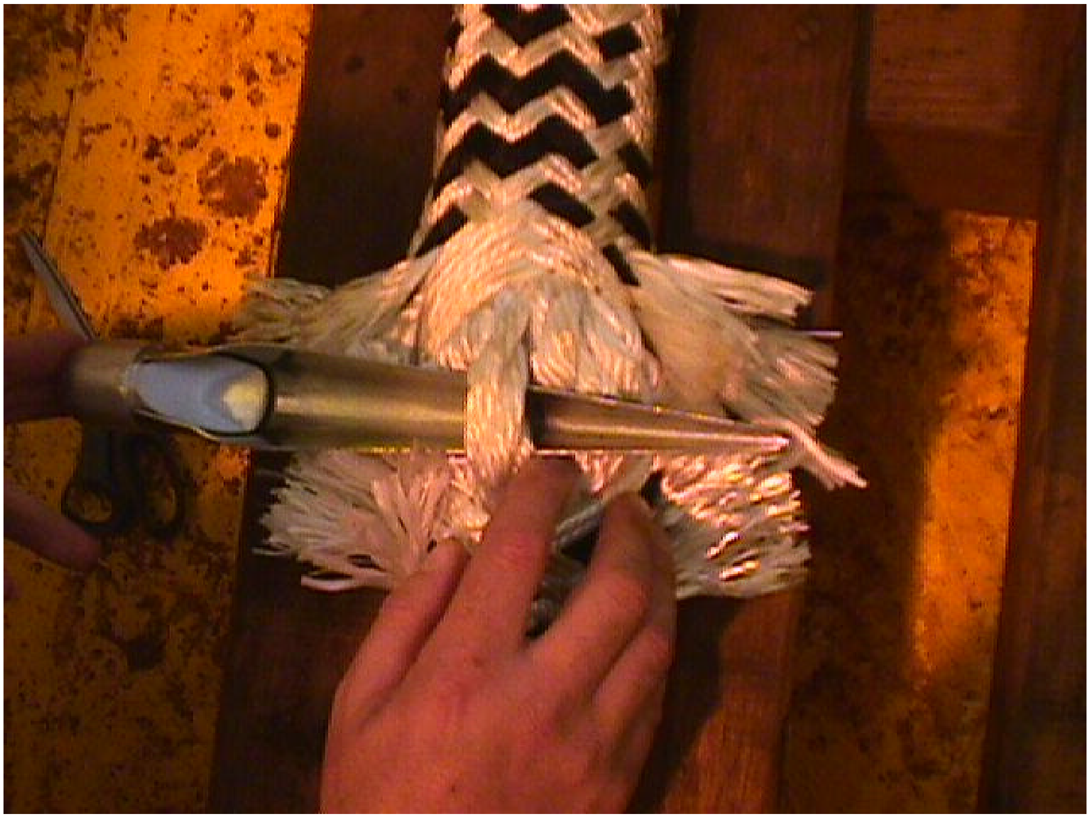


Figure A3. Isolation of Subrope to Cut

Figure A4. Cut Subrope Showing Black Marker in Each Element.

Figure A5. MQDE 4 With 3 Subropes Cut

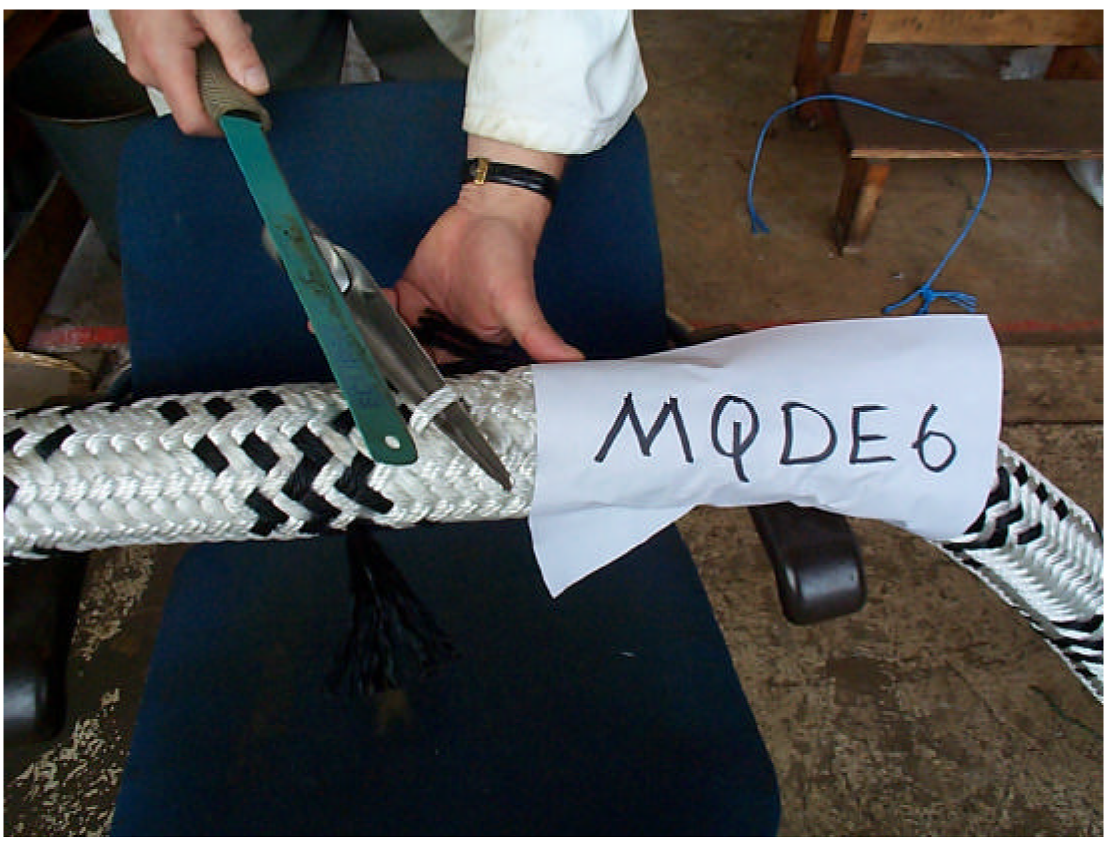


Figure A6. Beginning of Jacket Removal MQDE 6.

Figure A7. Jacket Removed.

Figure A8. Cutting a Subrope.

Figure A9. First of 9 Subrope Elements Cut.

Figure A10. One Element of Nine 3-Part Subropes Cut.

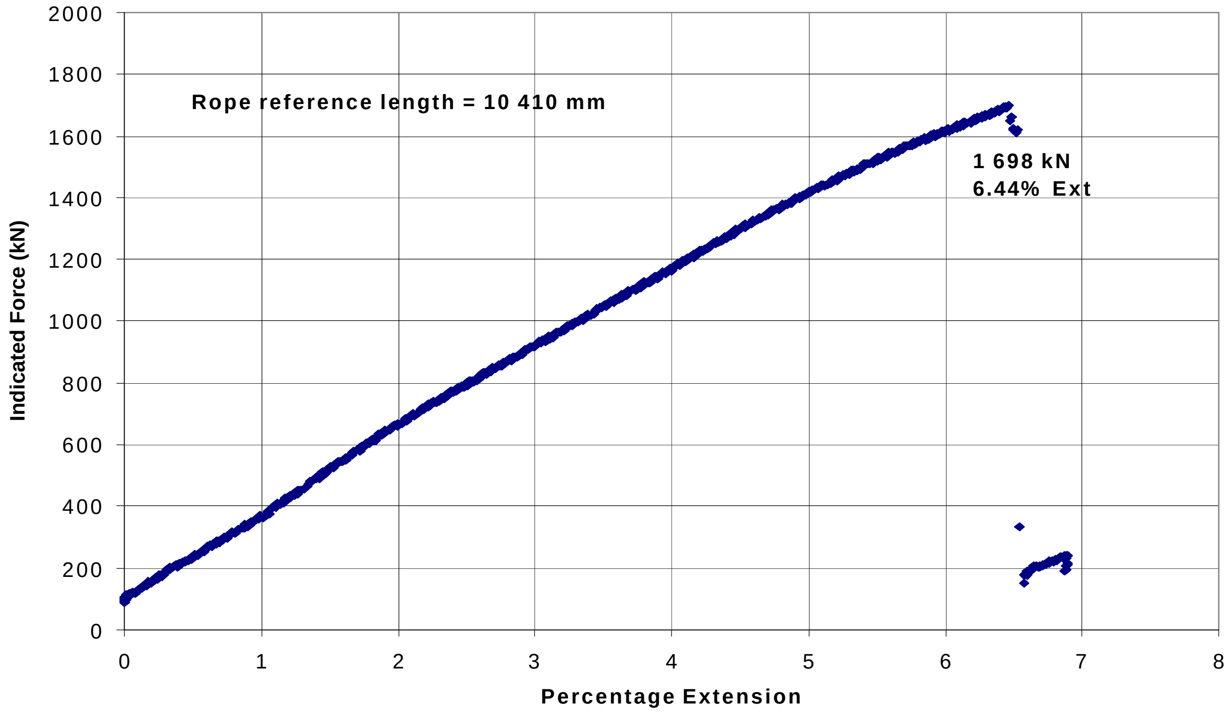


Figure A11. Load Extension Plot for MQDE 1.

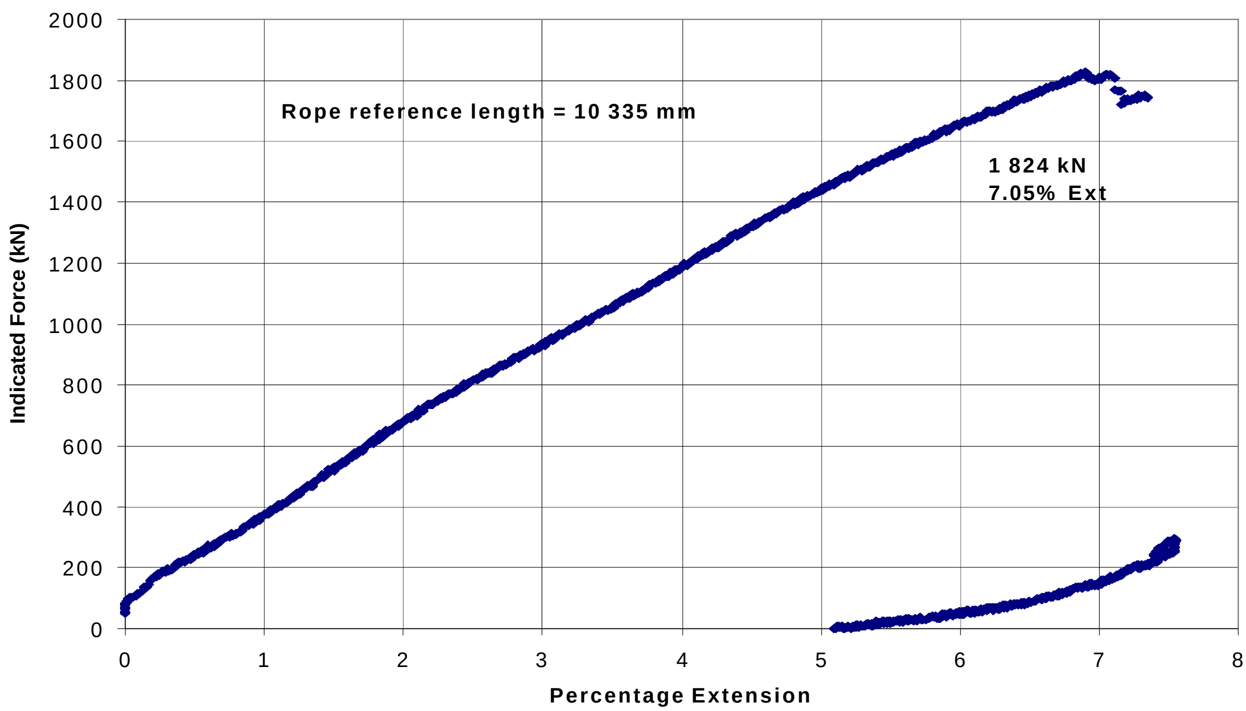


Figure A12. Load Extension Plot for MQDE 2.

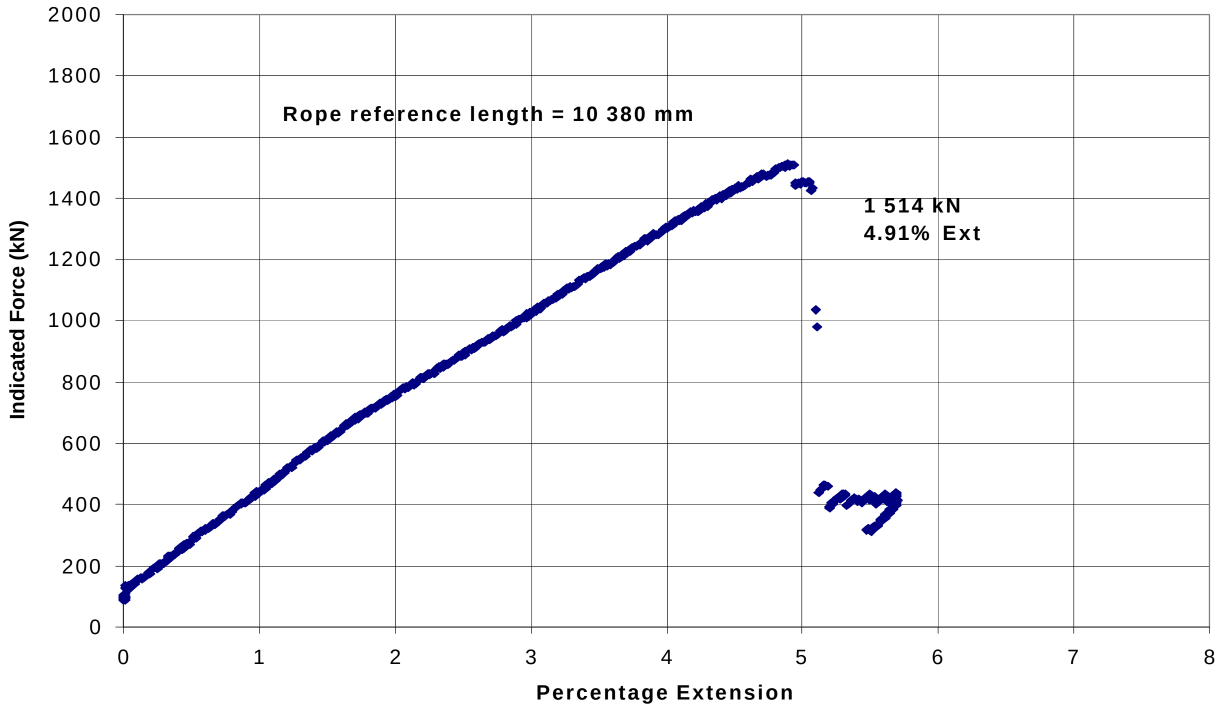


Figure A13. Load Extension Plot for MQDE 3.

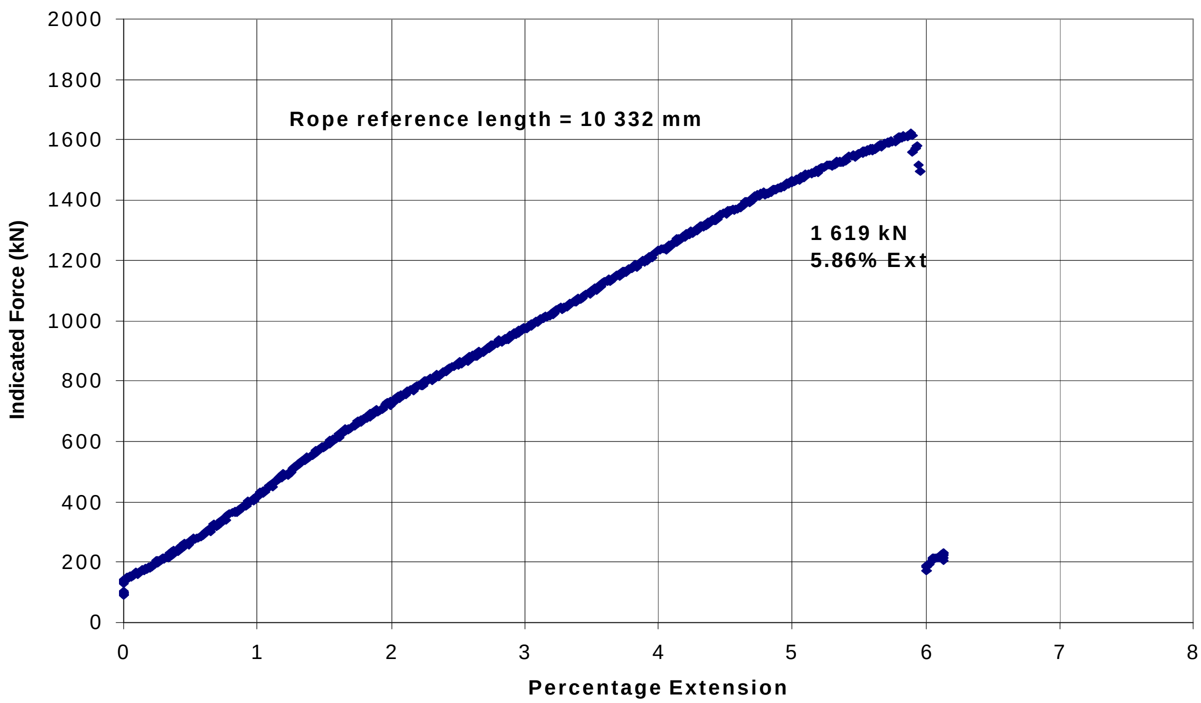


Figure A14. Load Extension Plot for MQDE 4.

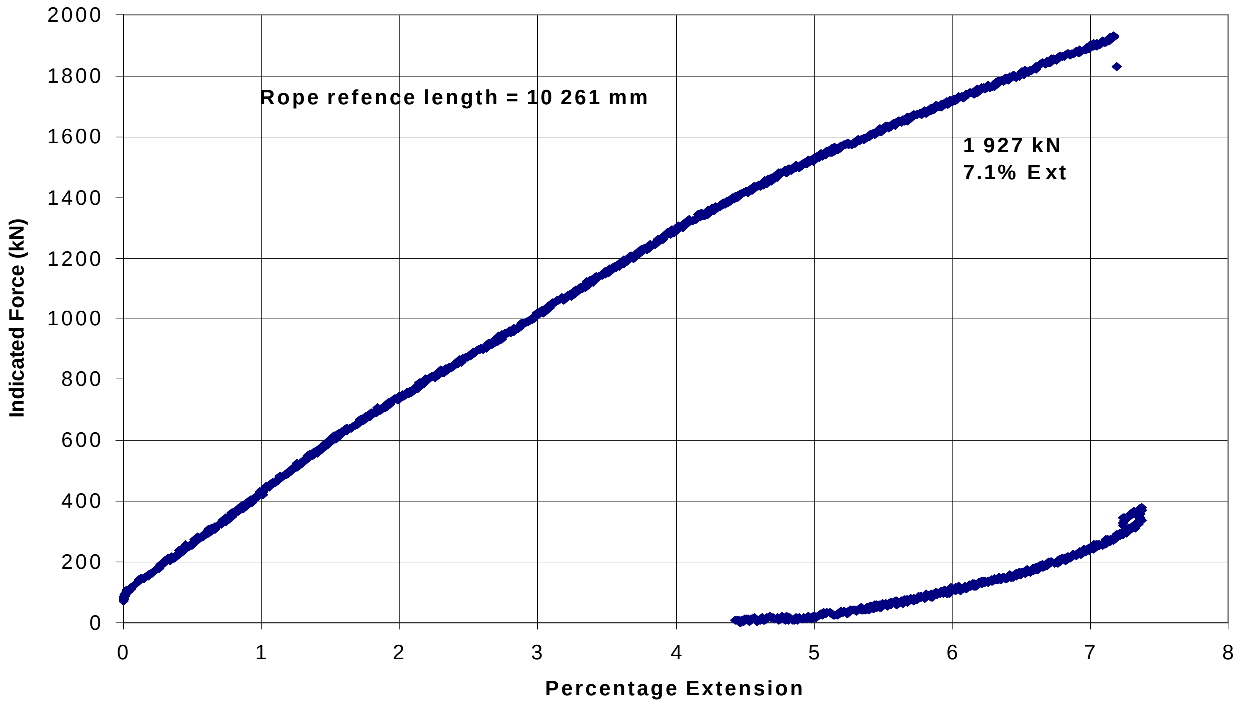


Figure A15. Load Extension Plots for MQDE 5.

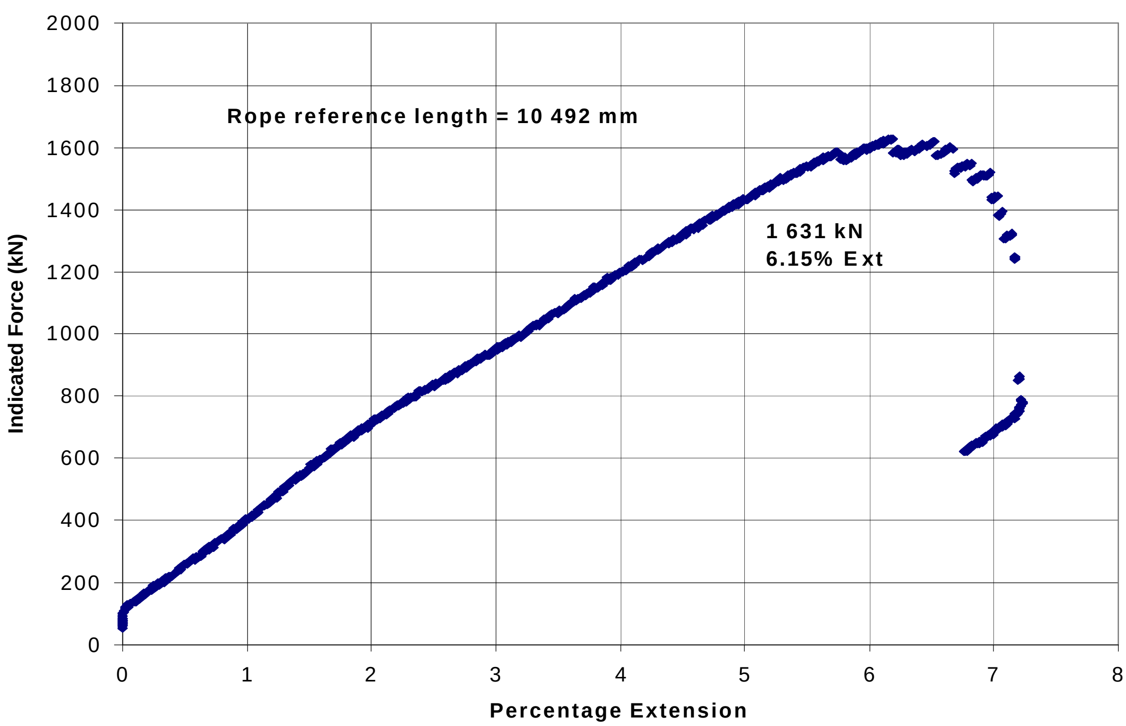


Figure A16. Load Extension Plots for MQDE 6.

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PART B: NEL/SES TESTS WITH NEW SPLICE DESIGN

Summary

The purpose of the work described in this Part is to obtain some base data on the strength loss associated with the introduction of simulated mechanical knife-cut damage into polyester rope, with a view to generating provisional discard criteria. In this second part, the rope samples were nearly identical to that in Part A, except the splices were of the new rather than the traditional design. The ropes in part B had a Polyurethane coating around the splice, and we used a smaller 6.30-inch by 3.62-inch wide spool at each end.

Rope samples were subjected to simulated storm runs under sinusoidal loading before being subjected to retained break strength tests. Some of the ropes had induced damage and others did not. Nine Marlow polyester Superline rope samples, with new splices, were originally delivered to NEL for testing, and later (after the NEL test machine was decommissioned after testing 3 samples), the remainder were sent to SES in Houston. The rope from which the test samples were made consisted of 28 subropes and had tested break strength of 461.0 kips.

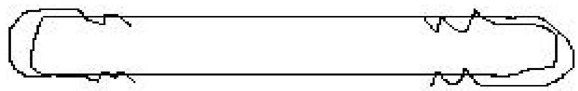
For this second series of tests the damage was introduced by using a butcher knife to slice the rope to a predetermined depth of cut. This knife cut had the effect of making both partial and complete cuts to the subropes that were in the path of the knife blade.

The second test series (MQIQ at NEL and SES at Stress) produced results for this new splice design. Although the ropes were of the same construction as the original samples the improved splices raised the tested break strength from 421.5 to 461.0 kips, a 9.4% improvement.

After three tests into the second series of tests, the NEL test machine (after suffering a major failure) was permanently taken out of service and the tests were completed by SES.

Conclusions to Part B

1. Test results vary widely on effect of damage.



2. Indications are that partial damage to one subrope results in a total break in that subrope, and then slacks the subrope pair.
3. Using a reduced breaking strength based on an area ratio is not a conservative assumption for this new splice.
4. Damage tolerance of the subrope sample appears to be a function of area ratio and splice design, and not area ratio only.
5. Our results could be affected by the sample being too short, but we see no compelling technical reason to support this belief.

Introduction

The objective of Part B of the study reported here was to provide some additional information on damaged rope discard criteria, this time using rope samples with the new Marlow splice design. This objective was achieved by evaluating the effect of externally induced knife-cut damage upon the retained strength of polyester ropes after being subjected to simulated storm cycles. After three samples of the new spliced rope were tested, the NEL test machine (after suffering a major failure) was permanently taken out of service, and the final 6 tests were conducted at SES in Houston.

This part of the report provides a description of the test equipment, procedures and results of the study for the new splice design.

Rope Samples

Rope samples for this part of the testing had the same core of 28 subropes as that for Part A, but the splice was the new splice design. Other small changes were (a) that the rope jacket was slightly different in design, and the final 6 samples had a plastic coating around the eye for additional protection against the thimble. The following sketch shows for one pair of subropes, how 14 pairs of subropes are joined together in the splice. The 14 pairs are jacketed for the main body, and bound together at each end to form an “eye splice”.

Although the ropes were of the same construction as the original samples (with a slight difference in the jacket) the improved splices raised the theoretical break strength by 9.4%.

SES L2000 Test Machine

For the first three tests, the test machine was the NEL test machine, described in Part A. The final 6 tests were conducted on the SES L2000 Test Machine.

The SES L2000 machine is capable of supplying 2000 kips static tension and a cyclic alternating tension in a range from 70-700 kips axial tension using its dedicated hydraulic system (Refer to Figures B1 and B2 for photographs). However, for instances when the dedicated hydraulic system cannot achieve desired cycling rates, a smaller 1000 kip hydraulic cylinder was installed in series with the dedicated system. When set up in this fashion, the dedicated system can be used to take the initial slack out of the rope assembly. The dedicated cylinder is then fixed and the cyclic load is applied using the smaller 1000 kip system. General specifications for the machine are as follows:

1. Specimen length: 10 feet minimum to 60 feet maximum (with secondary hydraulic system installed)

2. Maximum stroke: 6 feet (Note: using the 1000 kip hydraulic cylinder, the sample may be preloaded to increase the effective stroke of the machine).

3. Maximum moving head rate with 100 kip tension: 24 inches/minute assuming ¾ of the pump full flow rate is achievable.

4. Maximum cycles per minute depend on the load magnitude: At our load magnitudes, and a 3.5-inch stroke, a 15 second period is possible with the current hydraulic system.

5. Data acquisition and measurements: SES is a National Instruments Alliance member and has many experts in the field of data acquisition. Our technicians routinely monitor load cells, strain gages, extensometers, and thermocouples with computer controlled data acquisition systems. SES has the ability to store data on a variety of magnetic media for future data reduction by our engineers or by our clients.

- o Load measurement: For this series of tests SES used pressure from a 1,000 kip hydraulic cylinder, calibrated against a strain gage instrumented load cell.
- o Extension measurement: SES routinely uses rotary extensometers (yoyos) to measure extension.
- o Control/Data Acquisition: The control/data acquisition system on the frame has an existing capability to record load cells and extensometers (a maximum of 16 channels) at rates far exceeding those required for this cycle rate.

6. Cyclic Control: This machine is load controlled with a calibrated load based on hydraulic cylinder pressure that controls a precision hydraulic servo valve.

Operation of the SES L2000 test machine is designed around a 3000-psi hydraulic system. The main hydraulic cylinder, built into the machine is a 3000-psi hydraulic cylinder. A requirement of the project was to test the ropes fully immersed in ordinary tap water. In order to achieve this condition, a tank was constructed of steel plate and angle iron to fit inside the twin pipes that comprise the main longitudinal structure of the machine. The arrangement was such that both of the machine's clevis assemblies, to which the rope was attached, were contained within the tank and the rope samples were fully submerged in tap water. This meant that the entire rope sample was surrounded by water.

Test Procedures

Table A-1, shown previously, provides the cyclic loading test matrix that was agreed upon between NEL and SES at the start of the study, and has been used throughout both parts of the testing program. For each rope sample the test matrix was conducted twice. After cyclic testing, the ropes were subjected to break testing. As reported earlier, test sequences 2 and 4 are simulated windward and leeward hurricanes respectively. Test sequences 1 and 4 were periods of relative calm to allow the rope to bed in and recover from the storm loadings.

As at NEL, upon receipt of the test samples at SES they were each allocated with a unique test mark. These test marks have been used throughout the report. In this part of the testing, involving the rope samples with the new Marlow splice, the "MQIQ" designations were used by

NEL, and the "SES" designations were used by SES. Care was taken in all cases to ensure that the sample was not damaged while installing it in the test machine.

For the MQIQ series of tests (new splice design), the ropes were placed around (6.3-inch diameter, 3.62-inch core width, and 3.15-inch flange height) spools provided by Marlow. The spools were fitted to the 7-inch-diameter pins. For the SES tests, a new set of spools was constructed by SES according to Marlow specifications: 10.87-inch core diameter, 5.04-inch core width, and 3.07-inch flange height.

Rope Cut Damage

In this part, the knife cut damage was inflicted on the rope after it was fitted into the test machine, but before any loading. This would simulate the effect of external damage occurring during installation operations. We determined the degree of damage to be introduced using results from prior tests and with knowledge of the API RP 2SM[3] advice.

The knife-cut conditions used for part B are contained in Table B-1

Table B-1
Knife cut Damage Conditions Imposed

Test	*Cut Depth*	*Equiv. Number of Subropes Cut*	*Number of Subropes Damaged or Partly Damaged*	*% Area Cut*
MQIQ 4	**0.7**	**n/a**	**n/a**	**n/a**
SES 1 (ref.)	**0.0**	**0.**	**0.**	**0.00**
SES 2	**0.7**	**4.064**	**6**	**14.51**
SES 3	**0.7**	**2.757**	**5+**	**?? 9.85**
SES 4	**0.5**	**1.710**	**4**	**6.11**
SES 5	**0.5**	**2.907**	**5+**	**10.38**
SES 6	**0.5**	**1.770**	**4+**	**6.32**

For the cut at NEL: Figure B3 shows a 0.7-inch deep cut being made on sample MQIQ 4. The jacket was removed around the area of induced damage. The cut was made with a sharpened hacksaw blade (teeth removed). Either side of the blade aluminum angle was glued to the blade with the distance from the base of the angle plate to the blade edge set at 18 mm. Care was taken not to rock the blade during cutting. The potential for rocking is real however and could be eliminated by suitable jigging of the blade to the rope and ensure repeatability of cut. It is possible, however, that rocking could occur in real-world damage situations. **For *cuts at SES***, Figures B4 and B5 show a typical rope cut, using a butcher knife with cut depth limiting devices attached.

Test Procedures

After the damage was introduced (or after the rope was fitted into the test machine if no damage was required) the rope was fully submerged in tap water and allowed to soak for a minimum of 24 hours before testing. The rope was then loaded to an indicated 2% reference tension and the pin-to-pin length taken as the reference length.

After the test matrix was completed, the load was reduced to a nominal value, the water was drained from the tank (at NEL, but not drained at SES) and the rope loaded to failure at a loading rate of around 0.10 to 0.15 in/sec. In some severe damage cases the testing was terminated during cyclic storm loading and before break testing, because the rope came apart. These cases are noted in the results to follow.

During the cyclic load testing, the machine load and the crosshead displacement were recorded on a regular basis to provide information on loading, modulus and rope length. For the break test, load and displacement data were recorded on a continuous basis. After the rope had failed the provisional location of failure was determined and recorded.

Upon completion of the break test the sample was removed from the machine, laid out on the floor of the laboratory and the location of failure confirmed. Relevant photographs were taken during and after the test program.

Results

Table B-2 gives the results of the retained break strength tests, which include maximum load, % extension to break and failure location. The % extension to break values are based on the reference rope length taken at approximately 2% of theoretical break load prior to the start of the entire test matrix.

Table B-2

Results from Tests with New Splice Design

Sample	*Condition*	*Break Strain %*	*Break Kips*	*% Cut*	*Load Based on % Area*	*% Diff.*
MQIQ 1	**Reference Test**	**7.5**	**480.4**	**0**	**461.0**	**4.22**
MQIQ 2	**Reference Test**	**8**	**442.9**	**0**	**461.0**	**-3.92**
SES 1	**Reference Test**	**13.2***	**459.6**	**0**	**461.0**	**-0.30**
MQIQ 4	**0.70 Inch Cut**	**5.7**	**336.3**	**?**	**396.0**	**-15.07**
SES 2	**0.70 Inch Cut**	**n/a**	**(Storm)**	**14.5**	**394.0**	**n/a**
SES 3	**0.70 Inch Cut**	**n/a**	**(Storm)**	**9.9?**	**415.4?**	**n/a**
SES 4	**0.50 Inch Cut**	**10.2**	**306.0**	**6.1**	**432.8**	**-29.31**
SES 5	**0.50 Inch Cut**	**n/a**	**(Storm)**	**10.4**	**413.1**	**n/a**
SES 6	**0.50 Inch Cut**	**11.6**	**355.0**	**6.3**	**432.8**	**-17.98**

This table shows that the average break load for the reference samples, MQIQ 1, MQIQ 2 and SES1 with the new splice design was 461 kips, as contrasted with 421.5 kips for the reference samples in Part A with the traditional splice design. Thus, the new design is 9.4 % more effective than the traditional one. Also note that the one reference sample tested at SES had a break load that fell nicely between the two values obtained at NEL. Note also that the break strain measured at SES (Sample SES 1) was 13.2 %, much greater than the values shown for MQIQ 1 and 2 at NEL. We discovered that while testing SES 1, a valve setting caused the accumulator to be activated at the higher loads near failure, causing the loading rate to slow down, thus producing the higher elongation value. This problem was avoided in subsequent tests. Figures B6 through B11 show the load vs. % elongation for the Part B samples.

Tests MQIQ 4 and SES 1 and 2 were performed using the 0.7-inch knife cut damage, adopted after the testing in Part A. The MQIQ 4 sample remained viable during the cyclic testing, and failed during the break test at 336.3 kips, or 27 % lower than the average reference load determined by test. Based on measurements from SES 2, discussed later, we believe that the %area cut by the 0.7-inch knife cut was about 14.5%. If the residual strength of the damaged rope was determined by reducing the undamaged breaking load by 85.5 %, the "theoretical breaking load would be 396. kips, our NEL test result, 336.3 kips, was 15% below that value. Thus using an area ratio assumption would not hold true in this case. At this point in the testing program we began wondering why the test result was lower than the prediction based on using the area ratio.

After the SES L2000 test machine was ready for rope testing, test SES 2 was conducted, intended to be identical to MQIQ 4 in the 0.7-inch knife damage inflicted. During the cyclic loading series of SES 2, the test machine shut down because of exceeding preset test limits on cylinder extension. The preset conditions are used to protect the hydraulic system from damage should unusual test sample behavior occur. The shutdown occurred at 1500 cycles into the first hurricane sequence of 40% of the calculated breaking load plus or minus 15 %. The only prior cycling was 3000 cycles under lower conditions: 20% load plus or minus 10%.

Upon removing the safety covers from the water tank, we found that only 14 of the 28 subropes were still tensioned and resisting load. The remaining subropes were either cut and broken or not cut and slack. Another observation was that the splices at both ends were no longer symmetrical in shape, indicating that the eye splice had "rotated" around the eye. These conditions are shown in Figures B12 and B13. At the point where the machine stopped, and 14 subropes appeared undamaged, the breaking strength for the remaining subropes might be 14/28 times the reference strength or 230.5 kips. The Maximum cyclic load during the storm cycling would be about 55% of reference, or 253.6, great enough to cause failure of 14 subropes. Thus we conclude that if the machine had not automatically shut down, the rope likely would have broken.

At this point we informed John Hooker of Marlow Ropes of this result. After we consulted with BP we collectively decided to do the following:

1. Start testing SES 3, which was an identical test to SES 2 and MQIQ 4, in the event that the results of SES 2 were an anomaly. Also, perform a check on the result of the knife cut before testing by "opening" the rope at the damage location and counting the strands in each element of each subrope that were cut by the knife blade penetration into the rope.

2. Begin a forensic investigation of the rope sample SES 2, in order to determine the failure mechanism, or the cause of the anomaly. John Hooker

gave us permission to do this study. Results on the forensic results are reported later Part C of the report.

Test SES 3 shut down 329 cycles into the second hurricane loading. SES 3 survived longer than SES 002, which failed during the first hurricane loading, but the failure was similar. Upon inspection we learned that 7 subropes were tight, and holding load, 2 subropes had one of three elements remaining intact and the remaining subropes were at the bottom of the water tank, either broken or slacked.

The question we had was “why did MQIQ 4 fail differently from SES 2 and SES 3?” The possible answer came from the forensics investigation of SES 2 described more fully later. In summary, we found that new splice is formed by joining pairs of subropes in a closed loop, looking like the shape of a rubber band. If the cutting was all on one side, as we know it was for SES 2 and SES 3, subropes on that side would be weakened and those on the other would not. Since the weakened subropes are joined to their mating undamaged subropes, the weakened subropes could break and the other mating subropes could become slack as the affected subropes slip around the eye. We speculate that the knife cut performed at NEL may have resulted in a cut across both sides of the subropes, rather than on one side only. As a result, the cut could have damaged some subrope pairs and thus the effect on the rope strength would have been less severe than if all of the cutting were on one side. Unfortunately the sample was discarded, so we cannot confirm this speculation.

What other differences could exist between samples SES 2 and SES 3 and MQIQ 4? Examination of the eye splice protective covering on MQIQ 4 revealed that the protective cover had been worn away in each sample at the point where the rope first makes contact with the spools. After testing had ceased at NEL, Marlow Ropes retrieved the remaining samples and did some reworking of the covering of the rope samples and added a protective jacket, before the samples were sent to SES. Could the jacket reworking make the MQIQ different from SES 2 and SES 3? We do not know. Another possibility, but we think not likely, is that the knife cut at NEL was somehow different in character from that used at SES. Since both SES 2 and SES 3 broke during the storm loading, we decided to reduce the knife cut depth from 0.7 to 0.5 inches for the final three damaged rope tests. At this point we understood which subropes were on which side of the splice, so we insured that we would use the most conservative case, and made knife cuts on one side of the rope. Based on experiments and theory, a 0.5 inch knife cut would result in a 6% area loss, well under the 10% area loss value that is allowed by API RP 2SM[3].

For SES 4, a 0.5-inch knife cut caused partial damage to 4 subropes, resulting in the equivalent number of subropes cut equal to 1.71 subropes. The rope sample survived all of the cyclic testing. Inspection of the rope prior to break testing showed that 24 of the 28 subropes were carrying load and 4 subropes were hanging together on one element (not carrying load). SES 4 broke during residual load testing at 306.0 kips. Based on the assumption of using the area loss ratio times the average breaking strength of the reference samples, the "theoretical" rope strength would be 432.8 kips. Table B-2 shows the test load was 29.3 % below the theoretical. If one assumed that one cut subrope resulted in 2 subropes being lost, or two times the area lost, the test result still be 24% below theoretical.

The rope for SES 5 was cut to a 0.5-inch depth also, but inspection of the cut subropes revealed that in this case, 5 different subropes were damaged and the equivalent number of subropes cut was measured as 2.90, or 70 % greater than for SES 4. This difference is attributed to the variation in the way the subropes lay under the knife blade. Since the damage condition of 10.4 % was near the API[3] allowable, we decided to test the SES 5 rope as is. The rope broke at 90 cycles into the first storm cycle series. Several loud "pops" where heard between cycle 80 and cycle 90. Upon inspection, 10 subropes were tight and holding load, and 5 subropes were slack. The remaining subropes were broken.

For our final test, SES 6, we decided to make the cut identical to that of SES 4, which successfully passed the cyclic testing series. To insure this, we opened the jacket to impose the damage. Rather than using the knife cut, we used a scissors to duplicate the cuts on the same subropes measured for SES 4 as closely as possible. Thus, the cutting of SES 6 was forced to be nearly the same as SES 4. Break testing produced a load of 355 kips, 16% higher than SES 4. The "theoretical" load was the same as for SES 4, and the break load was 18 % lower than theoretical.

Failure Locations for Tests With New Splice

Inspection of the failed rope samples provided the results shown in Table B-3.

Table B-3
Type of Test and Failure Locations

SES & NEL Test No.	*Type of Test*	*Part of Testing Where Failure Occurred*	*Failure Location and Details*
MQIQ 1	**Reference**	**Final break testing**	**Splice region.**
MQIQ 2	**Reference**	**Final break testing**	**Splice region.**
SES 1	**Reference**	**Final break testing**	**Splice region. At toe of splice on the stationary end.**
MQIQ 4	**0.7-Inch Knife Cut**	**Final break testing**	**Predominately at cut location.**
SES 2	**0.7-Inch Knife Cut**	**During storm cycling, before break test.**	**At cut locations, with slipping around splice. 14 subropes holding load, 6 broken at toe of splice, 8 in center.**
SES 3	**0.7-Inch Knife Cut**	**During storm cycling, before break test.**	**At cut locations, with slipping around splice. 8 tight, 7 loose, 6 breaks at toe of splice. 6 breaks during test, 4 at stationary end, 2 at moving end. Of 7 cut subropes 4 broke at center and 3 at stationary end.**
SES 4	**0.5-Inch Knife Cut**	**Final break testing**	**At center.14 subropes undamaged, remainder broke at center because rope-stuffed jackets at either end forced breaks to the middle.**
SES 5	**0.5-Inch Knife Cut**	**During storm cycling, before break test.**	**At cut locations, with slipping Around Splice. 15 subropes undamaged, 13 broken, 2 at moving end.**
SES 6	**0.5-In.Knife Cut (equiv.)**	**Final break testing**	**At toe of splice. 14 undamaged, 11 broke at moving end, 3 missing.**

Notes on Failure Locations

For the MQIQ samples, examinations revealed that the protective cover had been worn away in each sample at the point where the rope first makes contact with the spools. Prior to the SES tests, Marlow Ropes recovered the remaining six samples and added coverings and a plastic outer coating in the splice area to improve this wear situation.

Figure B14 shows MQIQ 1, where the outer cover has been worn away. The secondary inner cover still appears to be intact however. Figure B15 shows the failure site of MQIQ 2, which was at one of the splices. Figure B16 shows the eye at the opposite end where it can be seen that the outer cover has worn away.

Figures B17 and B18 show overviews of the damage on SES 1, another reference test with no damage applied.

Figure B19 shows the failure site of MQIQ 4 (0.7 inch knife cut), which was predominantly at the area of induced damage. Figures B20 and B21 show the wear that took place at both eyes. In Figure B20 the subropes were not exposed because of the inner protection. However at the other eye (Figure B21) subropes have been exposed. Figures B22 and B23 show damage to SES 2 and SES 3 respectively, each having the 0.7-inch knife cut. The Table B-3 above shows that these samples contained failed subropes either at the damage site or at the toe of one of the splices.

Figures B24, B25 and B26 show damaged photographs of SES 4, SES 5, and SES 6 respectively. In these tests with a 0.5-inch knife cut, subrope failures occurred as shown in Table B-3 above.

Studies on the Knife Cutting of Test Ropes

The break test results pointed to some possible inconsistencies in knife cut results. Specifically the knife cut data for SES 3 appeared to provide a lower than expected % area cut result. Our first effort in explaining the anomaly was to compare the actual knife cutting data with theory. We built a spreadsheet to calculate the percent area cut of a perfect circular cross section using a predetermined knife cut depth. Figure B27 shows data points compared with the theory for a 3.3-inch diameter perfect circle, assumed to be our rope diameter, excluding the jacket.

The data points on the figure come from the cutting tests described in Table B-4 below. To confirm the % area cut for the SES tests, we began confirming the result of the knife cuts by counting the actual strands cut after the knife cut was made. From this counting procedure we could determine that a given knife cut had the effect of inflicting partial or full damage to a given number of subropes, resulting in a given number of "equivalent" fully cut subropes. We compared the equivalent number of fully cut subropes with the total number of subropes (28) to determine the experimental value for % area cut.

Test	Cut	Equiv. No. SR	No. SR	% Area Cut	Failure
MQIQ 4	0.7	No data			336.3
SES 002	0.7	4.064	6	14.51	Storm
SES 003	0.7	2.757	5+	? 9.85	Storm
(DS 3)	0.7	4.070	7+	14.51	n/a
SES 004	0.5	1.710	4	6.11	306
SES 005	0.5	2.907	5+	10.38	Storm
SES 006	0.5	1.770	4+	6.32	355
(DS 1)	0.5	2.167	6	7.74	n/a
(DS 2)	0.4	1.063	4	3.80	n/a

To confirm the cuttings on the SES test samples, we needed to make additional "trial" cuts to check our techniques and determine the reason for the apparent low % area cut value for sample SES 3. Remembering that we had stored some footage of Marlow Rope of the same size, recovered from the DeepStar[5] test deployment in the Gulf of Mexico, we extracted a segment to allow us to perform test cuts using the same butcher knife cutting device used in the SES cut rope tests. Results of these test cuts are shown as DS 1, DS 2, and DS 3 in the table. Detailed data from the cut studies are shown in Appendix BB.

Comparing area cut results for SES 2, SES 3 and DS 3, all 0.7-inch cuts, we see that the SES 3 area cut percentage of 9.85 did not agree with the 14.51 values for SES 002 and DS3. Clearly some problem in measurement occurred. Using Figure B-27 to compare experiment with theory, we find the following:

1. In general, the experimental results fall below the theory by a difference of about 6% area cut – a pretty large difference. This will be explained below

2. The results for the 0.5-inch cuts and the 0.4-inch cut support the finding that the SES 3 result is in error. We have no explanation for this except that it was human error.

3. For a given knife cut depth, the amount and severity of strands cut can vary. Compare the % area cut for SES 5 with that for SES 4 and DS 1. (The SES 6 cut was made by strand cutting to match SES 4, and not by knife cut.)

The first finding was not completely a surprise to us. Although we tried to maintain a round cross section during the cutting, the pressure of the cut probably flattened the rope cross section such that more subropes were cut than a % area calculation would show. Secondly, we found (see Figure B-5) that the cut fibers would want to expand outward, tending to raise the angle iron cut- depth supports on the butcher knife, and restrict the blade from cutting so deep.

The third finding may be another explanation for the second finding, but the degree of cutting damage is affected by how many subropes in their loose bundle happen to be in front of the knife blade.

Figure B1. Overview of the SES L2000 Test Machine.

Figure B2. Close-Up of the Moving End of the SES L2000.

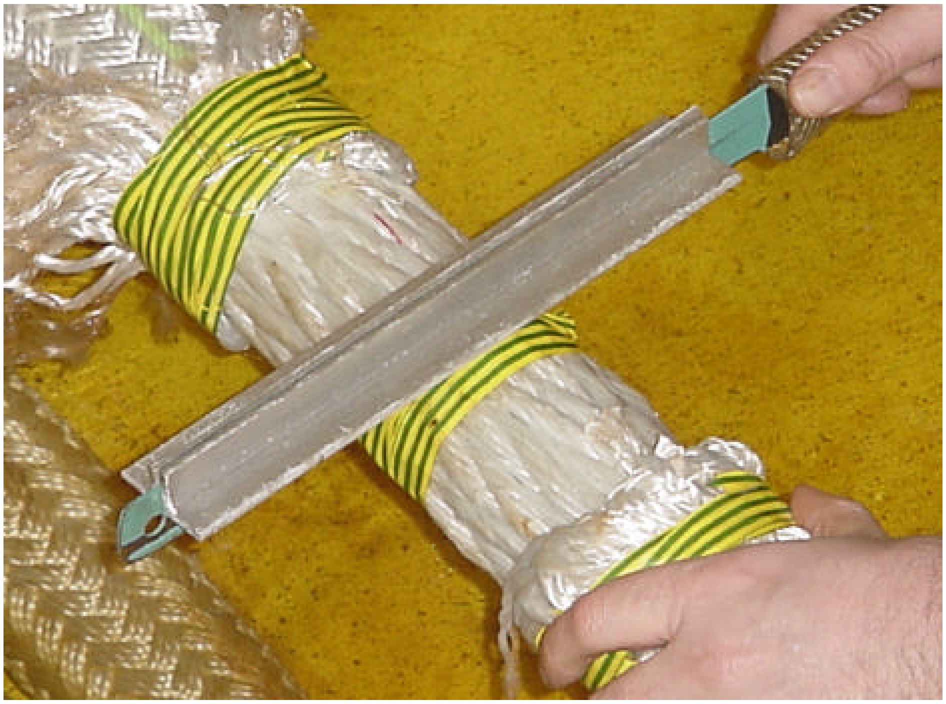


Figure B3. Knife Cut of Rope at NEL.

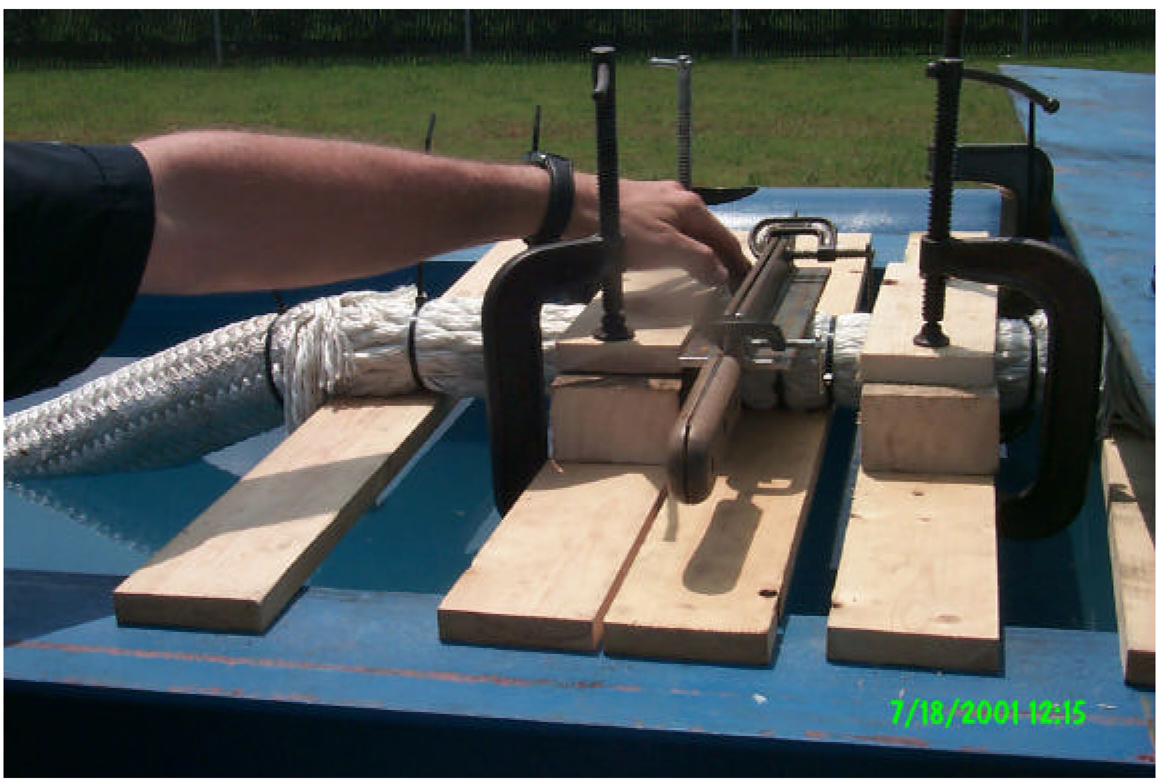


Figure B4. Butcher Knife Cuts at SES.

Figure B5. Close-Up of the Cut Rope. Note Raised Cut Region.

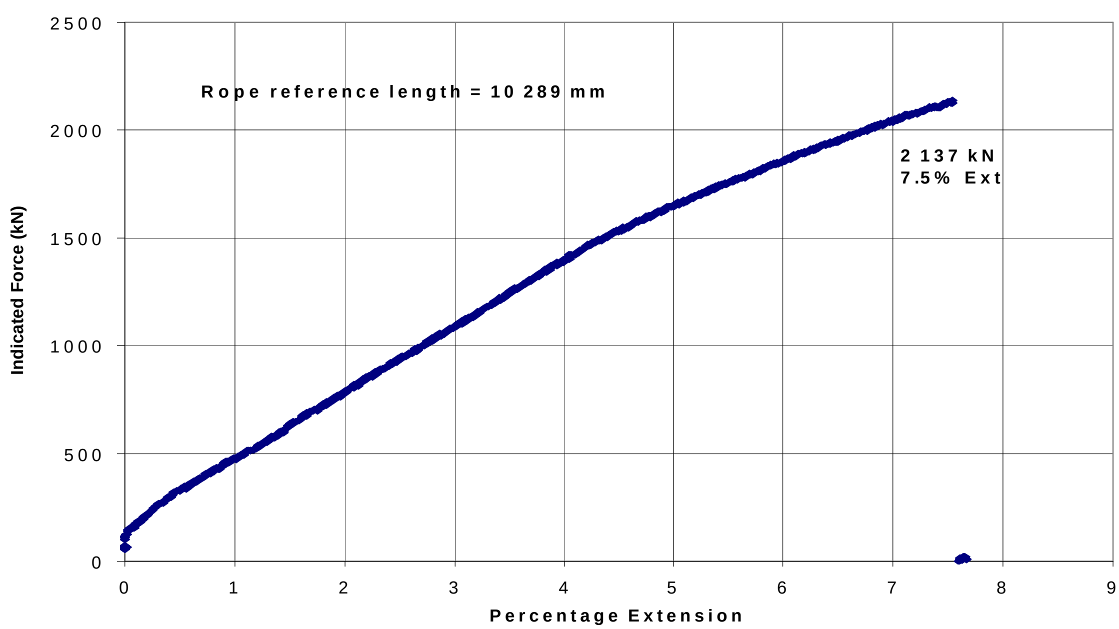


Figure B6. Load vs. % Elongation Curve for MQIQ 1.
Note 1000 kN = 224.8 kips.

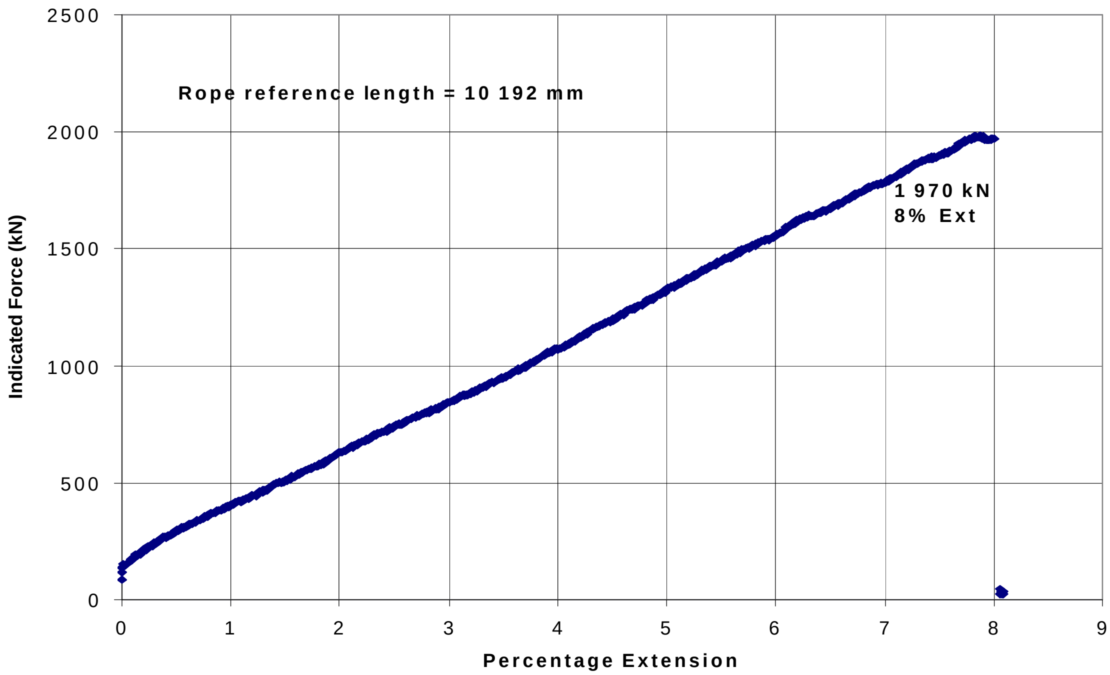


Figure B7. Load vs. % Elongation Curve for MQIQ 2. Note 1000 kN = 224.8 kips.

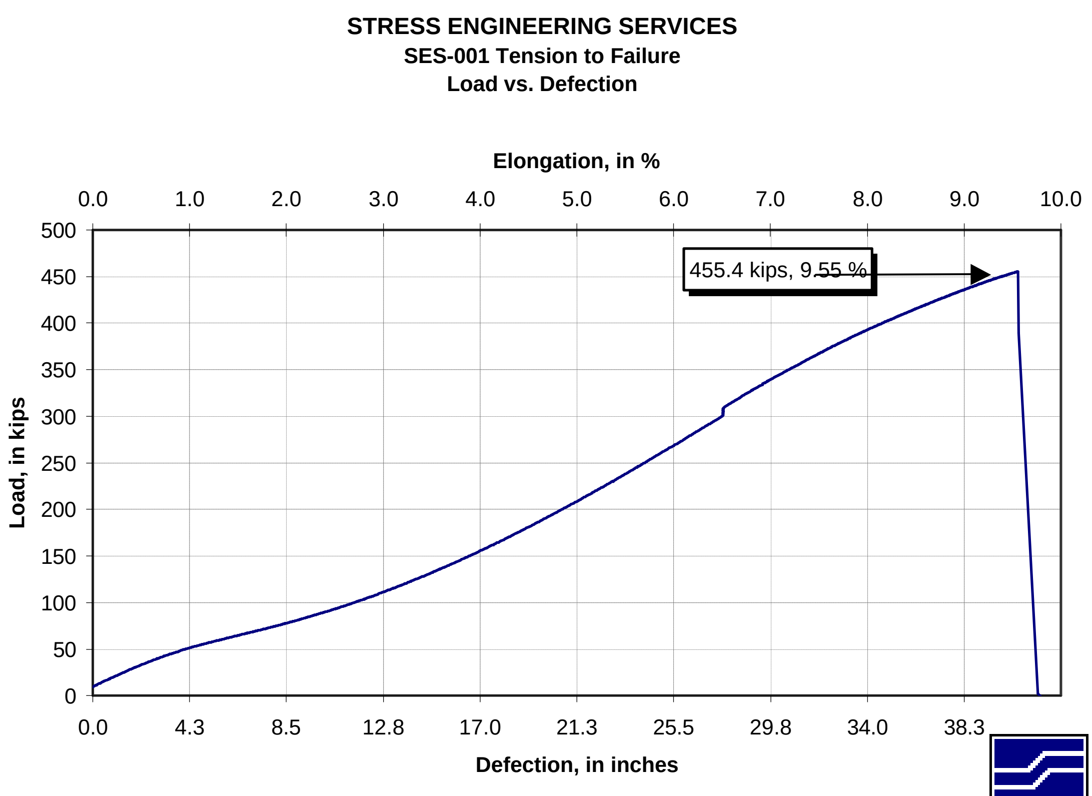


Figure B8. Load vs. % Elongation Curve for SES 1.

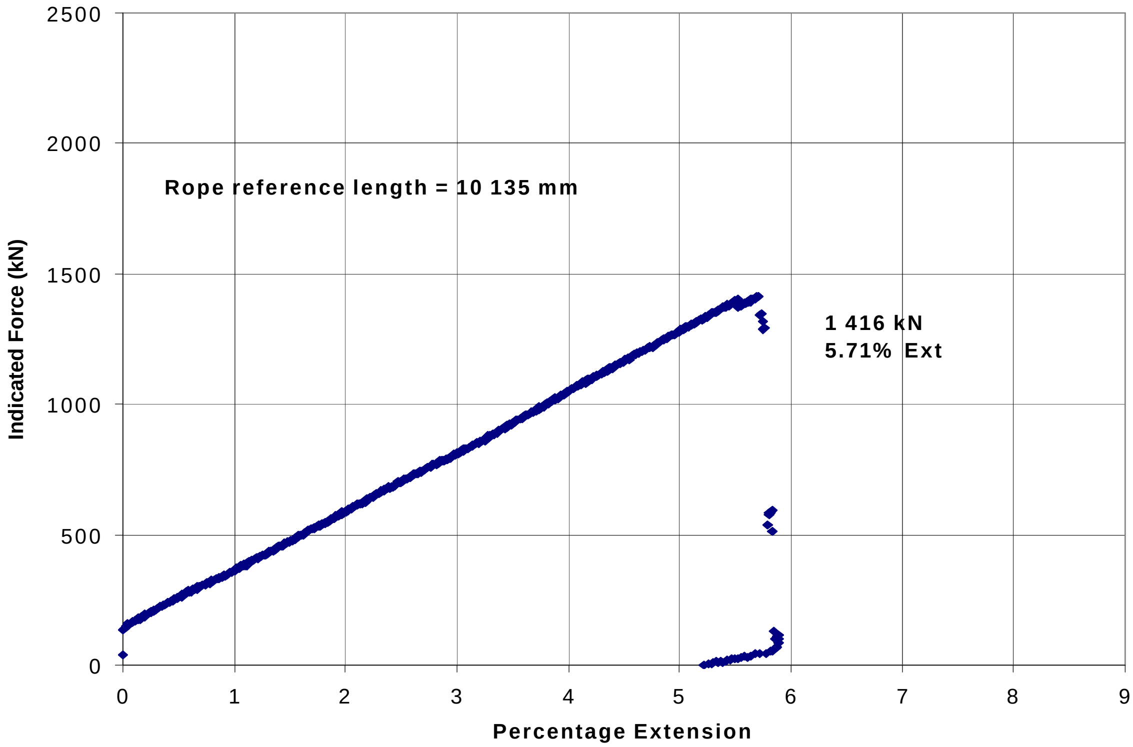


Figure B9. Load vs. % Elongation Curve for MQIQ 4. Note 1000 kN = 224.8 kips.

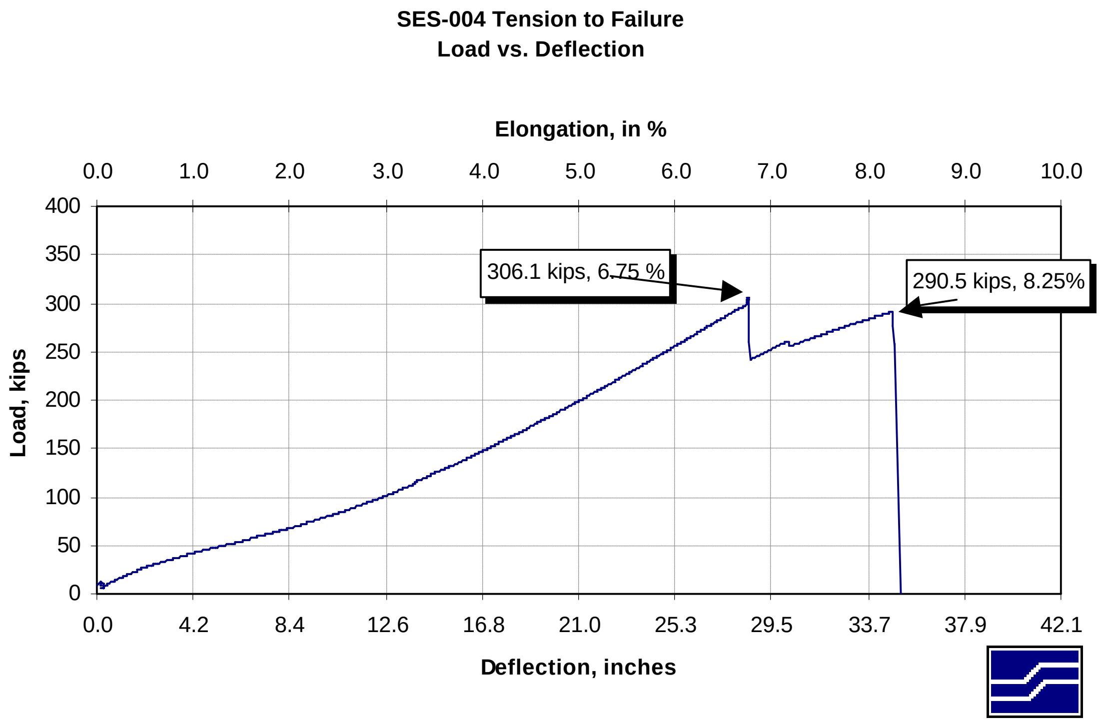


Figure B10. Load vs. % Elongation Curve for SES 4.

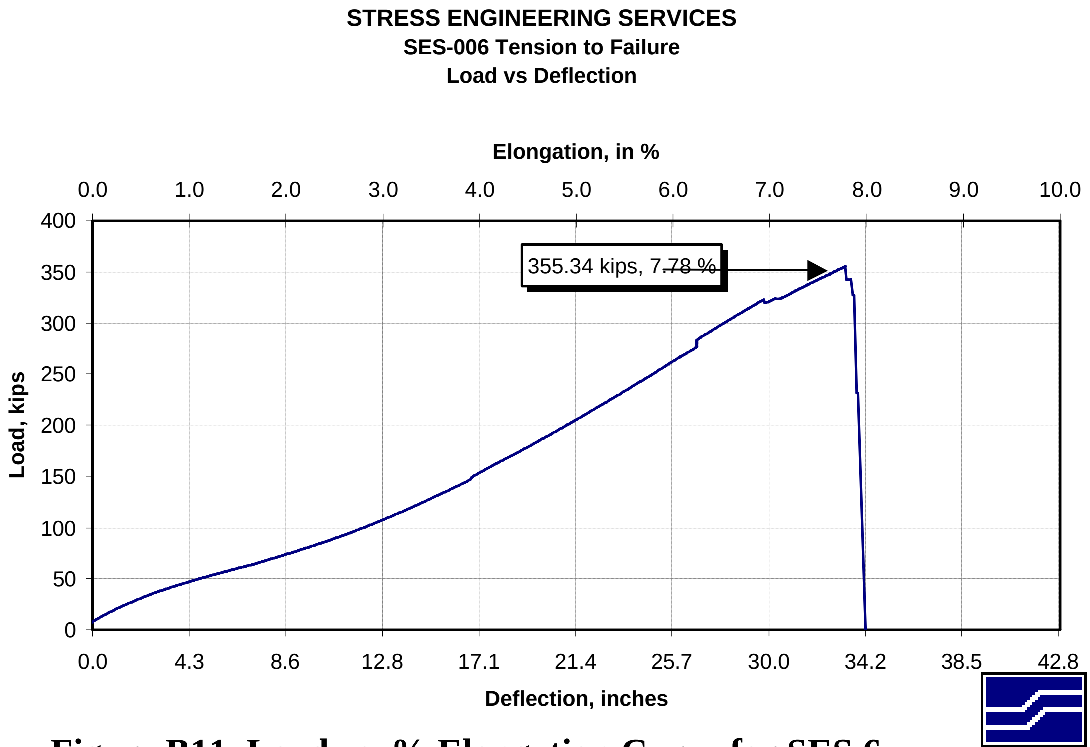


Figure B11. Load vs. % Elongation Curve for SES 6.

Figure B12. Photograph of Splice Rotation on SES 2. Note Lack of Symmetry.

Figure B13. Close-Up of Joining Point of Splice.

Figure B14. Photo of Wear in Outer Cover at Upper and Lower Tangent Points.

Figure B15. Failure of MQIQ 2 at One of the Eyes.

Figure B16. Wear of Eye at Opposite End of MQIQ 2.

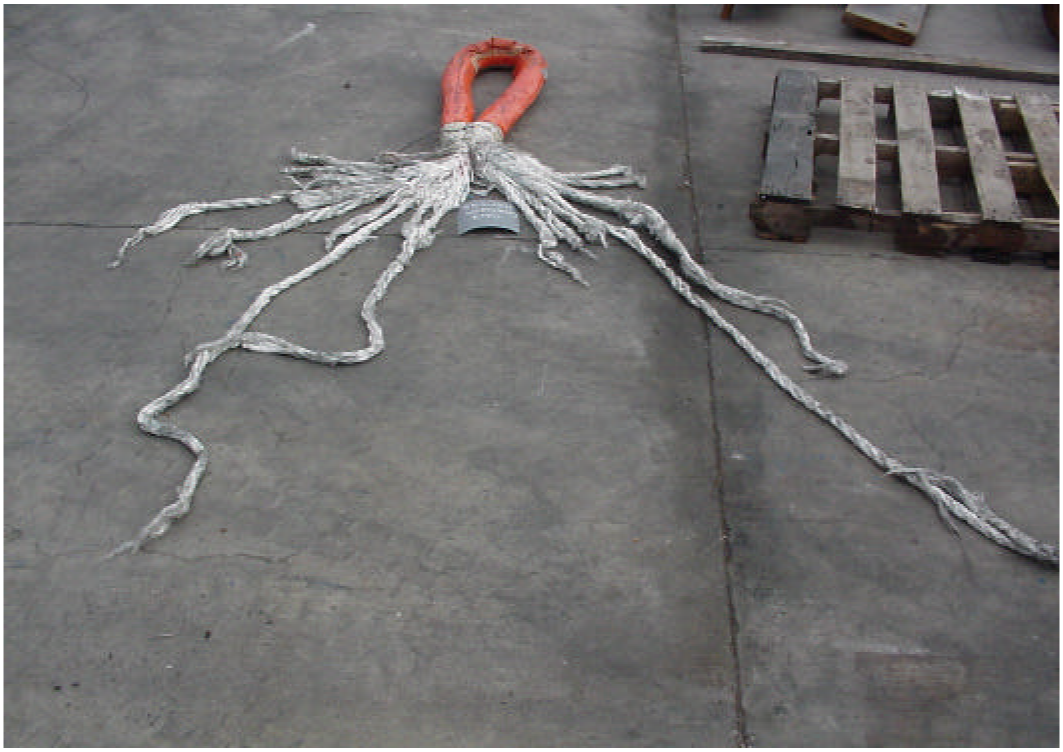


Figure B17. Damage of SES 1. First End.

Figure 18. View of Other Splice of SES 1.

Figure B19. Failure of MQIQ 4 in the Center Section.

Figure B20. Wear of Outer Cover of Splice in MQIQ 4.

Figure B21. Eye Wear at Other End.

Figure B22. Failure Photo of SES 2.

Figure B23. Failure Photo of SES 3.

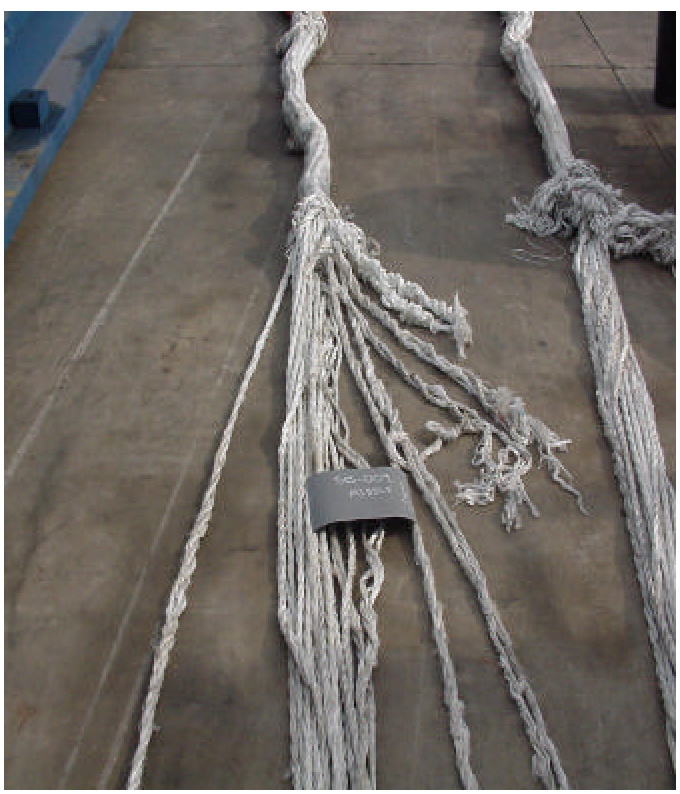


Figure B24. Failure of SES 4.

Figure B25. Failure Photo of SES 5.

Figure B26. Failure Photo for SES 6.

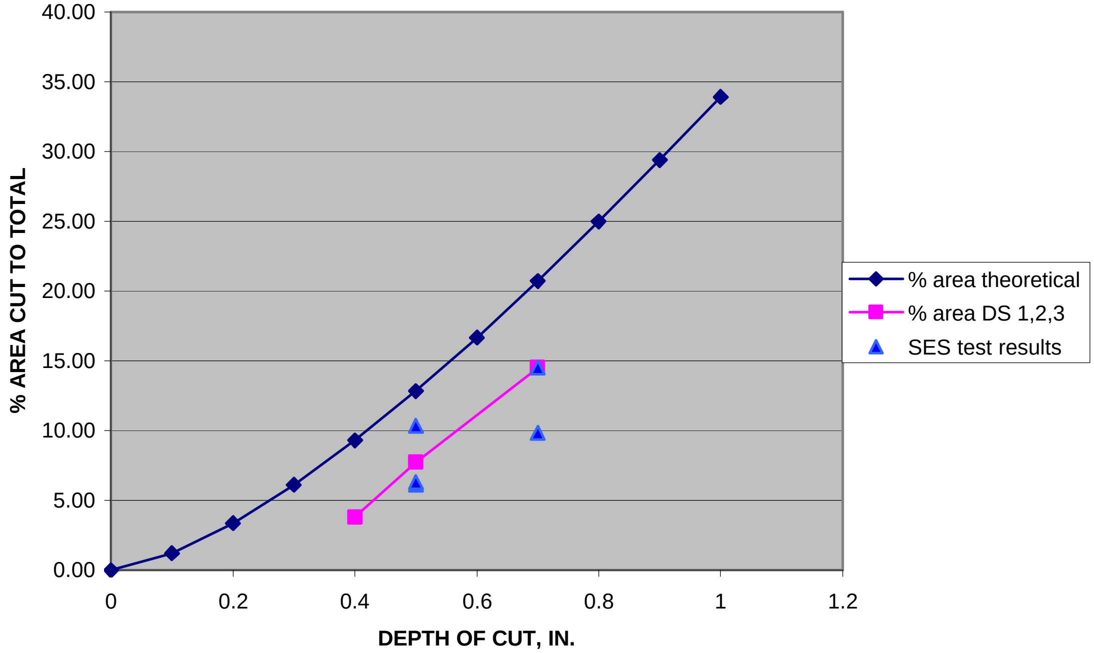


Figure B27. Comparison of Knife Cut % Area Theory vs. Test Data.

PART C: SPLICE EFFECTS ON DAMAGED ROPE RESIDUAL BREAKING STRENGTH

Introduction

After test results for SES 2 failure were initially evaluated, BP asked SES to perform a more detailed forensic evaluation on the failed rope sample. Objectives of this evaluation were to:

1. Confirm that the subropes were properly spliced in pairs according to the Marlow design.
2. Attempt to determine the mechanism of failure based on detailed inspection of the rope body and the splices.

Conclusions

1. We determined by forensic investigation that the subrope pairs were mated correctly in the splices on each end of SES 2.
2. We have determined for SES 2 that the unique design of the new splice causes loading conditions in the subropes that do not fit the "reduced area concept" being proposed by industry for determining the residual strength of damaged (cut) rope assemblies. We believe that this result can be true in general for all Marlow ropes terminated with the new splice design.
3. The new splice design causes the rope to act as if half of the total rope force must be carried in each side of the two-sided rope assembly, regardless of the number and condition of subropes resisting the force. If a cut occurs on one side of the new Marlow splice containing 14 subropes, the cut subrope condition will cause the uncut subropes on that side to try to resist half of that force as if they were not cut, while the 14 uncut and undamaged subropes on the other side are resisting the other half of the force. The first rope side with cut or partially cut subropes will break before those on the other side.
4. If a Marlow 3-part subrope is partially cut the remaining intact parts must also resist the force of the cut or partially cut part. This results in overload of this subrope, and it will break before the others.

These conclusions will be explained in more detail in the evaluation results that follow.

Initial Rope Findings

Before removing the sample SES 2 from the test machine, examination of the rope occurred. Figures B12 and B13, shown previously, are photographs of the splice region of SES 2. Before testing, this splice was symmetrical about the centerline of the rope midsection, but after the testing machine stopped based on extension limits being exceeded, the splice appeared asymmetrical, indicating that subropes had slipped around the thimble.

After removing the safety covers from the water tank, in the center of the tank, we found that only 14 of the 28 subropes were still tensioned and resisting load. The remaining subropes were either cut and then broken, or not cut and slack. The cut/broken subropes are shown in Figure C1.

Figure C2 is a photograph of an interesting condition at the toe of the splice and extending toward the midspan of the rope assembly. One can clearly see that even in the water tank, the jacket is bulging beyond its nominal diameter. We found that the slack rope (broken and unbroken) had a tendency to wedge under the jacket, presumably due to cyclic displacements resulting from the cyclic loading pattern.

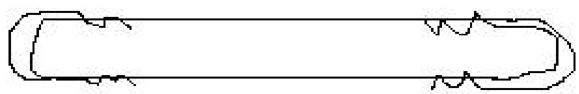
Findings From Disassembling Rope

Figures C3a and C3b show the plastic coating on the splice for SES 2. The plastic coating shows damage, but the orange protection coverings below it showed no damage, so the coating damage is superficial.

Figures C4 and C5 show SES 2 with the rope jacket removed. The inner two bunches of subropes are the undamaged subropes that were holding tension when the machine shut down. The outer two bunches represent either slack but undamaged/uncut subropes or cut/broken subropes. Note that the outer two groups of subropes show surface patterns caused by their being wedged under the jacket as shown previously in C2.

Figure C6 shows the eye splice with outer jackets removed. One can see three layers of subropes separately jacketed. The jacketed bundle closest to the thimble (layer 1) has 10 subropes in it. The middle bundle (layer 2) also has 10 subropes. The outer layer, farthest from the thimble contains 8 subropes. Thus all subropes are accounted for. Figure C7 (not for SES 2) shows how the layers typically form in the back of the eye and C8 shows how a cut through the splice section (not SES 2) shows the three jacketed layers in the "round" configuration of the splice.

Each of the 28 subropes (14 right lay and 14 left lay) has a unique color code to identify it. The splice design calls for matched "A-B"pairs to be joined together like this:



By completely disassembling the rope into subropes, we were able to determine that all of the 14 subrope pairs that were designed as matched were indeed properly matched at each end for each subrope pair. This confirms that the splice was, in general, constructed as designed. We did not look for details other than this.

Damaged Rope/Splice Failure Mechanism

Based on our investigation of SES 2, we developed a hypothesis for the mechanism that caused sample SES 2 to break during the storm cyclic loading series. Figure C-9 shows on the left a sketch of how the splice is bound together to make the two sides of the splice come together at the toe. If the binding rope is removed, the sides will separate from each other as shown on the right hand side of the figure. This means that the left and right hand group of subropes must each handle half of the total force.

Based on the previously shown sketch, we believe that a purposefully cut subrope will be required to carry the same force as the subrope spliced to it. If the force is sufficiently high to break the cut rope side, the mating subrope will continue trying to resist its loading, but since the subrope to which it is structurally joined is broken and slack, the intact subrope will pull into the splice, causing that subrope to slip through the eye, creating an unloading condition, and hence became slack. If the subrope pair we are discussing happens to lie in the first and inner layer of the splice, the curvature force of outer layers pressing on the inner layer could hinder the slipping. If, on the other hand, the subrope pair is in the outer layer of the splice, slipping to unload the undamaged subrope can more easily occur.

Figure C-10 is a simplified example of how forces would be handled in a rope spliced with the new design. If, for instance, 4 subropes were completely cut, and if the subropes in each side must resist half of the force, the effect of 4 subropes cut on the right side would leave the remaining 10 subropes to resist half of the force. Thus, the overload on the remaining uncut subropes is 14/10 or 40% higher than those on the opposite side. During the storm loading, the maximum load is 55% of the undamaged breaking strength of the sample. If one side of the splice has subropes with a 40% overload, the resulting load will be 55% x (14/10) or 77% of the breaking strength. If we assume failure occurs at 100%, approximately 8 subropes would need to be broken to produce a failure condition.

This result is in direct contradiction to the "reduced area ratio concept", where 4 cut subropes would transfer the load to the remaining 24 subropes, and the overload would be 28/24, or 16.7 % to all the remaining subropes. In this latter case, the expected breaking strength would be (100 – 14.7), or 85.3% of the undamaged breaking strength.

If the cut conditions are different, say if some of the subropes are partially cut, the test evidence suggests that the partially cut subropes will then fully break, again due to overload conditions. A three-part subrope that has one part cut, will be anchored by its matching subrope which is not cut or damaged, and this will want to transfer the full subrope force into the subrope with one part missing. ***We believe that the result will be that the remaining subropes are overloaded by as much as 50%, depending in part in the slack caused by the change in the helical geometry going from 3 parts into 2.*** Subropes to which these broken subropes are joined will then slip around the eye and go slack. We further believe that this result explains why the partially cut subropes break before the uncut subropes do.

References

1. Minerals Management Service (by Stress Engineering Services, Inc.); *Characterizing Polyester Rope Mooring Installation Damage*; November 2001.

2. DeepStar IV Project (by Stress Engineering Services, Inc.); *An Evaluation of Deepwater Polyester Rope Mooring Technology, CTR 4406*; November 1999.

3. American Petroleum Institute; *API Recommended Practice 2SM, First Edition*; March 2001.

4. BP Upstream Technology Group; *Deployment Readiness Plan for Deepwater Polyester Moorings for FPS*; September 2001.

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

Appendices

AA NEL Report: Polyester Rope Damage Tests, July 2001.

BB Results of Analysis to Determine Percent Rope Cut By Counting Cut Strands.

Figure C-1. Broken/Cut Subropes Found After Test SES 2 Stopped. Note Tensioned Ropes in the Water.

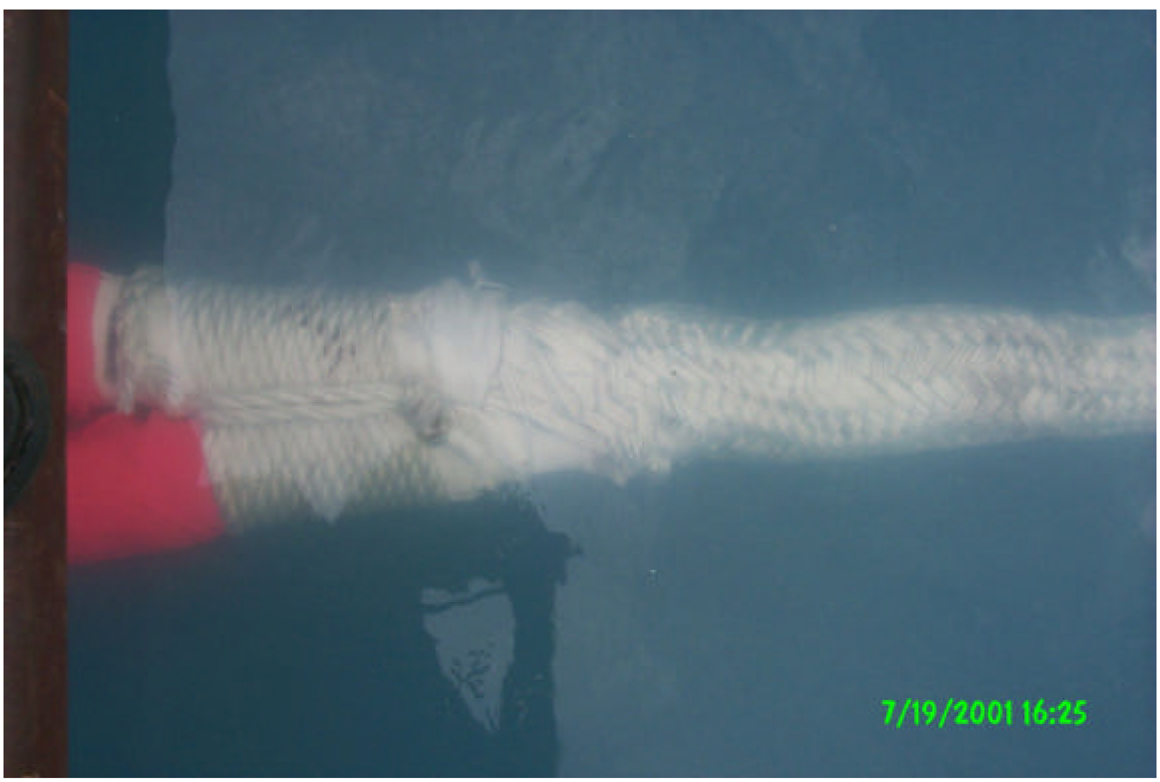


Figure C-2. Photo of Broken/Cut "Bunching Up" Under the Cover. Note Also the Asymmetry of the Splice.

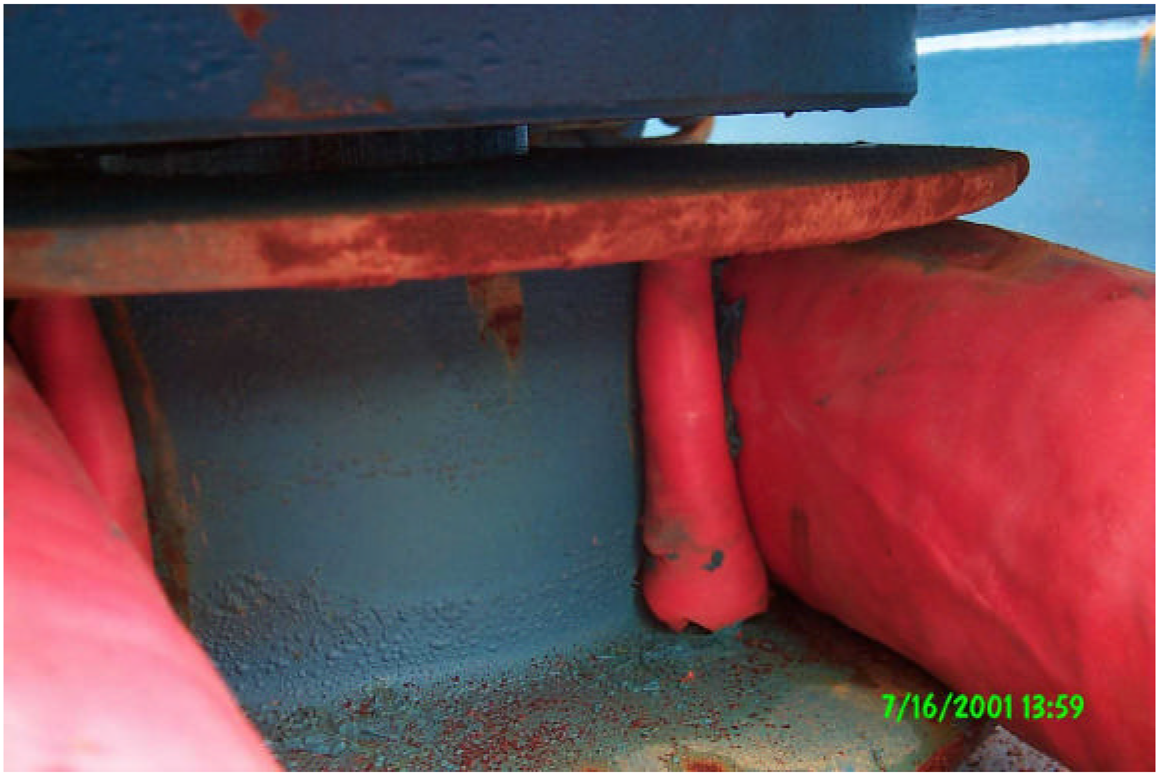


Figure C-3a. Coating Extrusion Damage Caused by Thimble Loading.

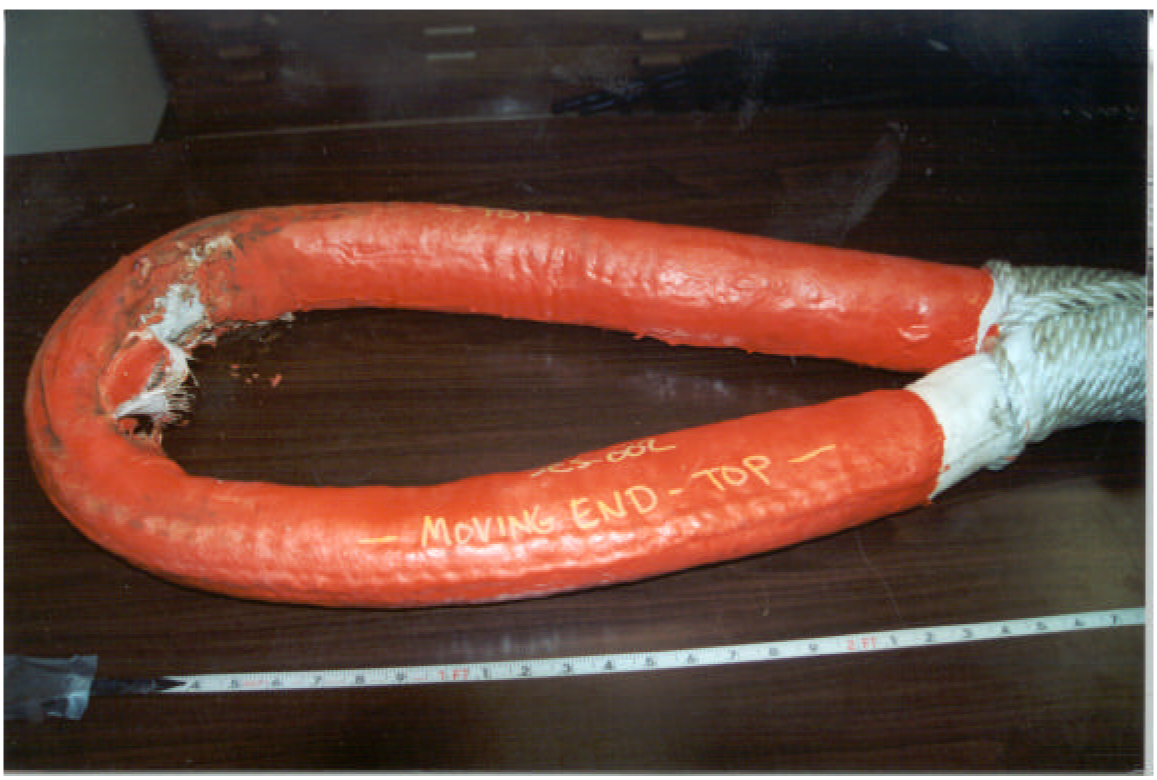


Figure C-3b. Photo Showing Rope Removed, and Splice Plastic Coating Damage.

Figure C4. Sample SES 2 with Jacket Removed, Showing Inner Two Bundles of Undamaged Subrope, and Outer Two Bundles of Broken/Cut Subrope.

Figure C-5. Close-up of SES 2 Showing Outer Bundles Containing Subropes Affected By Bunching Up Under the Jacket.

Figure C6. SES 2 Eye Splice Region with Outer Jackets Removed. Note Subrope Bundles in Three Layers.

Figure C7. This Photo (Not for SES 2) Shows how Layers Reside in Eye.

Figure C8. Cut Through Eye Cross Section Showing Three Layers.

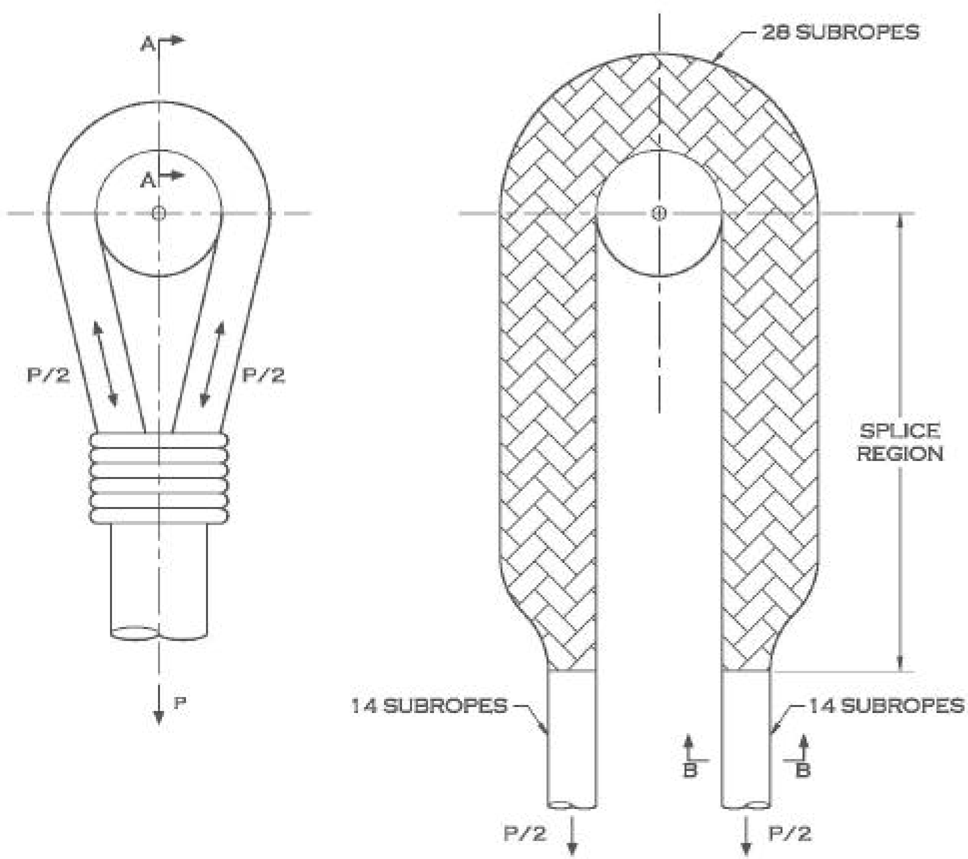


Figure C9. Sketch of Eye Design.

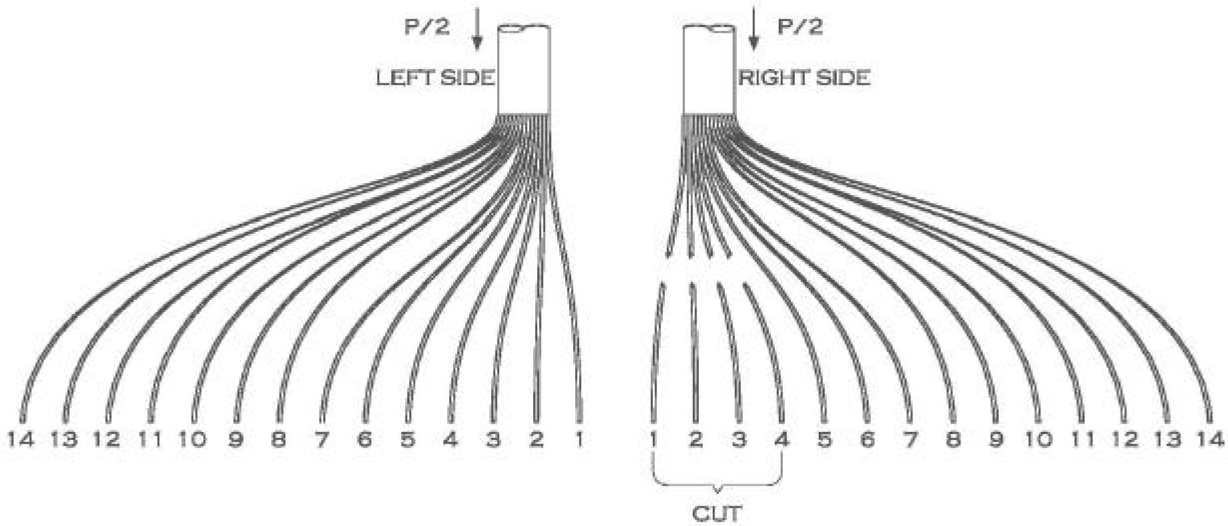


Figure 10. Sketch Showing Effect of Cut Subropes.

APPENDIX AA

Polyester Rope Damage Tests

A Report for

Stress Engineering Services Inc
13800 Westfair Drive
Houston
Texas 77041

Prepared by: ………………….. Date: ..………....
Dr N F Casey
Section Manager, Fatigue

Approved by: ………………….. Date:..…....………
Mr R Whitson
Section Manager, Dynamics & Analysis

Product Engineering Services	*Direct Tel: +44 (0) 1355 272763*
National Engineering Laboratory	*Direct Fax: +44 (0) 1355 272851*
East Kilbride	*Email: ncasey@nel.uk*
GLASGOW G75 OQU	
UK	*Switchboard: +44 (0) 1355 220222*

SUMMARY

The purpose of the work described in this report, is to obtain some base data on the strength loss associated with the introduction of simulated mechanical damage into polyester rope, with a view to generating some provisional discard information.

Rope samples were subjected to simulated storm runs under sinusoidal loading before being subjected to retained break strength tests. Some of the ropes had induced damage and others did not. Nine Marlow polyester Superline rope samples, with ‘standard’ splices, were originally delivered to NEL for testing. The rope from which the test samples were made consisted of 28 subropes and had a theoretical break strength of 1 886 kN.

For this first series of tests the damage was introduced by cutting individual subropes. After six tests were conducted it became apparent that, as a result of the splicing design, the induced damage had a tendency to ‘migrate’ to the splices and influence the break test by reducing the efficiency of the splices. As a possible consequence of this there does not appear to be an obvious correlation between either loss in residual strength or in extension to break with induced damage.

As a result of this significant finding, Marlow Ropes Limited took the decision to change their traditional splice design (for large mooring ropes only) to an improved design. The final test series (MQIQ) produced results for this improved, more damage resistance splice design. Although the ropes were of the same construction as the original samples the improved splices raised the theoretical break strength from 1 886 to 2 091 kN, a 10.9% improvement. For the second series of tests the damage was introduced by cutting the rope to a predetermined depth using a knife slice.

In addition to the revised samples, Marlow (at the request of Stress Engineering Services) also delivered two ex Deepstar samples that were previously in service in a Gulf of Mexico test. These would have formed the basis of a small extension to the study, however, one of the Deepstar ropes was inadvertently used for a ‘rope handling test’ (defined later) which was introduced into the test programme.

Part way through the second series of tests the 30 MN machine (after suffering a major failure) was permanently taken out of service, which meant that the test programme was terminated at NEL. The work will now be completed by Stress Engineering Services and it is hoped this report will assist in this process.

CONTENTS

AUTHORITY FOR WORK

Stress Engineering Purchase Order 6941-RRA dated 6 December 2000. Agreement for extra tests was given by email on 28 November 2000.

1 INTRODUCTION

The objective of the study reported here was to provide some provisional information on rope discard. This was to be achieved by evaluating the effect of externally induced mechanical damage upon retained strength of polyester rope after being subjected to simulated storm runs. The study originally called for nine ropes to be tested. After six tests were conducted it was decided to revise the splice design, therefore new samples were supplied. However, part way through the revised test programme the 30 MN machine (after suffering a major failure) was permanently taken out of service, which meant that the test programme could not be completed at NEL.

This report provides a detailed description of the test equipment, procedures and results of the study up to the point where it had to be terminated at NEL. The test programme will be completed by Stress Engineering Services in Houston.

2 ROPE SAMPLES

The original programme called for nine tests to be conducted. Nine Marlow polyester Superline rope samples, with Marlow ‘standard’ splices, were therefore delivered to NEL for testing. The ropes were made up of 28 subropes and had a theoretical break strength of 1 886 kN.

During the course of the work it became clear that, as a result of the splicing, the damage (although induced at mid length) effectively had a tendency to migrate to the splices and influence the break test by reducing the splice efficiency.

To overcome the problem Marlow supplied new samples with revised splices to minimise the effect of ‘damage migration’. Although the ropes were of the same construction as the original samples the improved splices raised the theoretical break strength from 1 886 to 2 091 kN. In addition to the first batch of new samples, Marlow (at the request of Stress Engineering Services) also supplied two ex Deepstar samples. These would have formed the basis of a small extension to the study. However, one of the Deepstar ropes was inadvertently used for a handling test (MQIQ 3), which was introduced into the test programme. Because it was tested inadvertently the theoretical break strength of 2 091 kN for the new replacement ropes was used to set the load values.

The splice design for the new rope was used for the Deepstar rope, except that the subropes could not be matched to predetermined subropes. Matching was impossible because the subropes were not coded in this older rope design.

3 TEST EQUIPMENT

3.1 30 MN Test Machine

Operation of the 30 MN test machine is servo-hydraulic, normally through eight hydraulic actuators providing for a maximum static load capacity of 30 MN and a cyclic load capability of 20 MN. The 30 MN static load capability is provided by a 450 l/min supply of oil at 330 bar, whereas the 20 MN cyclic load capability is provided by an oil supply of 3 000 l/min at 210 bar. The tension end of the machine is 18 m long and a working stroke of up to 5 m can be applied. Crosshead movement is monitored by four non-contacting temposonic displacement transducers positioned at the four corners of the moving crosshead.

The forces generated by the 30 MN test machine are measured and controlled by a balanced pressure system integral with the actuators which drive the crosshead. The standard force measurement system, which is based on differential pressure, has recently been supplemented by a 20 MN strain gauged load cell. This load cell is attached directly to the moving crosshead and the force output from this load cell has been used to generate the results presented in this report.

In order to meet the required combinations of load range and cyclic frequency provided in the test matrix, the machine was reconfigured to maximise the velocity of the moving crosshead. This involved disconnecting the four inner load actuators from the moving crosshead and hydraulically isolating them. The effect of this operation was to reduce the maximum cyclic load capacity of the machine from 20 MN to 10 MN but at the same time increase the maximum crosshead velocity from 50 to 100 mm/sec.

Figures 3.1.1 and 3.1.2 shows the test machine and the control room respectively. For safety reasons the control room is located away from the machine but in the same building.

A requirement of the project was to test the ropes (with the exception of the break tests) fully immersed in ordinary tap water. In order to achieve this a flexible tank was produced which fitted inside the machine. The arrangement was such that both of the machine’s clevis assemblies, to which the rope was attached, were contained within the tank. This meant that the entire rope sample was surrounded by water.

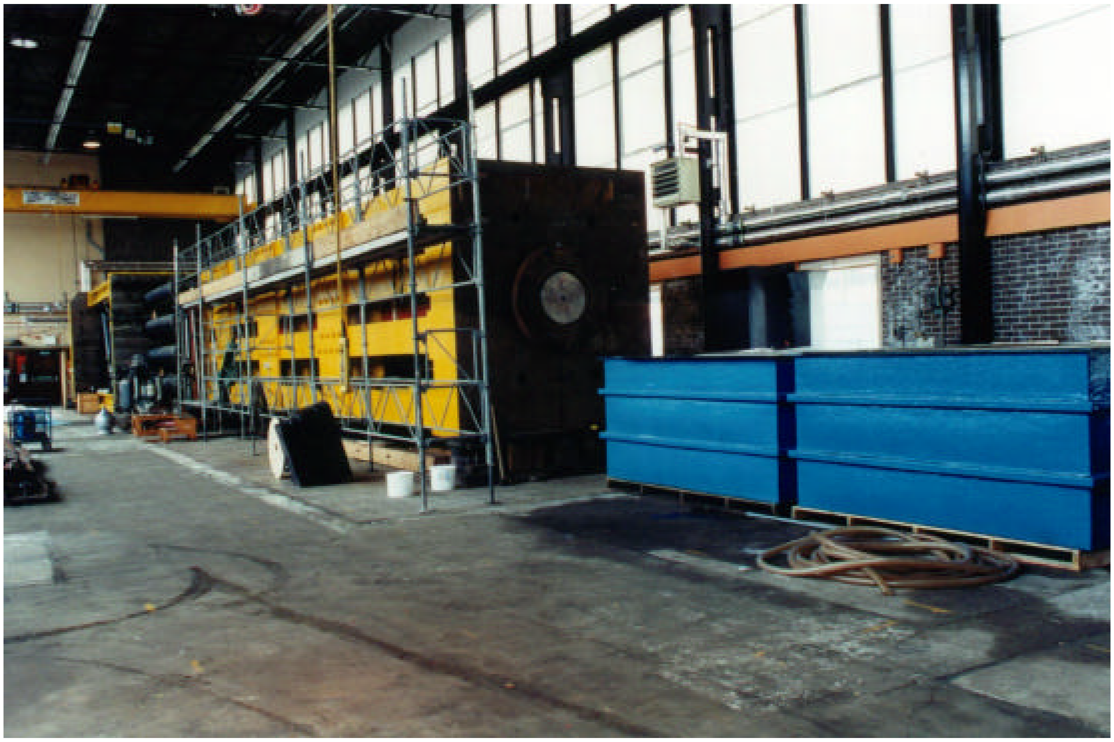


Figure 3.1.1 30 MN Test Machine

Figure 3.1.2 30 MN Machine Control Room

3.2 Data Acquisition

A data acquisition system using isolated measurement pods was used for the study. When operating under cyclic loading the system was pre-set to collect data during predetermined load/displacement cycles. Under these conditions the logger records around 50 values of load and displacement during a single load/displacement cycle. During the break test runs, the logger was set to collect load/displacement data on a continuous basis. The output from the data logger was imported into Microsoft Excel for post-test data processing.

4 CALIBRATIONS AND SYSTEM CHECKS

NEL is a registered ISO 9001 establishment and the study was conducted within the Product Engineering Services Centre.

Calibration of the standard force measurement system of the 30 MN machine is in accordance with BS 1610 Part 1: 1992 with the minimum calibration point being 1000 kN.

Since the ropes tested had an extremely low break strength in terms of the load capacity of the test machine. To provide confidence in the accuracy and repeatability of force measurement at low values, calibrations that had been performed for a previous study using a 2 MN reference load cell, are given. The machine was loaded ten times to an indicated load of 500 kN. The mean output from the reference load cell at a machine indicated load of 500 kN was 516.39 kN with a standard deviation of ±6.79 kN. The error was remarkably low at 3.28%.

Displacement calibrations were carried out, in accordance with an in-house document (NAM 10), using calibrated reference measuring equipment.

Load and displacement voltage inputs to the data acquisition system were checked using a calibrated direct current voltage source.

A functional check on the accuracy of the signal generator of the 30 MN machine is carried out periodically. Also a calibrated count time is used to verify the operation of the cycle counter on the 30 MN machine on an annual basis.

5 MEASUREMENT PARAMETERS

By collecting incremental values of load and displacement using the data acquisition system described in Section 3.2, the following length and load related properties were calculated.

Stiffness

This is the slope of the rising load portion of the fatigue load cycle and was determined using crosshead movement. A straight-line fit has been used in making the stiffness calculations, with correlation coefficients consistently in the high 0.9s.

Units - kN/mm.

NOTE: For a given rope, the numerical value of stiffness will depend upon the length of the sample over which it is measured (i.e. it is length dependent).

EA

This is modulus multiplied by the cross-sectional area of the rope or stiffness multiplied by length.

Units - kN.

Modulus (E)

Over the load range considered, stiffness can be used to determine modulus by multiplying the stiffness by the sample length, or rope gauge length, and dividing by the cross sectional area.

Units – kN/mm².

Reference Rope Diameter

The reference rope diameter is a calculated value using the following equation (provided by TTI for the testing and Optimisation Joint Industry Project).

$$\text{Reference diameter} = 0.0119 \times \sqrt{\frac{\text{Fibre denier} \times \text{Twist up-take}}{\text{Density} \times \text{Packing factor}}}$$

Twist uptake for low twist ropes = 1.05
Packing factor for parallel construction = 0.7

The packing factor is defined as the ratio between material volume and rope volume taking into account interstices between the filaments. The packing factors were used to define rope diameter and only applied in the calculation of modulus.

For the Marlow ropes:

Fibre denier = 30 240 000
Density = 1.38

Diameter = 68.225 mm
Cross sectional area = 3 656 mm^2

Note The cross sectional area of 3656 mm^2 was also used for the Deepstar rope.

6 TEST PROCEDURES

Table 6.1 provides the cyclic loading test matrix that was agreed between NEL and Stress Engineering Services at the start of the study. For each rope the test matrix was conducted twice. After that the ropes were subject to break testing. Test sequences 2 and 4 are simulated windward and leeward hurricanes respectively.

Upon receipt of the test samples they were each allocated with a unique test mark. These unique test marks have been used throughout the report: MODE series for the ropes with 'standard' splices, MQIQ series for the ropes with 'improved' splices. Care was taken to ensure that the sample was not damaged during installation of the sample into the test machine.

For the MQDE series of tests (standard splice design), the ropes were loaded directly around 179 mm diameter pins. For the later MQIQ series of tests (revised splice design), the ropes were placed around spools provided by Marlow. The spools were fitted to the 179 mm diameter pins. Normally the damage was introduced to the rope after it had been fitted into the test machine, but under no load. The degree of damage introduced was in accordance with instructions from Stress Engineering Services. For the MQDE series of tests, the damage was introduced by cutting individual subropes, taking care not to cut adjacent ones. For the MQIQ series of tests the damage was introduced by cutting the rope, with a knife, to a predetermined depth. This kind of damage produced both partial and complete damage, depending on what material was under the knife blade. After the damage was introduced (or after the rope was fitted into the test machine if no damage was required) the rope was fully submerged in tap water. It was then loaded to an indicated 2% reference tension and the pin to pin length taken.

After the test matrix was completed, the load was reduced to a nominal value, the water was drained from the tank and the rope loaded to failure at a loading rate of around 3-4 mm/sec.

During the cyclic load testing, machine load and crosshead displacement was recorded on a regular basis to provide information on modulus and rope length. For the break test, load and displacement data was recorded on a continuous basis. After the rope had failed the provisional location of failure was recorded.

Upon completion of the break test the sample was removed from the machine, laid out on the floor of the laboratory and the location of failure confirmed.

Relevant photographs were taken during the test programme.

With the exception of the handling test, the process was repeated for each rope.

Handling Test MQIQ 3

This test was introduced into the test programme at the request of Stress Engineering Services. The purpose of this test was to establish if rope handling, such as reeling from one drum to another drum after prior tensioning, adversely affects the retained breaking strength of the rope (prior bedding-in will be disturbed by handling). The specimen was therefore subjected to the matrix given in Table 6.1 but before the matrix was repeated the rope was taken out of the machine and subjected to the following handling procedure.

1. The rope was laid flat on the floor laying on side "A", with side "B" facing upward.
2. The rope was then rolled on a 17.5 inch (445 mm) drum with side B touching the drum to simulate a rope winding on a winch drum, with all the rope on the first wind (first layer). The end splices were not curled around the drum. The object was to get as many winds as possible on the drum under negligible tension.
3. The rope was then unwrapped from the drum and laid flat on the floor but this time having side B touch the floor. Step 2 was then repeated.

For the complete handling test steps (2) and (3) were repeated ten times. This resulted in sides B and A each being subjected to ten wraps, alternating between sides B and A.

Table 6.1
Test Matrix

Test sequence	Mean load (%Nominal strength)	Load amplitude (%Nominal strength)	Load range (%Nominal strength)	Cyclic period (Seconds)	Number of cycles
1	20	10	20	10	3000
2	40	15	30	10	2000
3	20	10	20	10	3000
4	15	10	20	10	2000

7 TEST RESULTS – MQDE SERIES

Table 7.1 gives details of the diameter calculations that were taken during the course of testing. The calculations were made, by measuring the rope circumference using a flexible tape. The distance between each diameter measurement was around 75 mm. The reference diameter measurement (D5) was around 800 mm away from D1 (towards the moving end of the test machine). The measurements were taken at approximately 2% tension.

In general, it can be seen from Table 7.1 that the rope diameter reduces during the first sequence of the matrix, with little or no change during the second sequence. This reflects the fact that most of the bedding-in is taking place during the first sequence.

<u>Notes on Damage Sites</u>

MQDE 1: (3 cut subropes). At the end of the first sequence (4th block or test run) the ends of the subropes were approximately 320 mm either side of the point where they were cut.

MQDE 3: (3 cut subropes). At the end of the second sequence (8th block or test run) the ends of the cut subropes were approximately 460 mm (towards the moving end of the test machine) from the point where the subropes were cut. Towards the fixed end of the test machine, the ends of the cut subropes were approximately 345 mm from the point where they were cut.

MQDE 4: (5 cut subropes). At the end of the first sequence the cut subropes were around 450 mm either side of the point where they were cut. At the end of the second sequence the ends of the cut subropes were now around 350 mm either side of the point where they were cut.

Table 7.2 gives the results of the retained break strength tests, which include maximum load, %extension to break and failure location. The %extension to break values are based on the reference rope length taken at approximately 2% of theoretical break load prior to the start of the test matrix. These reference rope lengths are also included in the table.

The associated load-extension plots for the break tests are given in Figures 7.1-7.6. It can be seen from the plots (and from Table 7.2) that the undamaged ropes (MQDE 2 and 5) yielded the highest loads and %extensions to break values. It is worth pointing out however, that with a theoretical break strength of 1 886 kN, only one of the ropes (MQDE 5) exceeded this value and only just with a load of 1 927 kN. There is around a 5.6% difference between the two break strength values. MQDE 2 yielded a break load value of 1 824 kN. Once damage has been introduced into the ropes the load and extension to break values both reduce.

Referring to the data in Table 7.2, there does not appear to be an obvious correlation between either loss in strength or extension to break with induced damage. In fact the average breaking load of the four tests with damage (MQDE 1 and 3 – 3 cut subropes, MQDE 4 – 5 cut subropes and MQDE 6 – 9 partially cut subropes) is 1 615±76 kN with a relatively low coefficient of variation of 4.7%. The average breaking strength of the two undamaged ropes is 1 876±73 kN. This gives a coefficient of variation of 3.9%, 17% lower than the damaged ropes. It is somewhat surprising that different degrees of damage result in similar break strength values. It was this finding, together with the failure locations of the damaged samples (with the exception of MQDE 6, all failed within the splice region) that led to the belief that the induced damage was propagating to the terminations an adversely affecting splice efficiency. This issue will be addressed in more detail by Stress Engineering Services, but the finding resulted in the MQDE series of tests being halted and new samples with revised splices being supplied by Marlow.

During the course of testing, load-displacement data was collected to calculate values of stiffness, EA and E. Only a snapshot of the data has been presented in Tables 7.3 and 7.4. Table 7.3 shows the data for the first sequence and Table 7.4 the data for the second sequence. The data for all six tests have been presented. The load displacement-plots used to provide the property data in Tables 7.3 and 7.4 are given in Figures 7.6-7.11. The ‘a’ plots represent the first sequence data and the ‘b’ plots the second sequence data.

Perusal of the tables and plots allow the following observations to be made:

- In general there is a marked increase in the properties from just after the start of the first block (or test run) in the first sequence to mid way through the same block. The effects of bedding-in are most noticeable during this period.
- The effect of mean load upon properties is apparent. The numerical value of the properties increase with increasing mean load.
- It can be seen from Figures 7.6a-7.11a that from just after the start of the first block (20±10%) of the first sequence to mid way through that block, that a noticeable increase in rope length takes place – due essentially to the bedding-in process. This increase in length was typically around 100 mm (~1%), based on the minimum load value.
- Again it can be seen from Figures 7.6a-7.11a that from mid way through the first block of the first sequence to mid way through the second block (40±15%) of the first sequence there is an increase in length of around 450 mm (~3.5%).
- However, from mid way through the second block (again Figures 7.6a-7.11a) to mid way through the third block (20±10%) the ropes have reduced in length typically in the order of 100 mm (~1%).
- There is a further slight reduction in length from mid way through the third block to mid way through the fourth block (15±10%). The biggest reduction in length during this period occurred in MQDE 1. For the remaining samples the reduction in length was quite small and consistent.
- A comparison between Figures 7.6a-7.11a and Figures 7.6b-7.11b reveals that, only between the first run of each sequence (the 20±10% runs), are the changes in length during the second sequence much less than those in the first sequence. This again shows that bedding-in is marked during the first run (block) of the first sequence.

Shown in Figures 7.12-7.16 (MQDE 1) and Figures 7.22-7.26 (MQDE 6), is a photographic record of the procedure adopted to induce damage. In the case of MQDE 1, where only 3 subropes were cut, the jacket was partially removed. However, for MQDE 6 where one strand was cut from 9 subropes (equivalent to 3 cut subropes) the entire jacket had to be removed locally for access.

The remaining figures (Figures 7.18-7.21 and 7.27) are photographs of the failure region. The exception to this is Figure 7.17, which shows the damaged are of MQDE 1 after the break test. The actual failure location was in one of the splices (Figure 7.18).

Table 7.1
Diameter Measurements
(Measurements in mm)

Test Mark	Damage	At start of test						After first sequence						After second sequence					
		Cut	D_1	D_2	D_3	D_4	D_5	Cut	D_1	D_2	D_3	D_4	D_5	Cut	D_1	D_2	D_3	D_4	D_5
MQDE 1	3 cut subropes	78.9	84.7	84.7	84.7	84.7	82.7	76.4	78.9	79.6	78.9	78.9	79.6	76.4	78.9	79.6	78.9	79.6	80.2
MQDE 2	Ref. Rope	D = 82.8						D = 79.6 (at end of 1st block of second sequence)						D = 79.6					
MQDE 3	3 cut subropes	80.2	84.3	85.3	84.7	84.7	82.7	78.3	80.2	80.2	80.8	80.2	80.2	76.4	79.6	79.6	79.6	80.2	78.3
MQDE4	5 cut subropes	74.5	84.0	83.4	83.4	83.4	82.7	70.7	75.7	73.2	75.7	75.7	78.9	71.3	79.6	75.7	73.2	76.4	79.6
MQDE5	Ref. rope	D = 83.1						D = 78.9						D = 78.9					
MQDE6	9 partially cut subropes	78.9						79.6						78.9					

Table 7.2
Type of Test and Break Test Results

NEL test mark	Type of test	Break strength (kN)	Rope reference length (mm)	%extension to break	Failure location
MQDE 1	3 cut subropes	1 698	10 410	6.44	At/around tail of splice.
MQDE 2	Reference test	1 824	10 335	7.05	At/around tail of splice.
MQDE 3	3 cut subropes	1 514	10 380	4.91	At/around tail of splice.
MQDE 4	5 cut subropes	1 619	10 332	5.86	At damage site.
MQDE 5	Reference test	1 927	10 261	7.1	At/around tail of splice.
MQDE 6	9 partially cut subropes	1 631	10 492	6.15	Clear length – probably at damage site.

Table 7.3
Property Data Acquired During First Sequence

CSA = 3 656 mm^2

		Just after start of 1st block	Mid way through 1st block	Mid way through 2nd block	Mid way through 3rd block	Mid way through 4th block
Test mark	Reference length (mm)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)
MQDE 1	10 410	2.7341 28 462 7.79	3.607 37 549 10.27	4.5111 46 961 12.85	3.9532 41 153 11.26	3.3548 34 923 9.55
MQDE 2	10 335	2.9674 30 668 8.39	3.7822 39 089 10.69	4.6163 47 709 13.05	4.2765 44 198 12.09	4.0991 42 364 11.59
MQDE 3	10 380	2.8841 29 937 8.19	3.4705 36 024 9.85	4.6454 48 219 13.19	3.9528 41 030 11.22	3.6795 38 193 10.45
MQDE 4	10 332	3.0184 31 186 8.53	3.5067 36 231 9.91	4.3792 45 246 12.38	3.7656 38 906 10.64	3.4609 35 758 9.78
MQDE 5	10 261	3.1408 32 228 8.82	3.8144 39 140 10.71	4.607 47 272 12.93	4.3398 44 531 12.18	4.143 42 511 11.63
MQDE 6	10 492	2.8771 30 187 8.26	3.5789 37 550 10.27	4.4719 46 919 12.83	3.7413 39 254 10.74	3.7328 39 165 10.71

Table 7.4
Property Data Acquired During First Sequence

CSA = 3 656 mm^2

		Mid way through 1st block	Mid way through 2nd block	Mid way through 3rd block	Mid way through 4th block
Test mark	Reference length (mm)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)	Stiffness (kN/mm) EA (kN) E (kN/mm^2)
MQDE 1	10 410	3.9624 41 249 11.28	4.4051 45 857 12.54	3.9315 40 927 11.19	3.7587 39 128 10.70
MQDE 2	10 335	4.4823 46 325 12.67	4.7004 48 579 13.29	4.3183 44 630 12.21	4.0572 41 931 11.47
MQDE 3	10 380	4.1284 42 853 11.72	4.6606 48 377 13.23	4.0021 41 542 11.36	3.6753 38 150 10.43
MQDE 4	10 332	3.8059 39 323 10.76	4.4222 45 690 12.50	3.8982 40 276 11.02	3.555 36 730 10.04
MQDE 5	10 261	4.3119 44 244 12.10	4.864 49 910 13.65	4.3701 44 482 12.67	4.0335 41 388 11.32
MQDE 6	10 492	3.8665 40 567 11.10	4.3723 45 874 12.55	3.9222 41 152 11.26	3.7507 39 352 10.76

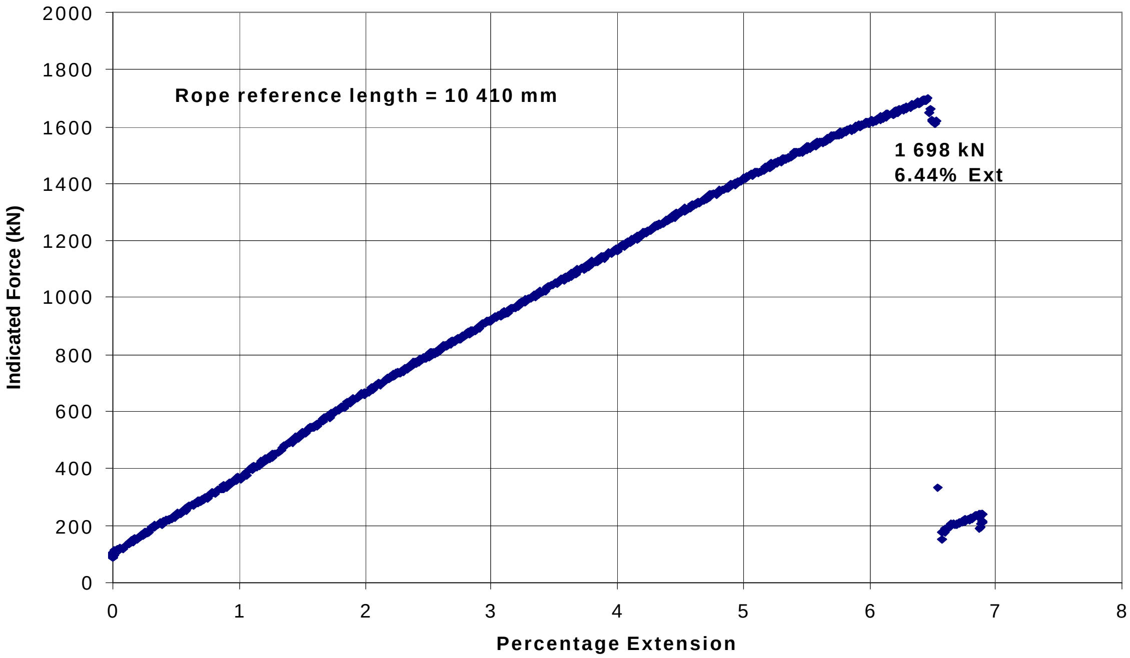


Figure 7.1 Load-Extension Plot: MQDE 1

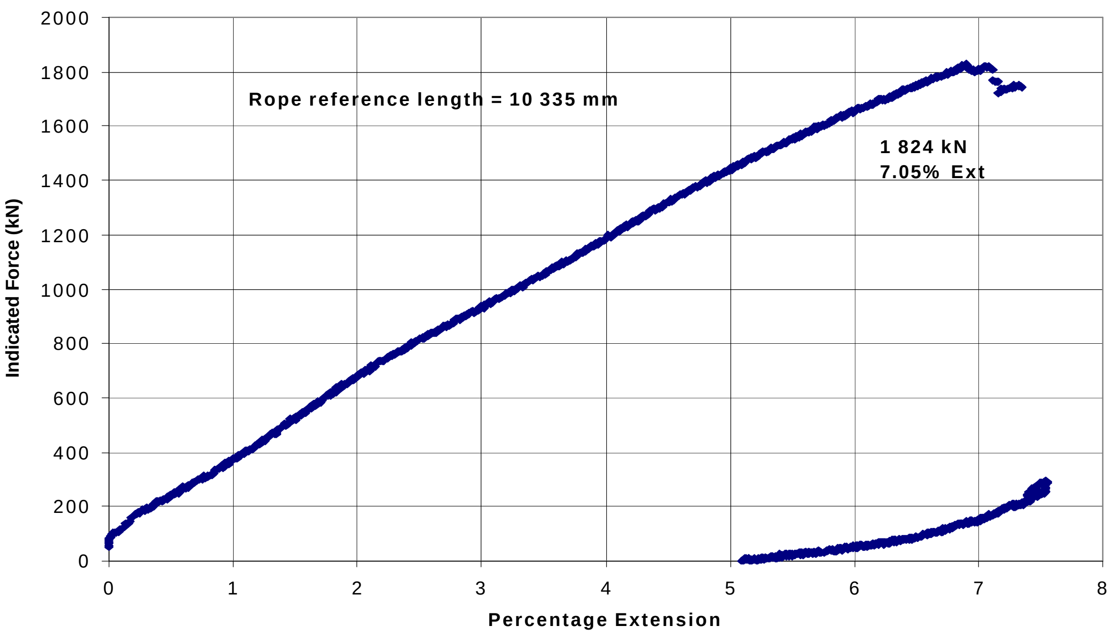


Figure 7.2 Load-Extension Plot: MQDE 2

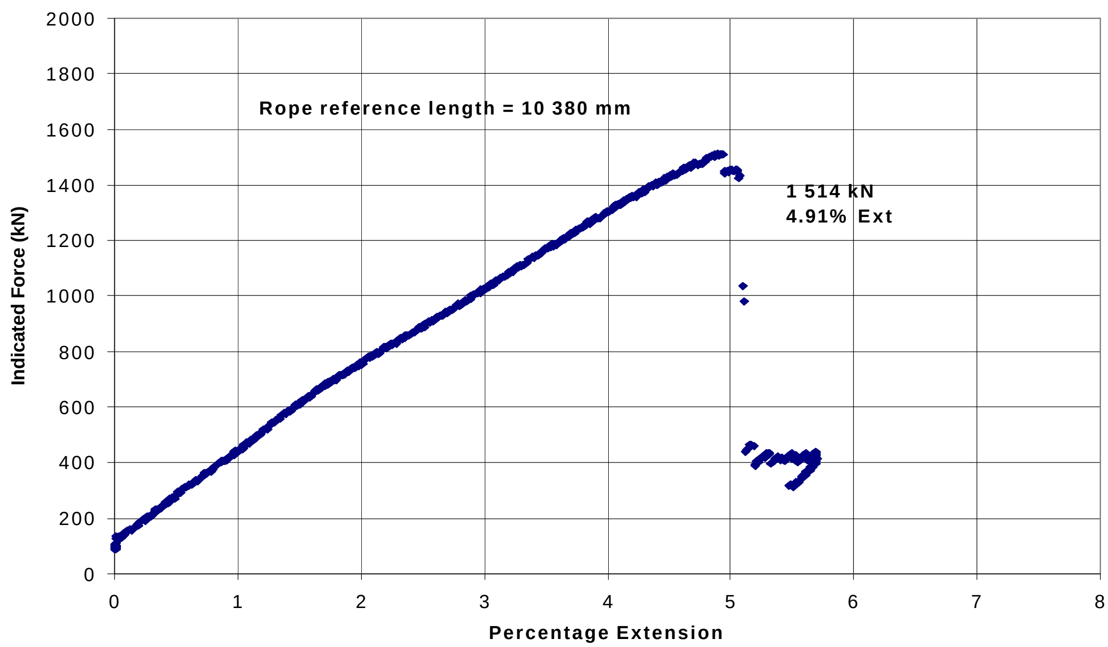


Figure 7.3 Load-Extension Plot: MQDE 3

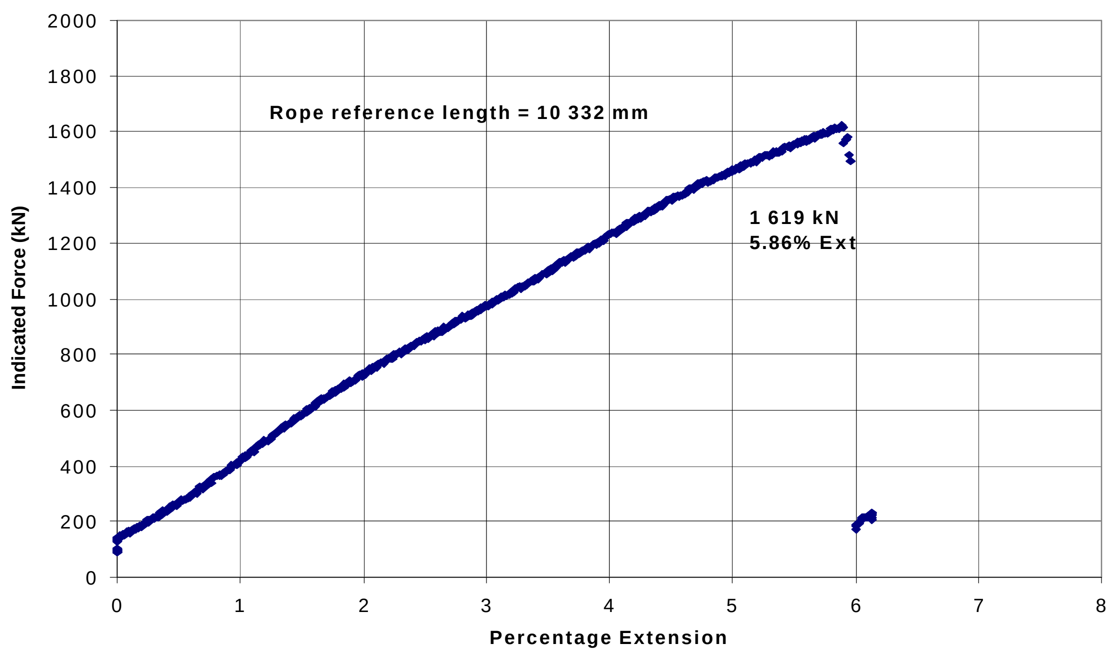


Figure 7.4 Load-Extension Plot: MQDE 4

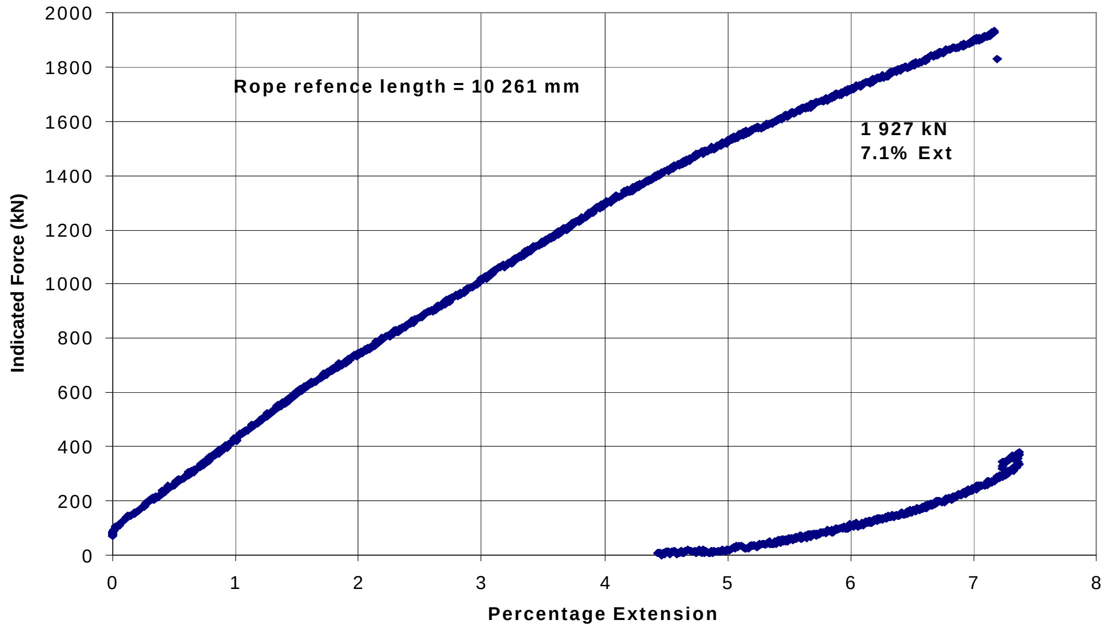


Figure 7.5 Load-Extension Plot: MQDE 5

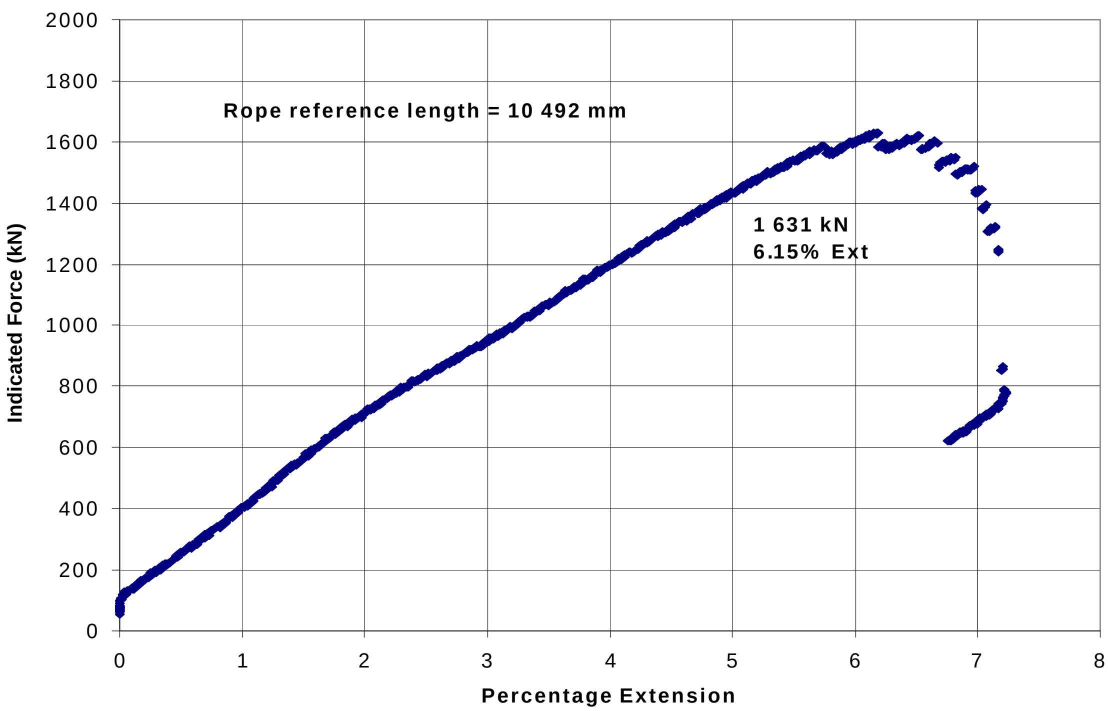


Figure 7.6 Load-Extension Plot: MQDE 6

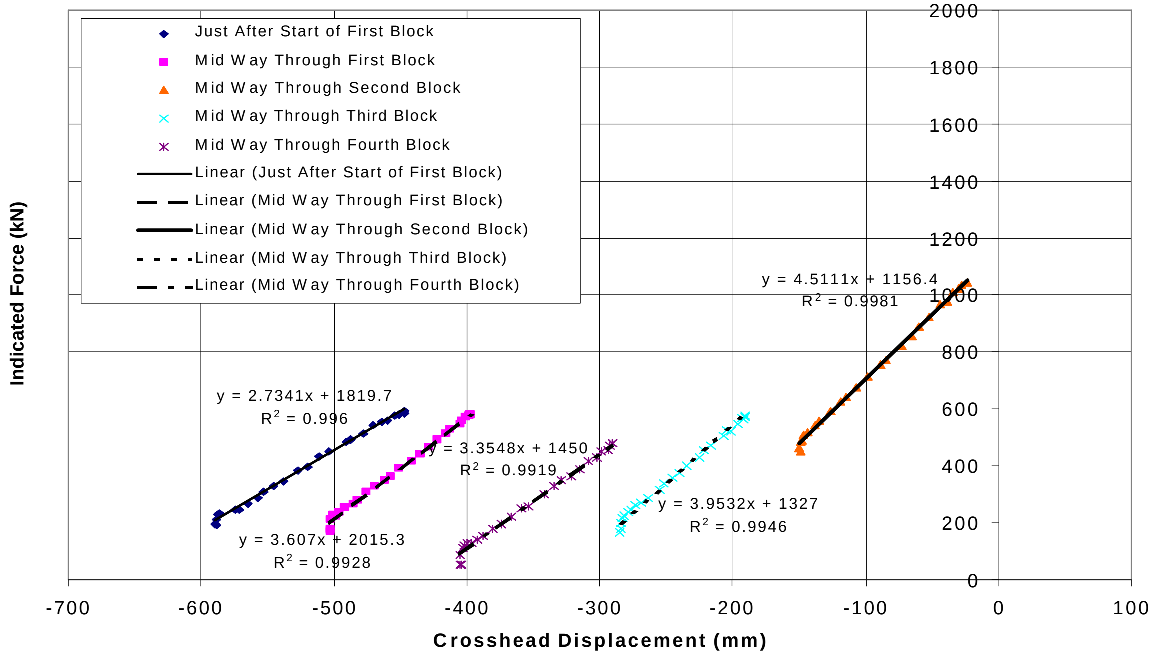


Figure 7.6a Example Load-Displacement Plots During First Sequence: MQDE 1

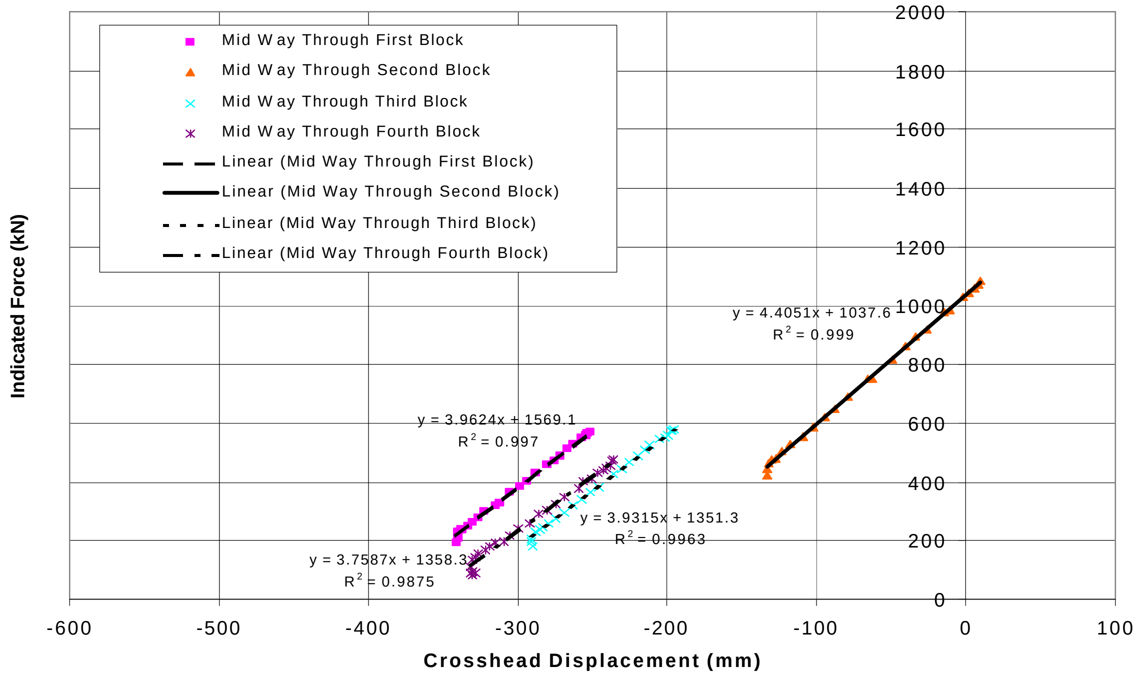


Figure 7.6b Example Load-Displacement Plots During Second Sequence: MQDE 1

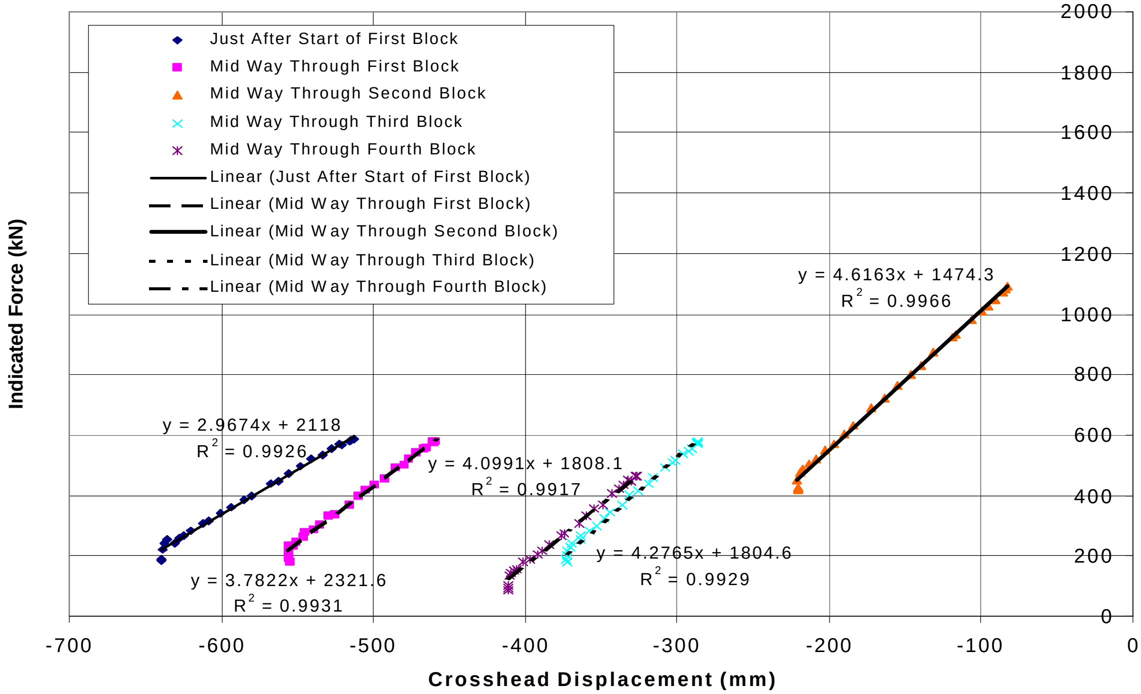


Figure 7.7a Example Load-Displacement Plots During First Sequence: MQDE 2

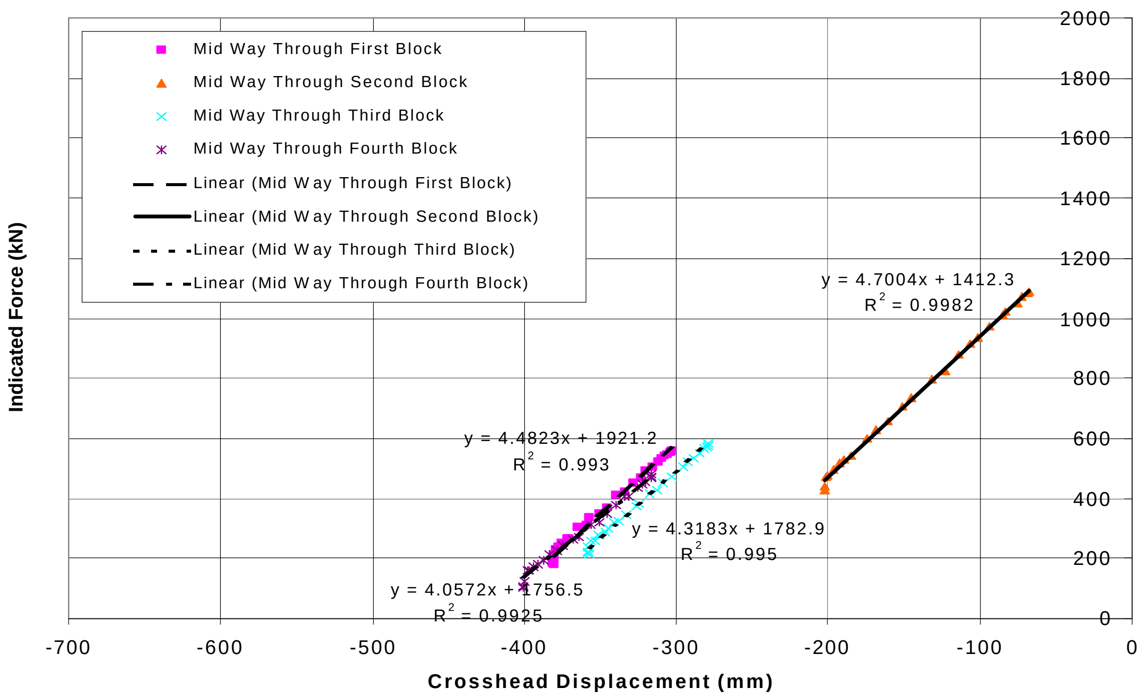


Figure 7.7b Example Load-Displacement Plots During Second Sequence: MQDE 2

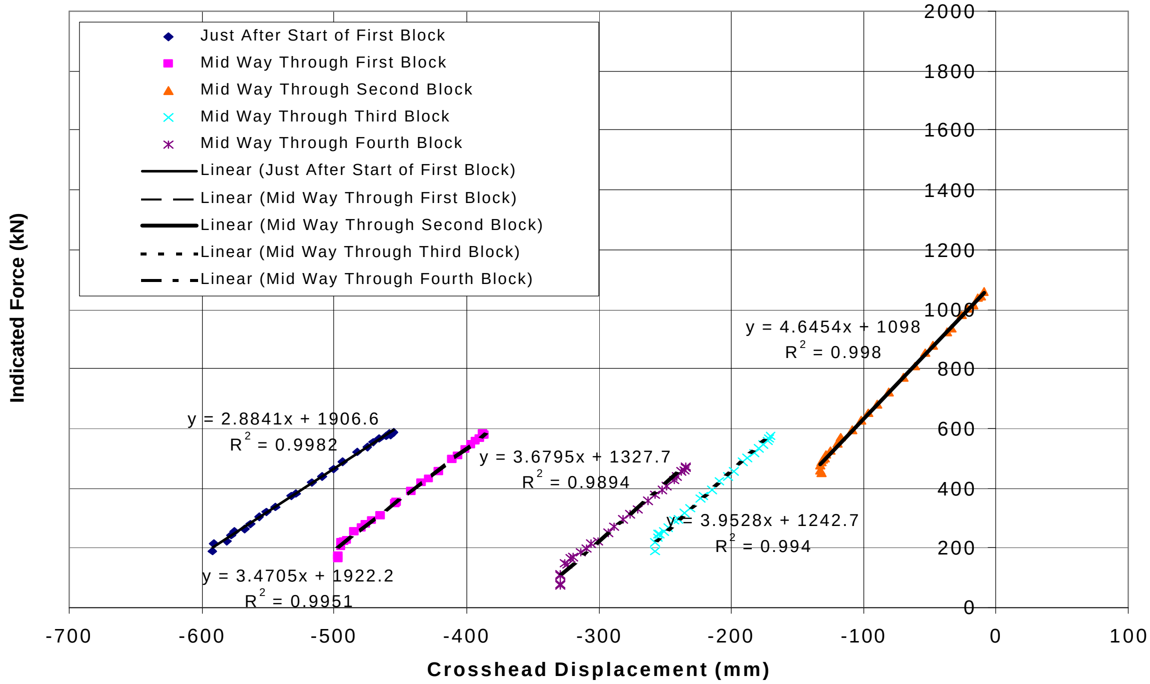


Figure 7.8a Example Load-Displacement Plots During First Sequence: MQDE 3

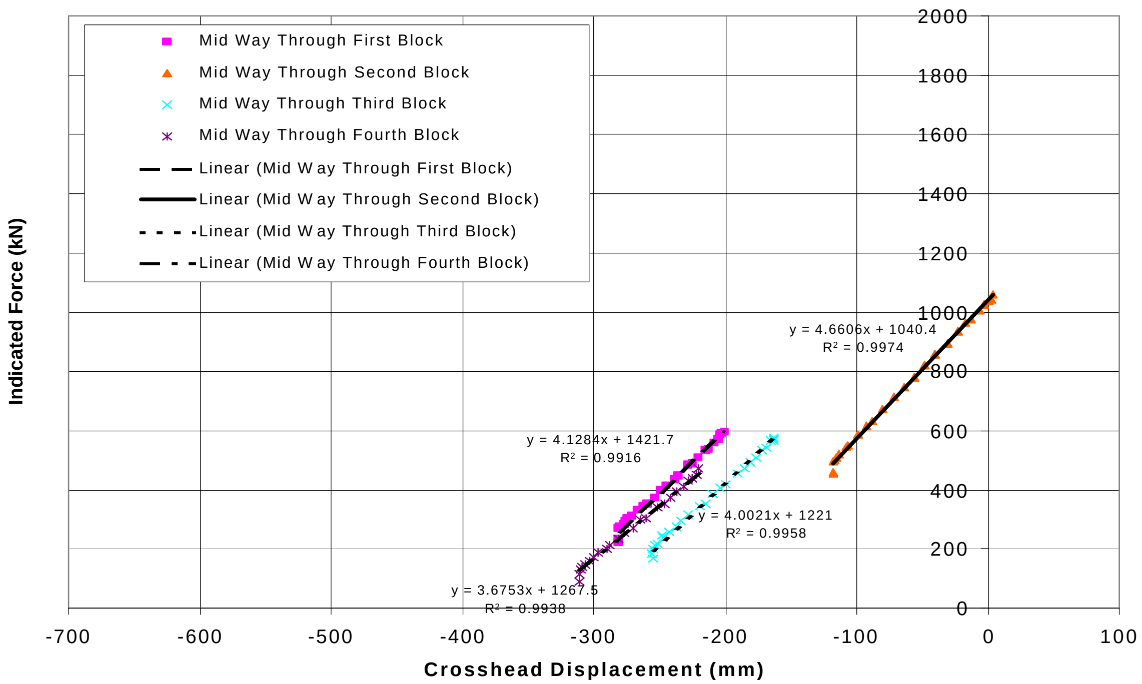


Figure 7.8b Example Load-Displacement Plots During Second Sequence: MQDE 3

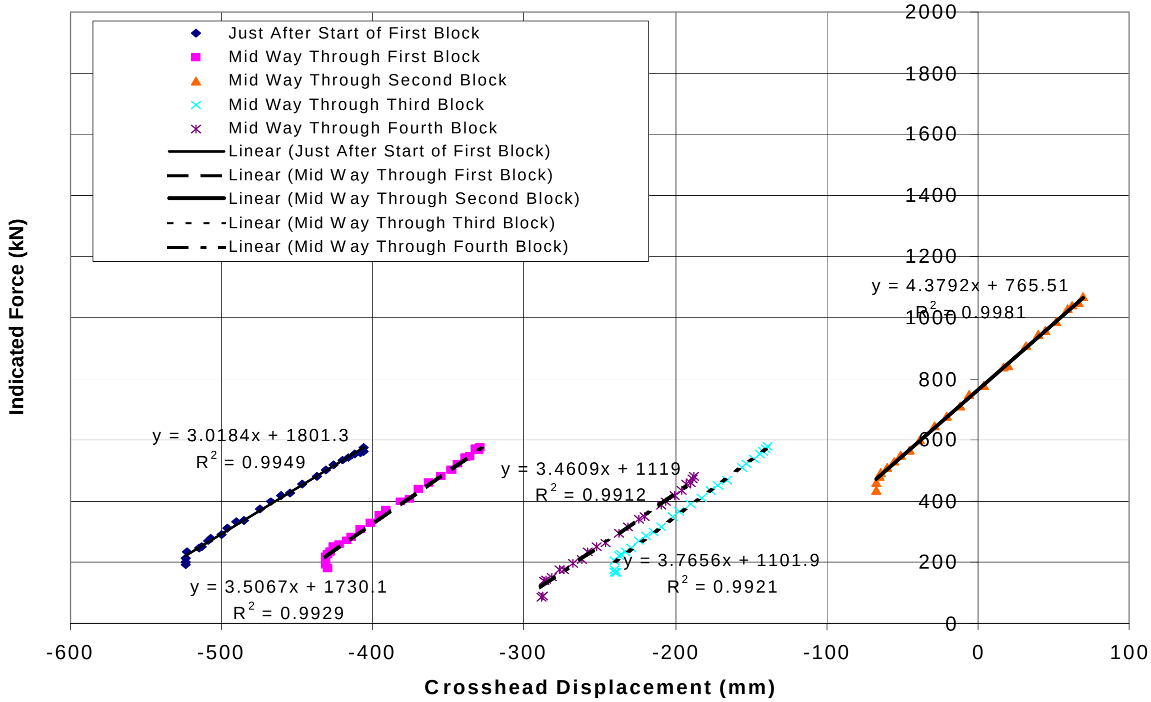


Figure 7.9a Example Load-Displacement Plots During First Sequence: MQDE 4

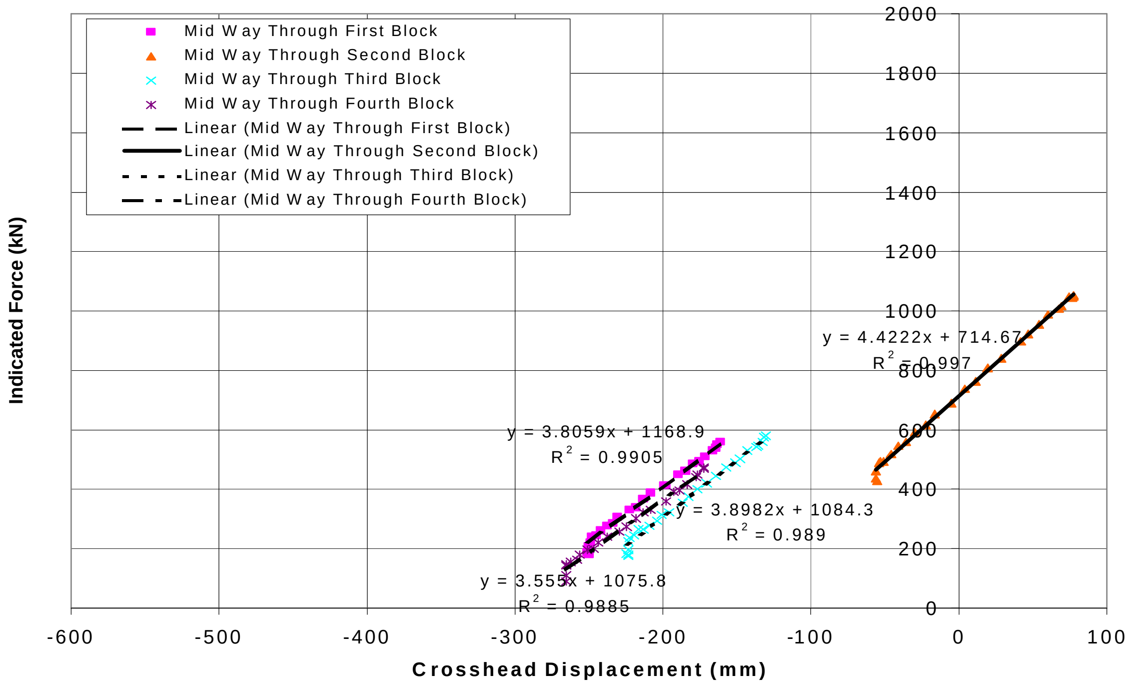


Figure 7.9b Example Load-Displacement Plots During Second Sequence: MQDE 4

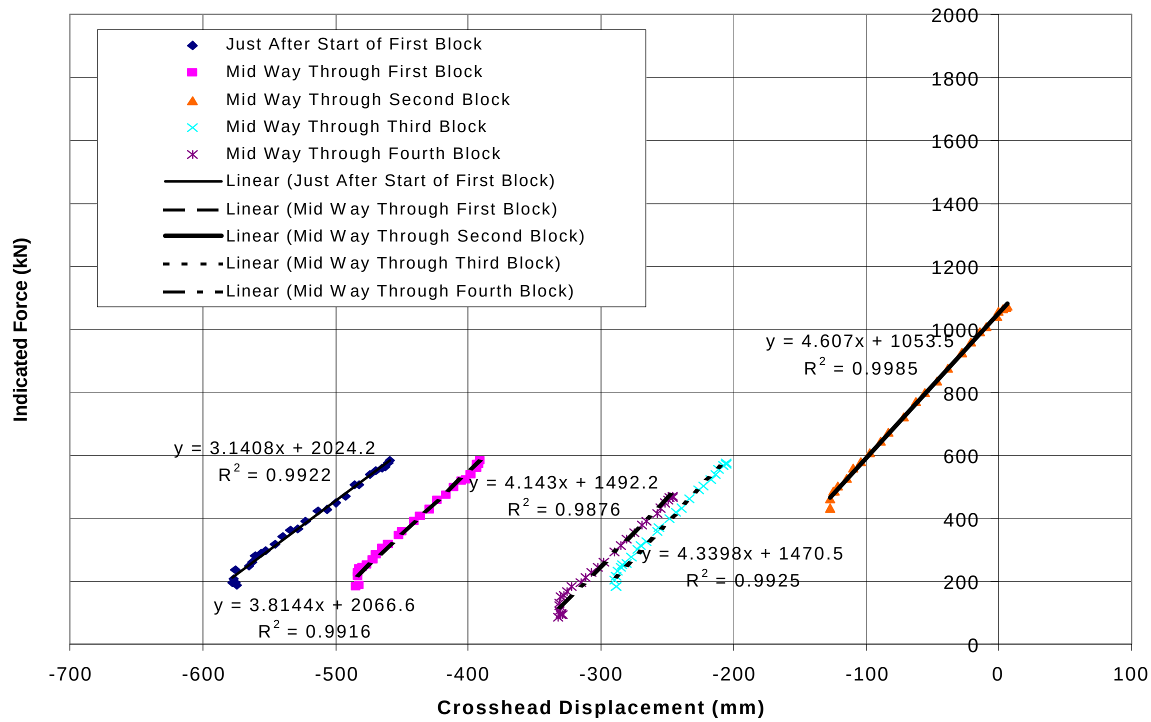


Figure 7.10a Example Load-Displacement Plots During First Sequence: MQDE 5

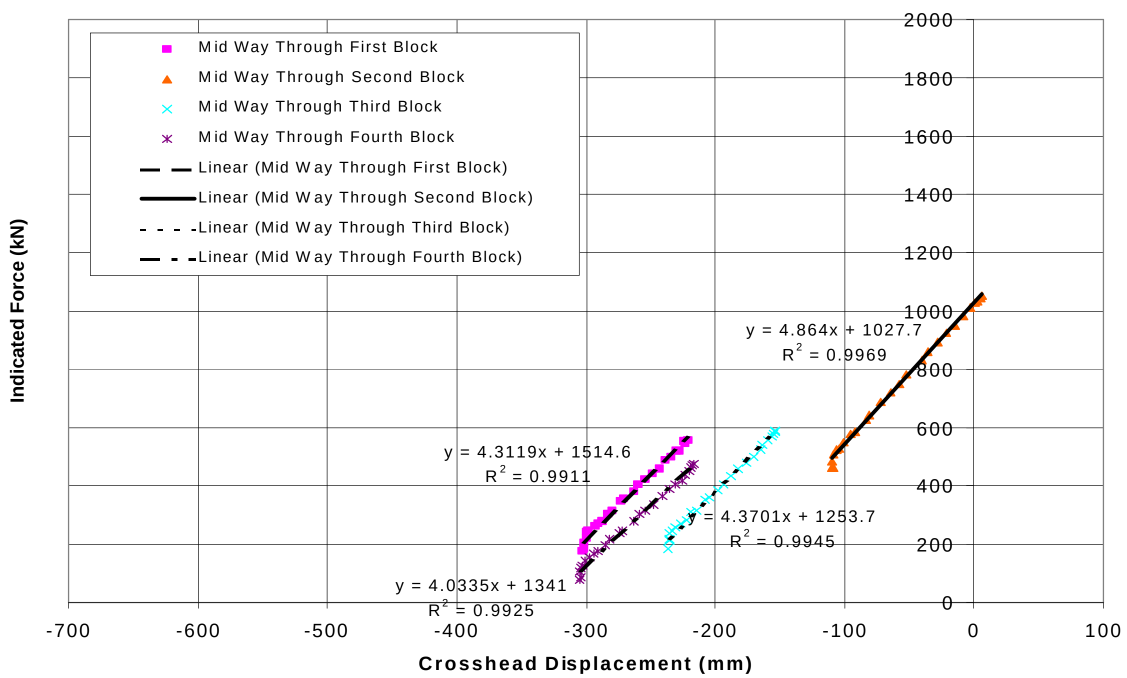


Figure 7.10b Example Load-Displacement Plots During Second Sequence: MQDE 5

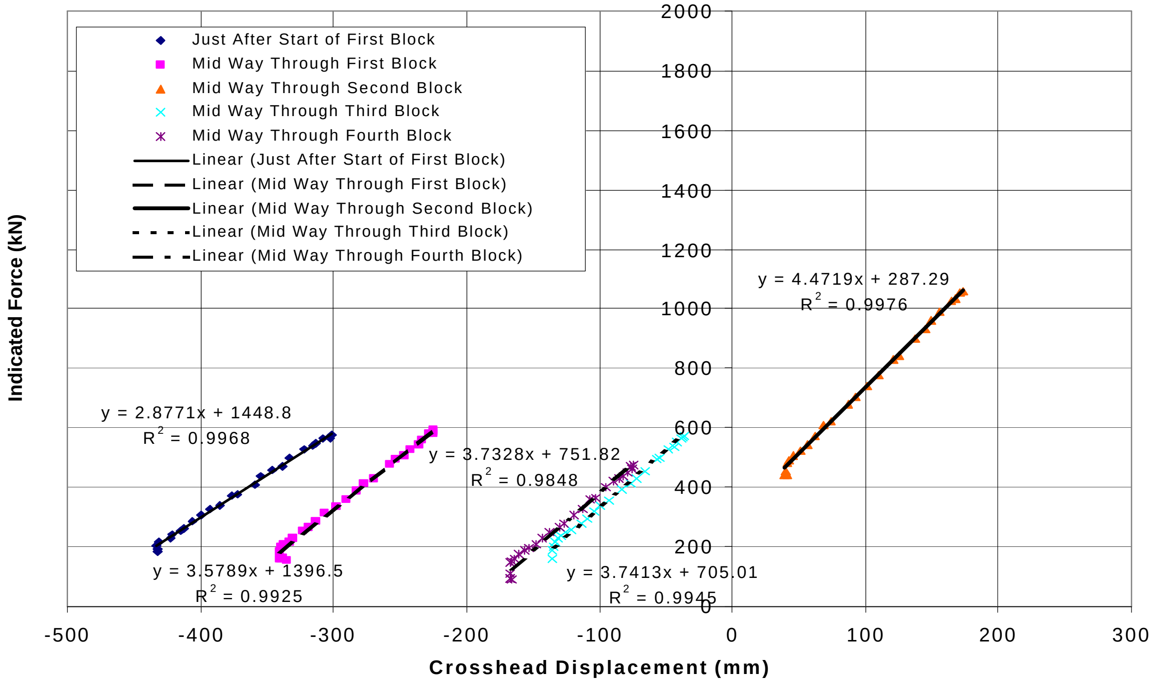


Figure 7.11a Example Load-Displacement Plots During First Sequence: MQDE 6

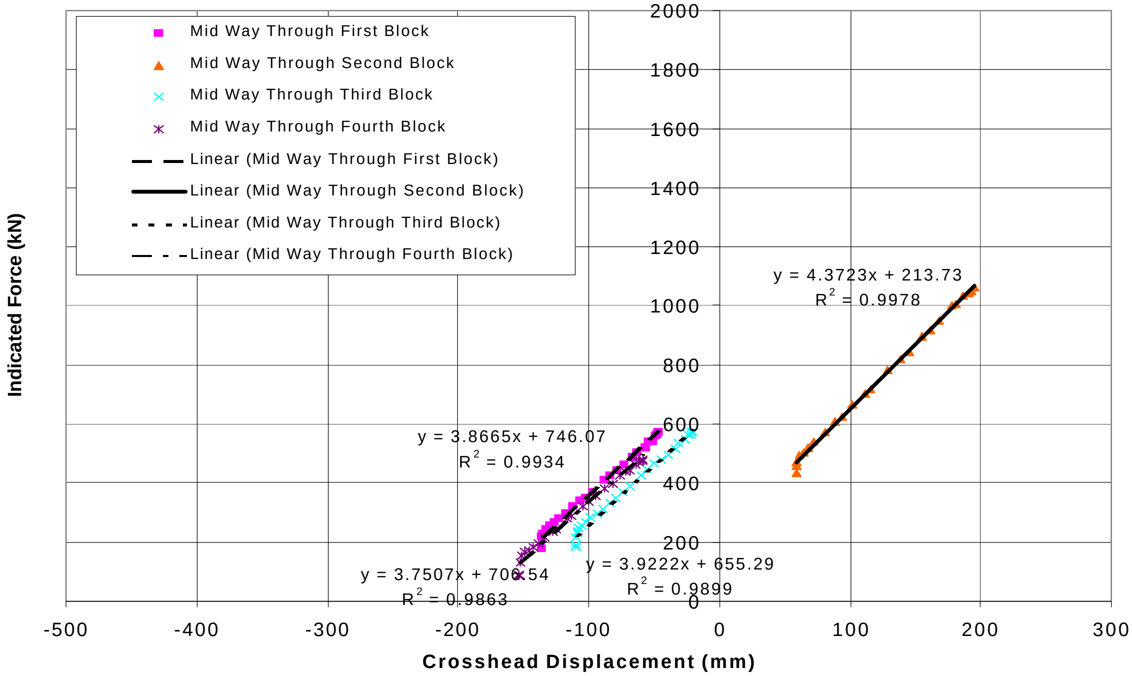


Figure 7.11b Example Load-Displacement Plots During Second Sequence: MQDE 6

Figure 7.12 MQDE 1 – Removal of Jacket

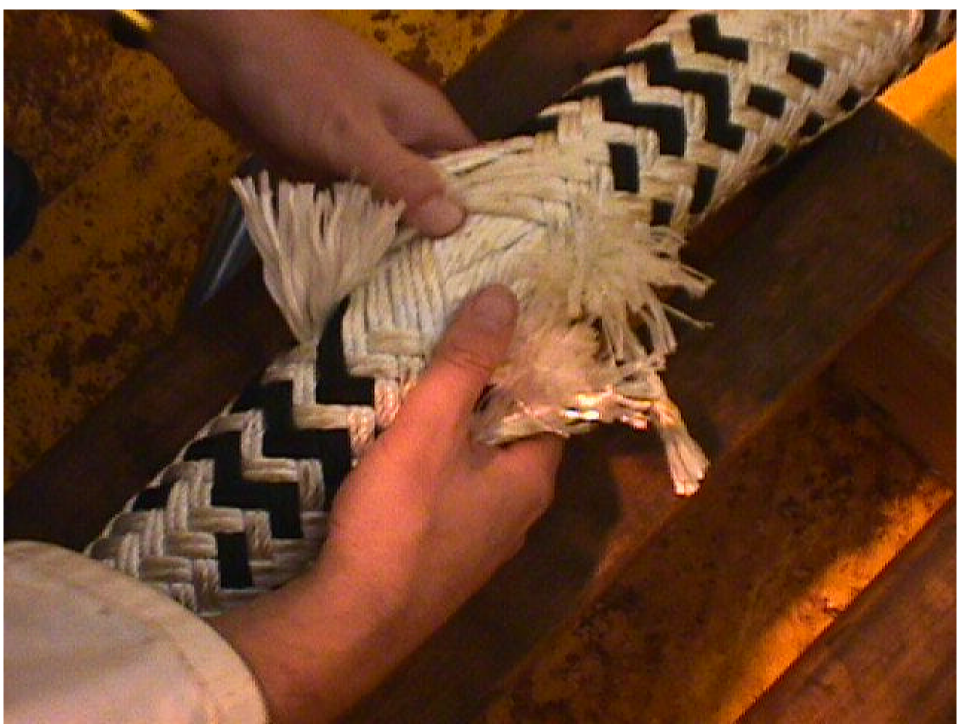


Figure 7.13 MQDE 1 – Removal of Jacket Continued

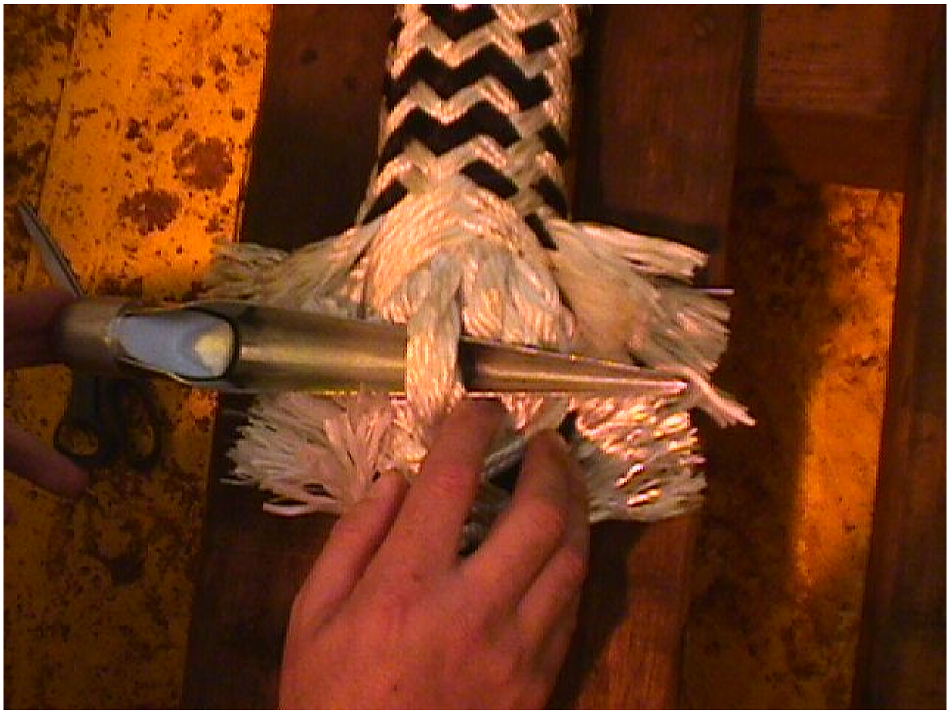


Figure 7.14 MQDE 1 – Isolation of a Subrope for Cutting

Figure 7.15 MQDE 1 – First Subrope Cut

Figure 7.16 MQDE 1 – All Three Subropes Cut

Figure 7.17 MQDE 1 – Induced Damage Region After Break Test

Figure 7.18 MQDE 1 – Failure Region Resulting From Break Test

Figure 7.19 MQDE 3 – Failure Region Resulting From Break Test

Figure 7.20 MQDE 4 – Failure Region Resulting From Break Test

Figure 7.21 MQDE 5 – Failure Region Resulting From Break Test

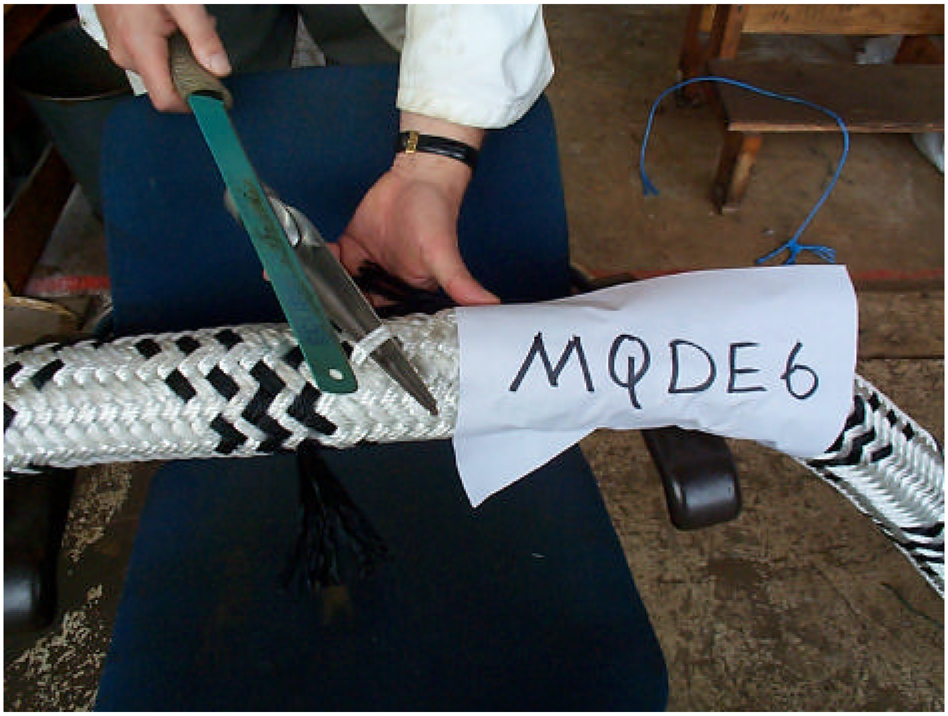


Figure 7.22 MQDE 6 – Commencement of Jacket Removal

Figure 7.23 MQDE 6 – Jacket Removed

Figure 7.24 MQDE 6 – Cutting of Subrope

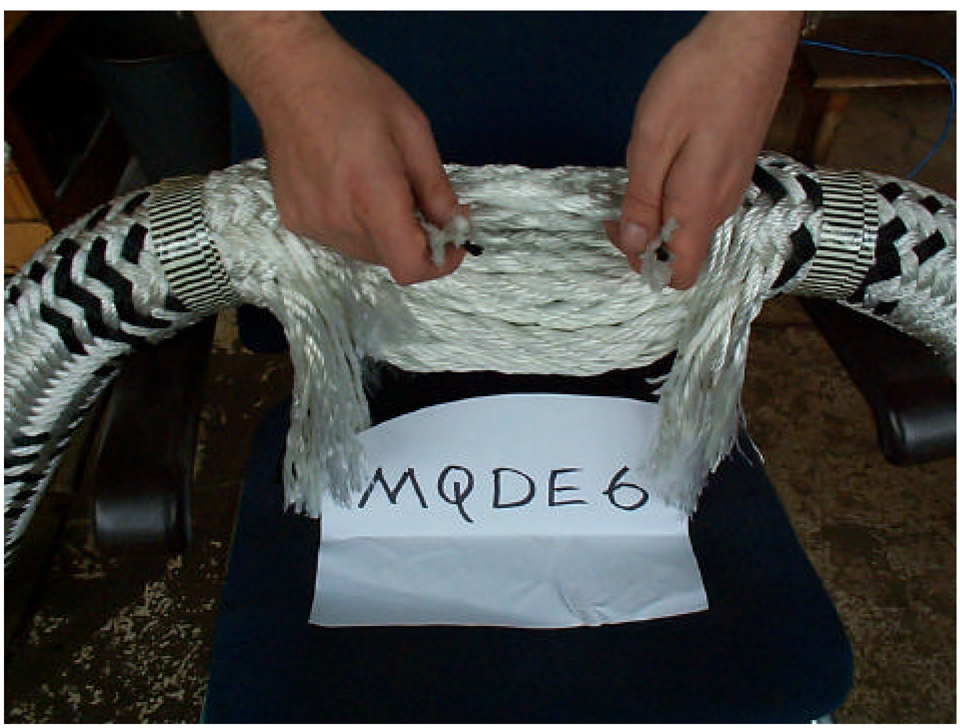


Figure 7.25 MQDE 6 – First of Nine Subropes Cut

Figure 7.26 MQDE 6 – Nine Subropes Cut

Figure 7.27 MQDE 6 – Failure Region Resulting From Break Test

8 TEST RESULTS – MQIQ SERIES

As with the MQDE series, the results of the retained break strength tests, together with extension to break values and failure locations are provided in Table 8.1. The extension to break values are based on the reference rope length taken at approximately 2% of theoretical rope strength, prior to the start of the test matrix. The reference rope lengths are also included in the table.

The associated load-extension plots for the break tests are given in Figures 8.1-8.4. It can be seen from the plots (and the table) that, as was the case for the MQDE test series, the undamaged ropes yielded the highest loads and extension to break values. With regard to the undamaged reference tests, it can be seen from Table 8.1 that whilst MQIQ 1 exceeded the theoretical rope strength of 2 091 kN with a value of 2 137 kN, MQIQ 2 did not with a value of 1 970 kN. There is around an 8.5% difference between the two break strength values. As with the case of the MQDE series of tests, once damage has been introduced (MQIQ 4) both the breaking strength and extension to break values reduce.

The handling test (MQIQ 3 – ex Deepstar) yielded both low breaking load and low extension to break values. It would appear that the Deepstar sample has suffered from load reducing damage that could be associated with one or more of the following:

- It has seen service.
- It has undergone the full test matrix.
- It was subjected to handling.
- Wear occurred at the eye of the splice as the rope made contact with the spool.
- The splice design is ad hoc.

During the course of testing, load-displacement data was collected to calculate values of EA and E. Given in Tables 8.2-8.5 are the average values of the properties calculated for each of the four tests conducted. Example load-displacement plots are provided in Figures 8.5-8.8. The ‘a’ plots represent the first sequence data and the ‘b’ plots represent the second sequence.

Perusal of the tables and plots allow the following observations to be made:

- The effect of mean load upon the properties is apparent, with the numerical value of the properties increasing with mean load.
- With the possible exception of the handling test (MQIQ 3 where some of the runs were not logged) the average value of the properties during run 1 of the first sequence is lower than the other runs at the same load ranges over both sequences (runs 3, 5 and 7). This highlights the effects of bedding-in during the first run.
- A comparison between Figures 8.5a-8.8a and Figures 8.5b-8.8b reveals that, only between the first run of each sequence (the 20±10% runs), are the changes in length during the second sequence much less than those in the first sequence. This again shows that bedding-in is marked during the first run (block) of the first sequence.

- The possible exception to the above comment is the handling test (MQIQ 3), where although some of the runs in the first sequence were not logged) the relatively large elongation values (whether increases or reductions) between test runs during the second sequence (Figure 8.7b) suggest the following;

1. The rope recovered during the handling part of the test,
2. Splice slippage could have taken place (although unlikely), or
3. The rope was changing length as a result of general deterioration.

Tables 8.6-8.9 present %elongation values that were recorded during each of the test runs. The values were recorded at the appropriate mean load before and after each test run. The lengths used to calculate the extension values were the rope reference lengths provided in Table 8.1. During the first four runs (i.e. the first sequence) the general trend is for increasing length during the first two runs followed by a reduction in length during runs 3 and 4. The trend is similar for the second sequence i.e. increase in length during runs 5 and 6 (although not to the same extent as in the first sequence) followed by reductions during runs 7 and 8.

The net elongation values are shown after runs 1-4 and 5-8 in Tables 8.6-8.9, where it can be seen for the two undamaged reference tests (MQIQ 1 and 2) the bulk of the elongation occurs during runs 1 and 2 of the first sequence. This again reflects the increase in length associated with bedding-in. The two reference tests yielded a total elongation over the eight test runs of 3% for MQIQ 1 and 2.5% for MQIQ 2.

The induced damage test (MQIQ 4 – Table 8.9) yielded a total elongation of 5.8%, double that of the two reference tests, with most of the elongation occurring during runs 1 and 2 of the first sequence. This must be associated with bedding-in together with the take up of the damage by the undamaged sections of the rope.

The handling test (MQIQ 3) – Table 8.8) displays slightly different elongation characteristics to the other tests in that a fair proportion of the total elongation occurred during runs 5 and 6 of the second sequence. Also the total elongation was 5.6% which was almost the same as the induced damage test (MQIQ 4). The reasons listed previously when discussing Figure 8.7a apply to Table 8.8. That is;

1. The rope recovered during the handling part of the test,
2. Splice slippage could have taken place (although unlikely), or
3. The rope was changing length as a result of general deterioration.

Examination of MQIQ 3 after the break test revealed two failure sites, the first one being within the splice region and the second at the point where the rope first makes contact with the spools (tangent point). It was suspected that the tangent point failure was associated with wear and for this reason it was decided to examine the eyes of all of the MQIQ series that were tested. The examination revealed that the protective cover had been warn away in each sample at the point where the rope first makes contact with the spools. It is understood that for the remainder of the work (to be conducted by Stress

Engineering Services) Marlow has reworked the cover and added a polyethylene jacket to the splices.

Figure 8.9 shows MQIQ 1, where the outer cover has been warn away. The secondary inner cover still appears to be intact however. Figure 8.10 shows the failure site of MQIQ 2 which was at one of the splices. Figure 8.11 shows the eye at the opposite end where it can be seen that the outer cover has worn away.

The main failure site for the handling test (MQIQ 3) is shown in Figure 8.13. There are effectively two failure sites, the first being the splice region and the second at the tangent point of the eye/spool of the same splice. Figure 8.14 shows a close up of the tangent point failure. It cannot be said with any certainty which failure occurred first. There are no indications from the load-extension plot (Figure 8.3) of any partial failures prior to the main failure to suggest that subrope failures might have occurred at the tangent point. The best can be said is that both failures must have occurred essentially at the same time. Shown in Figure 8.16 is a close up of the eye at the opposite of the rope where it can be seen that the outer cover is warn away together with an inner cover protecting a group of subropes. However, the subropes don’t appear to be damaged. Recall that this splice was ad hoc, a cross between the old design and the new one.

Figure 8.12 shows the wrapping of the rope around the drum during the handling test (MQIQ 3). Figure 8.15 shows the rope laid out after the break test. It cannot be said with confidence whether the wavy appearance is due to recoil from the break test or was induced when winding the rope on and off the drum.

Finally, Figure 8.17 shows the 18 mm deep cut being introduced into sample MQIQ 4. The jacket was removed around the area of induced damage. The cut was made with a sharpened hacksaw blade (teeth removed). Either side of the blade aluminium angle was glued to the blade with the distance from the base of the angle plate to the blade edge set at 18 mm. Care was taken not to rock the blade during cutting. The potential for rocking is real however and could be eliminated by suitable jigging of the blade to the rope and ensure repeatability of cut. It is possible, however, that rocking could occur in real-world damage situations.

Figure 8.18 shows the failure site of MQIQ 4 which was predominantly at the area of induced damage. Figures 8.19 and 8.20 shows the wear that took place at both eyes. In Figure 8.19 the subropes were not exposed because of the inner protection. However at the other eye (Figure 8.20) subropes have been exposed.

Table 8.1
Type of Test and Break Test Results

NEL test mark	Type of test	Break strength (kN)	Rope reference length (mm)	%extension to break	Failure location
MQIQ 1	Reference test	2 137	10 289	7.5	Splice region
MQIQ 2	Reference test	1 970	10 192	8.0	Splice region.
MQIQ 3	Handling test	1 590	10 350	6.06	Splice region and at tangent point of eye at same splice.
MQIQ 4	18 mm deep cut	1 416	10 135	5.71	Predominantly at damage site.

Table 8.2
Property Data Acquired During First Test: MQIQ 1

CSA = 3 656 mm^2
Reference Length =10 289 mm

Run No	Test Load (% NBL)	No of readings	Modulus (KN/mm^2)	EA (kN)
1	20 ± 10	13	10.77 ± 0.25	39 385 ± 898
2	40 ± 15	28	14.26 ± 0.34	52 138 ± 1 239
3	20 ± 10	31	12.56 ± 0.28	45 922 ± 1 008
4	15 ± 10	47	11.95 ± 0.19	43 703 ± 698
5	20 ± 10	32	12.84 ± 0.17	46 935 ± 614
6	40 ± 15	44	14.00 ± 0.40	51 183 ± 1 478
7	20 ± 10	31	12.58 ± 0.21	45 982 ± 750
8	15 ± 10	47	11.90 ± 0.17	43 498 ± 607

Table 8.3
Property Data Acquired During Second Test: MQIQ 2

CSA = 3 656 mm^2
Reference Length =10 192 mm

Run No	Test Load (% NBL)	No of readings	Modulus (KN/mm^2)	EA (kN)
1	20 ± 10	18	11.91 ± 0.15	43 559 ± 565
2	40 ± 15	256	14.33 ± 0.35	52 382 ± 1 266
3	20 ± 10	19	13.38 ± 0.34	48 927 ± 1 227
4	15 ± 10	293	12.40 ± 0.24	45 336 ± 868
5	20 ± 10	195	12.52 ± 0.19	45 780 ± 711
6	40 ± 13	293	13.91 ± 0.23	50 851 ± 853
7	20 ± 10	8	14.38 ± 0.72	52 583 ± 2 624
8	15 ± 10	2	15.05 ± 0.26	55 037 ± 961

Table 8.4
Property Data Acquired During Third Test: MQIQ 3

CSA = 3 656 mm^2
Reference Length =10 350 mm

Run No	Test Load (% NBL)	No of readings	Modulus (KN/mm^2)	EA (kN)
1	20 ± 10	7	11.59 ± 0.99	42 377 ± 3 619
2	40 ± 15	5	13.68 ± 0.25	50 003 ± 1 026
3	20 ± 10	194	11.93 ± 0.38	43 612 ± 1 376
4	15 ± 10	293	11.41 ± 0.66	41 725 ± 2 421
5	20 ± 10	195	11.67 ± 0.19	42 671 ± 677
6	40 ± 15	293	13.75 ± 0.31	50 278 ± 1 138
7	20 ± 10	195	12.30 ± 0.25	44 968 ± 913
8	15 ± 10	292	11.88 ± 0.24	43 441 ± 860

Table 8.5
Property Data Acquired During Third Test: MQIQ 4

CSA = 3 656 mm^2
Reference Length =10 135 mm

Run No	Test Load (% NBL)	No of readings	Modulus (KN/mm^2)	EA (kN)
1	20 ± 10	195	9.57 ± 0.43	34 997 ± 1 579
2	40 ± 15	293	11.27 ± 0.23	41 211 ± 823
3	20 ± 10	195	10.16 ± 0.17	37 149 ± 616
4	15 ± 10	293	9.29 ± 0.15	33 982 ± 547
5	20 ± 10	195	9.65 ± 0.29	35 277 ± 1 046
6	40 ± 15	293	11.18 ± 0.18	40 877 ± 644
7	20 ± 10	195	10.16 ± 0.22	37 137 ± 806
8	15 ± 10	293	8.95 ± 0.14	32 725 ± 527

Table 8.6
Percentage Elongation Values During Each Load Sequence: MQIQ 1

Run No	Test Load (% NBL)	%elg during test run
1	20 ± 10	2.3
2	40 ± 15	1.6
3	20 ± 10	-0.6
4	15 ± 10	-0.2
	Net Elg	**3.1**
5	20 ± 10	0.2
6	40 ± 15	0.7
7	20 ± 10	-0.7
8	15 ± 10	-0.3
	Net Elg	**-0.1**
	Total Elg	**3.0**

Table 8.7
Percentage Elongation Values During Each Load Sequence: MQIQ 2

Run No	Test Load (% NBL)	%elg during test run
1	20 ± 10	1.6
2	40 ± 15	1.6
3	20 ± 10	-0.4
4	15 ± 10	-0.9
	Net Elg	**1.9**
5	20 ± 10	0.2
6	40 ± 15	0.8
7	20 ± 10	0.4
8	15 ± 10	-0.8
	Net Elg	**0.6**
	Total Elg	**2.5**

Table 8.8
Percentage Elongation Values During Each Load Sequence: MQIQ 3

Run No	Test Load (% NBL)	%elg during test run
1	20 ± 10	3.1
2	40 ± 15	2.1
3	20 ± 10	-0.7
4	15 ± 10	-0.6
	Net Elg	**3.9**
5	20 ± 10	0.9
6	40 ± 15	1.4
7	20 ± 10	-0.3
8	15 ± 10	-0.3
	Net Elg	**1.7**
	Total Elg	**5.6**

Table 8.9
Percentage Elongation Values During Each Load Sequence: MQIQ 4

Run No	Test Load (% NBL)	%elg during test run
1	20 ± 10	2.9
2	40 ± 15	3.0
3	20 ± 10	0.1
4	15 ± 10	-0.5
	Net Elg	**5.5**
5	20 ± 10	0.8
6	40 ± 15	1.1
7	20 ± 10	-0.5
8	15 ± 10	-1.1
	Net Elg	**0.3**
	Total Elg	**5.8**

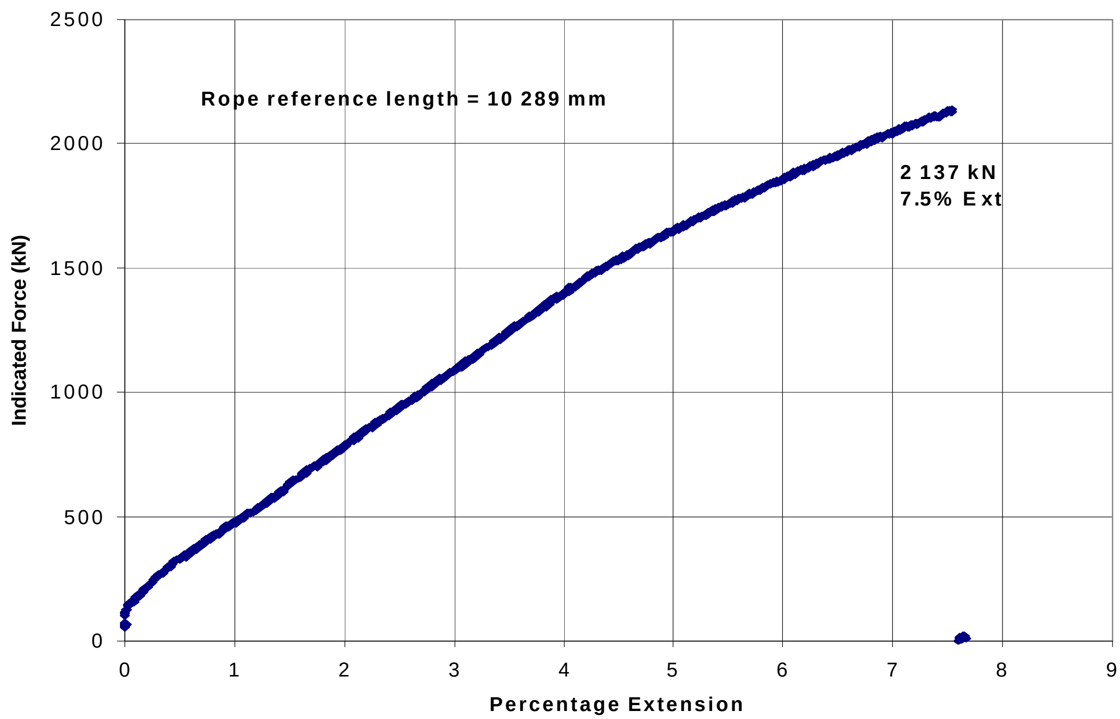


Figure 8.1 Load-Extension Plot: MQIQ 1

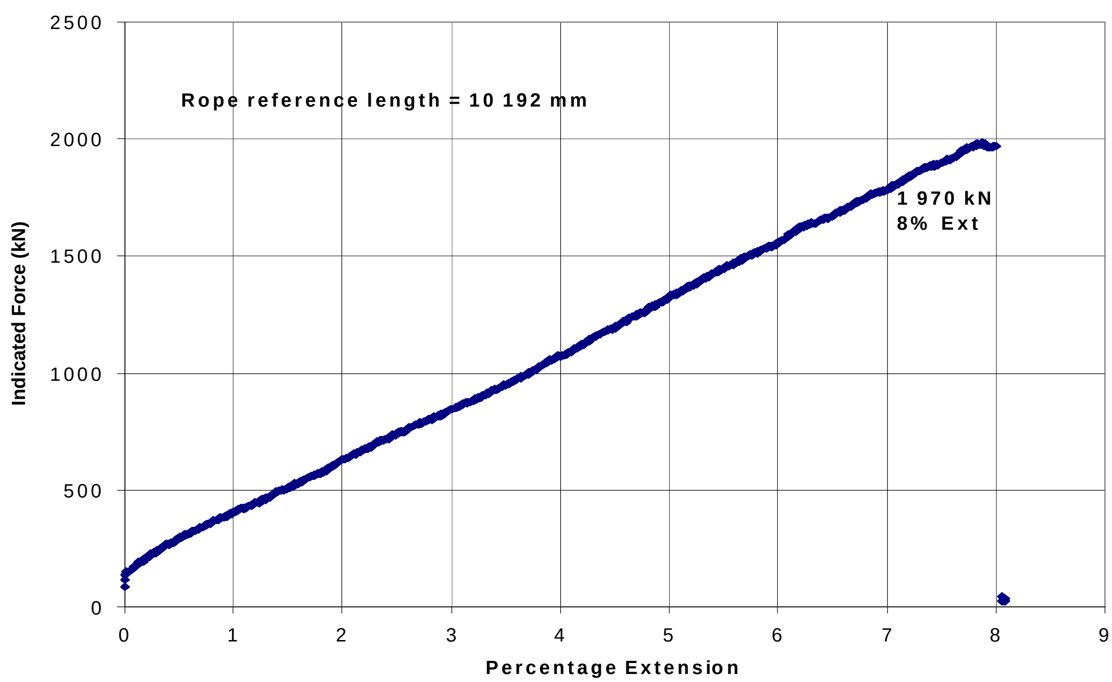


Figure 8.2 Load-Extension Plot: MQIQ 2

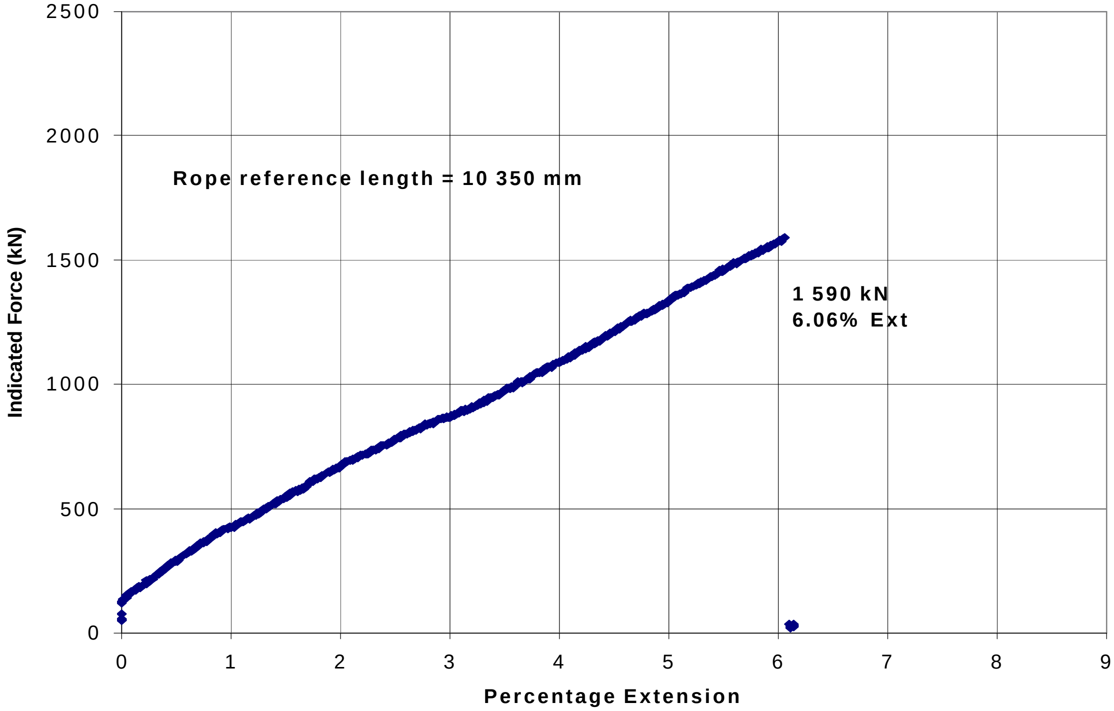


Figure 8.3 Load-Extension Plot: MQIQ 3

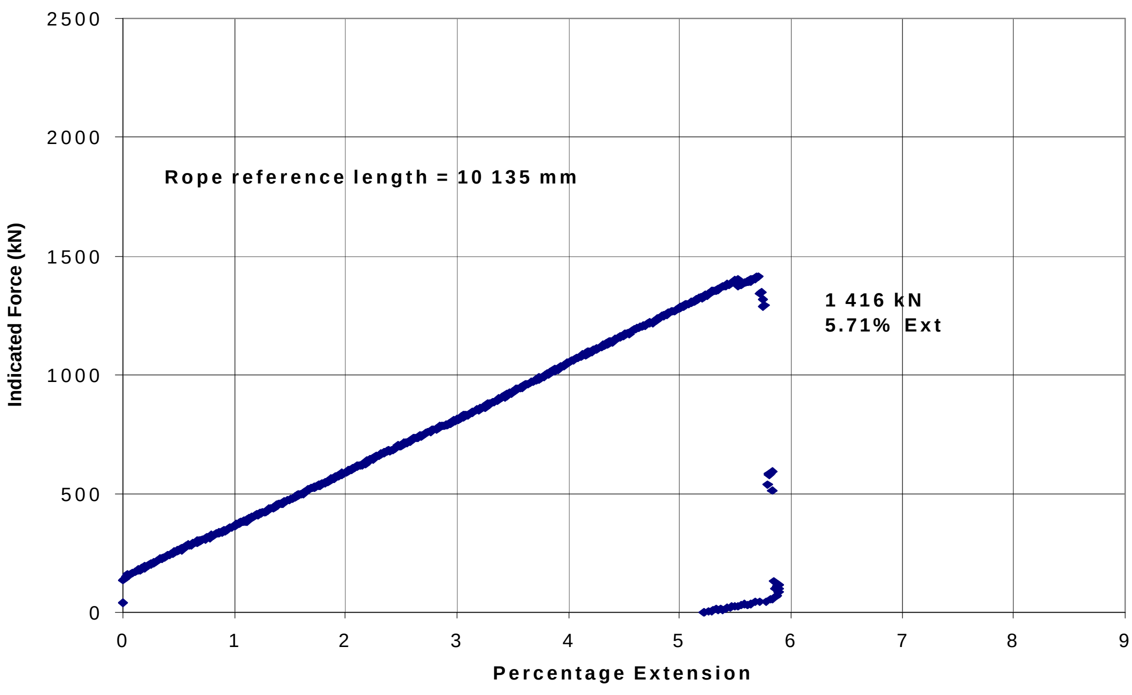


Figure 8.4 Load-Extension Plot: MQIQ 4

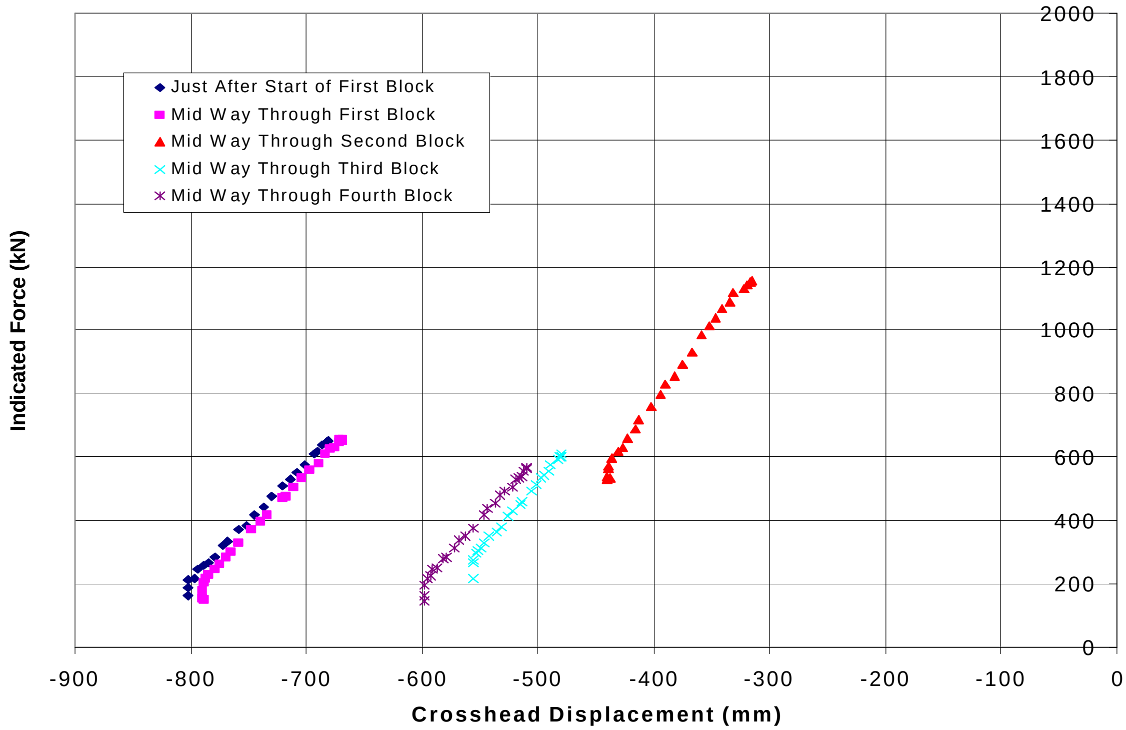


Figure 8.5a Example Load-Displacement Plots During First Sequence: MQIQ 1

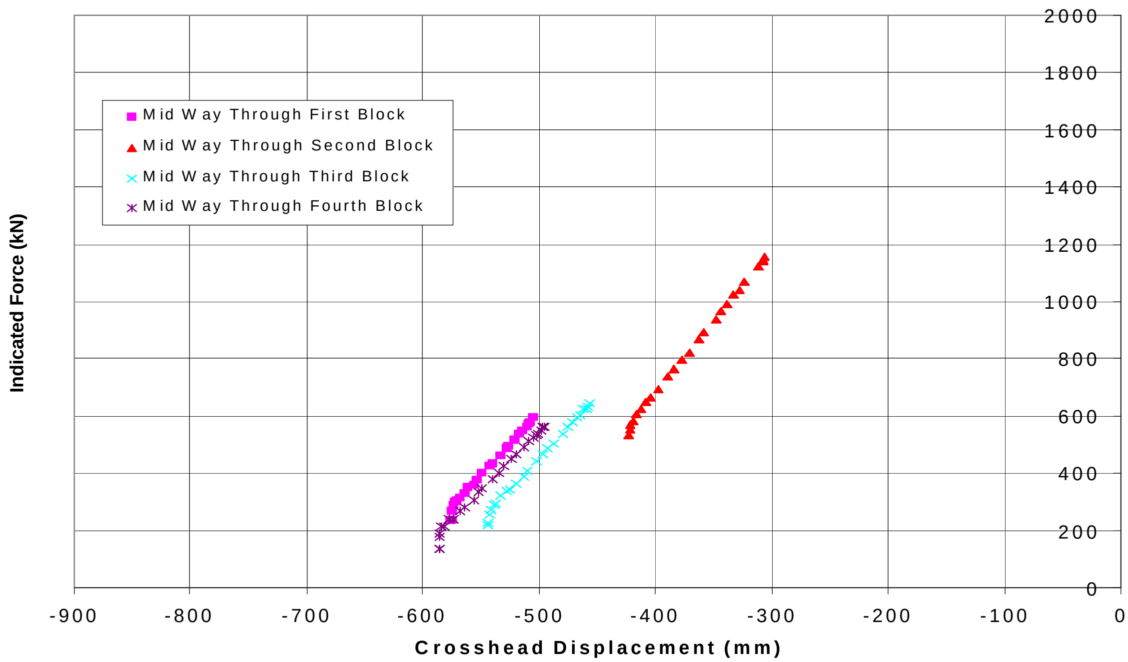


Figure 8.5b Example Load-Displacement Plots During Second Sequence: MQIQ 1

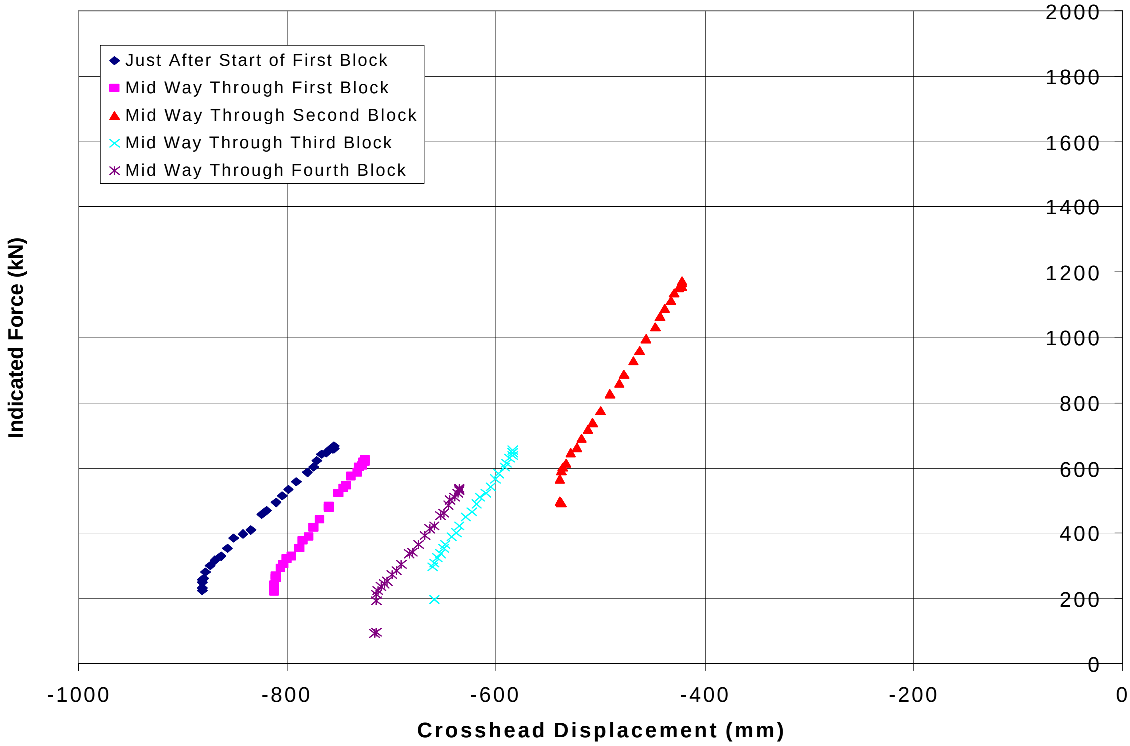


Figure 8.6a Example Load-Displacement Plots During First Sequence: MQIQ 2

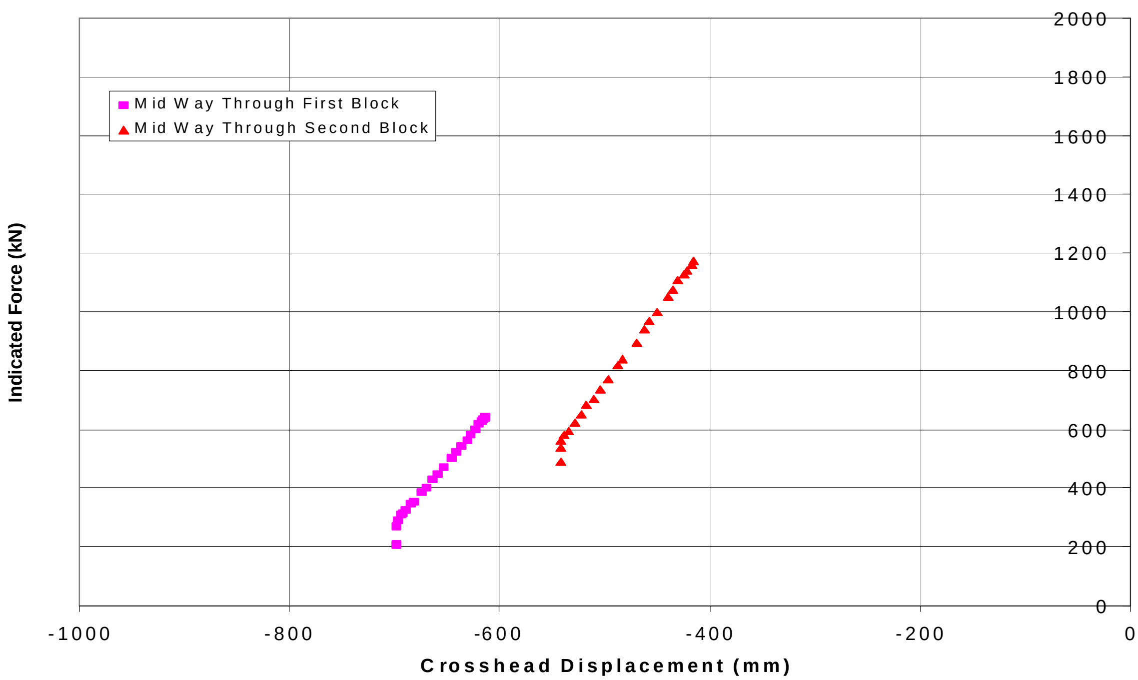


Figure 8.6b Example Load-Displacement Plots During Second Sequence: MQIQ 2

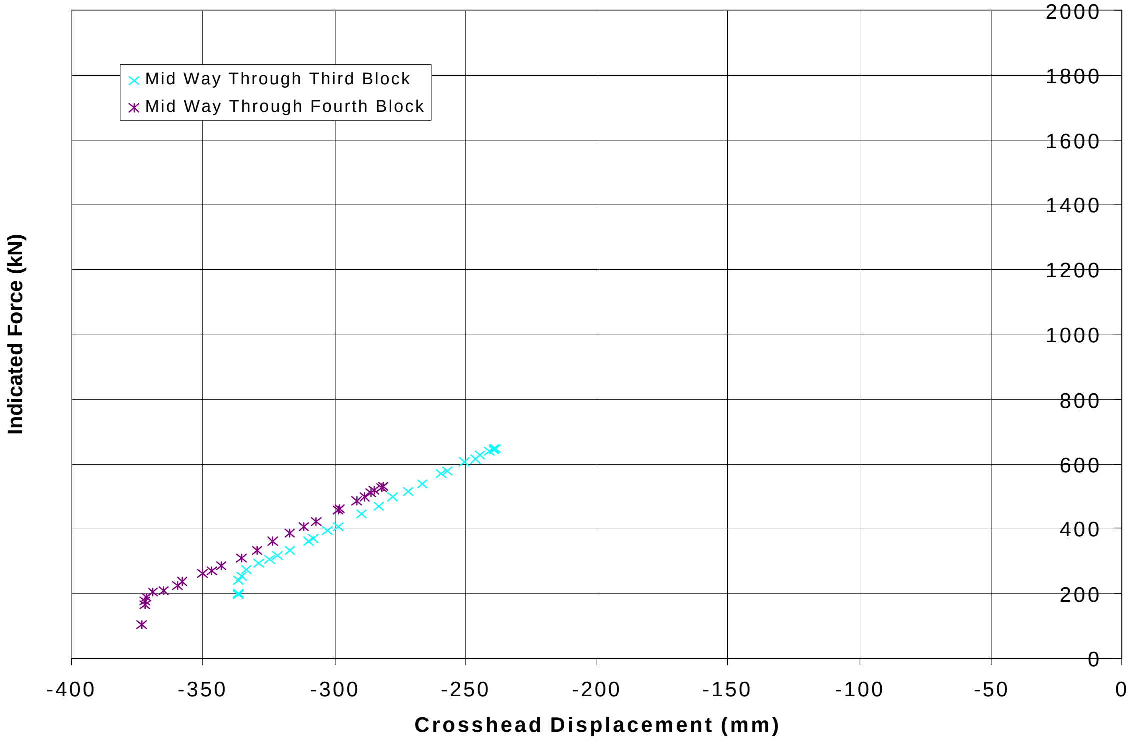


Figure 8.7a Example Load-Displacement Plots During First Sequence: MQIQ 3

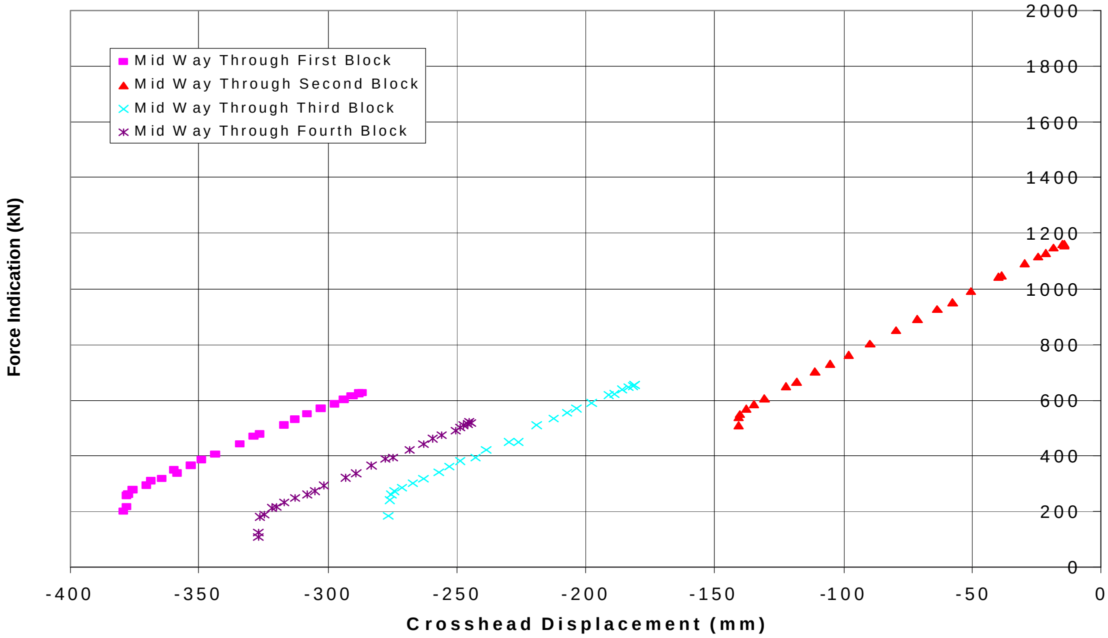


Figure 8.7b Example Load-Displacement Plots During Second Sequence: MQIQ 3

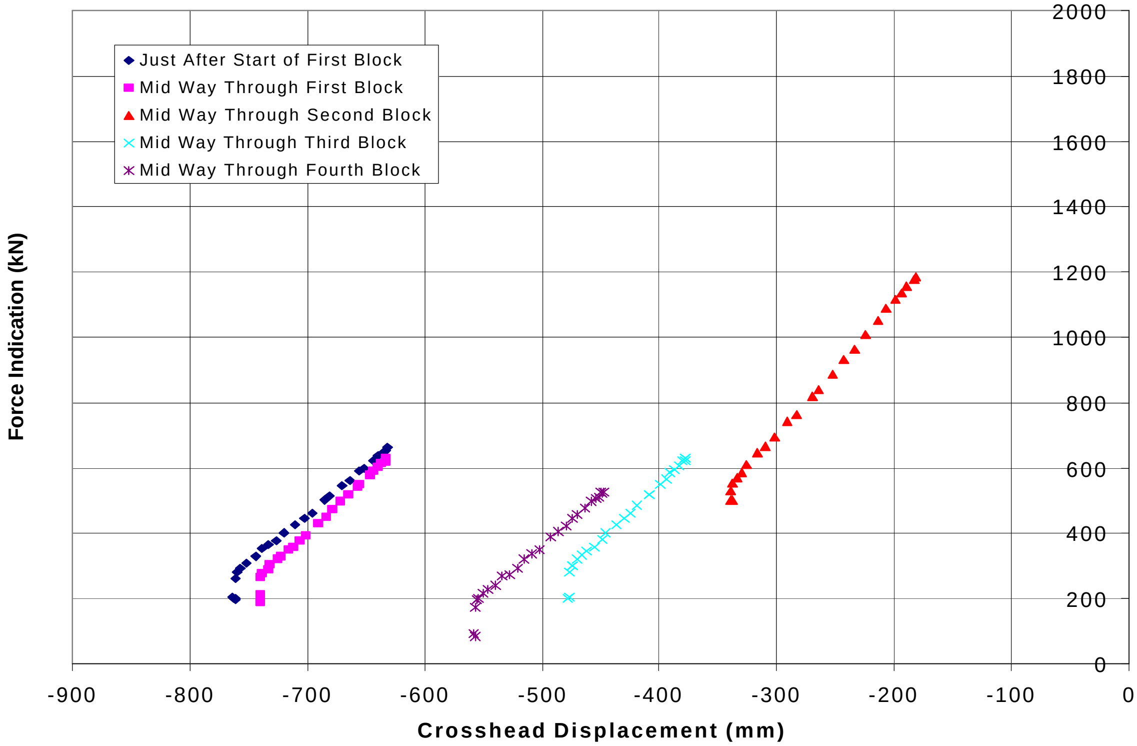


Figure 8.8a Example Load-Displacement Plots During First Sequence: MQIQ 4

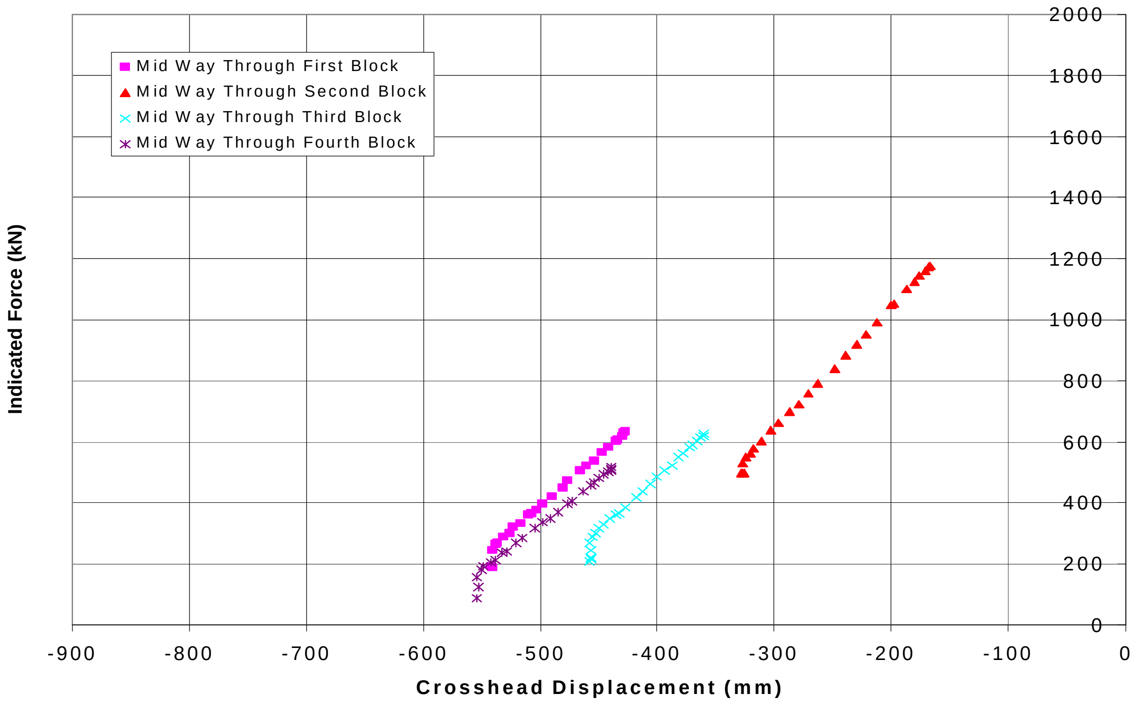


Figure 8.8b Example Load-Displacement Plots During Second Sequence: MQIQ 4

Figure 8.9 MQIQ 1 Wear of Outer Cover at Point Where Rope First Makes Contact with Spool (Tangent Point)

Figure 8.10 MQIQ 2 – Failure Region Resulting From Break Test

Figure 8.11 MQIQ 2 Wear of Outer Cover at Point Where Rope First Makes Contact with Spool (Tangent Point)

Figure 8.12 MQIQ 3 – Wrapping of Rope Round Drum

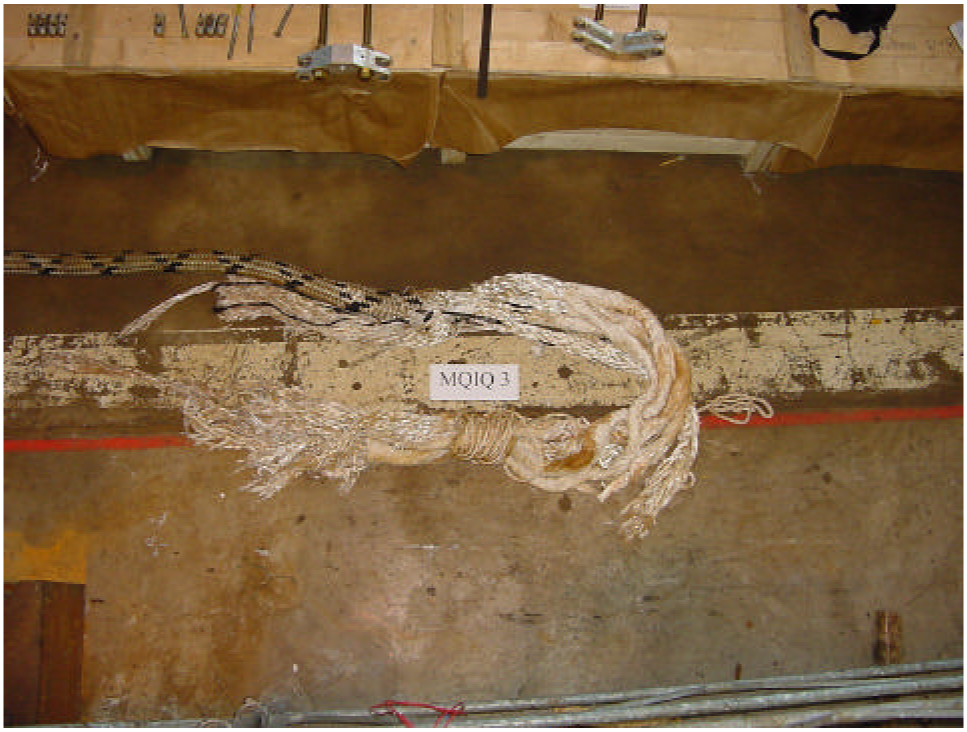


Figure 8.13 MQIQ 3 – Failure Region Resulting From Break Test (Splice Plus Tangent Point)

Figure 8.14 MQIQ 3 – Close-up of Tangent Point Failure

Figure 8.15 MQIQ 3 – Rope Laid Out After Break Testing

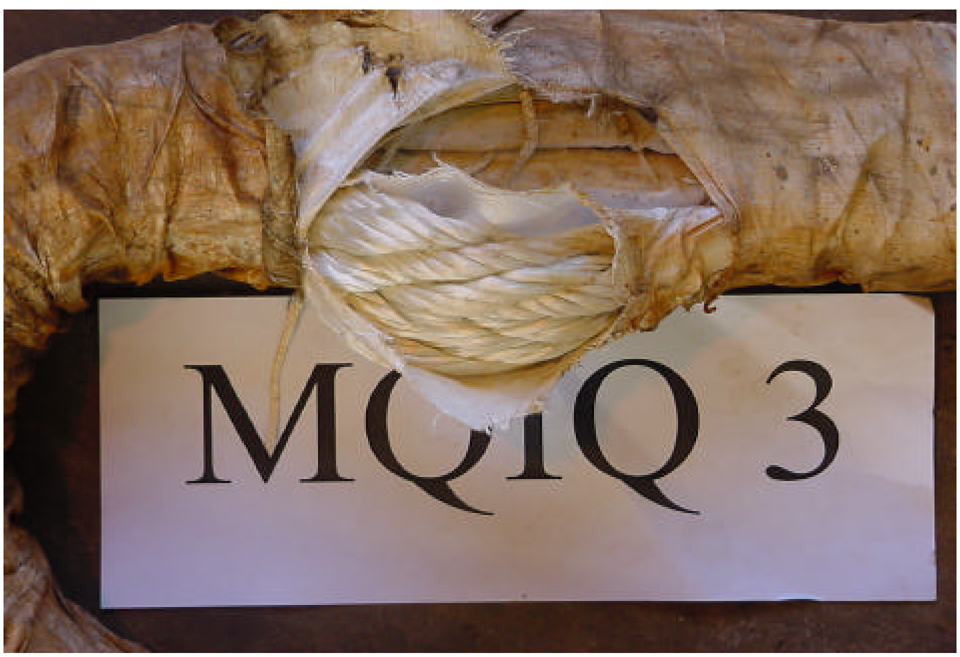


Figure 8.16 Wear of Outer Cover Plus Cover Protection a Group of Sub-cores (Where Rope First Makes Contact with Spool (Tangent Point))

Figure 8.17 MQIQ 4 – Introduction of Damage by Cutting

Figure 8.18 MQIQ 4 – Failure Region Resulting From Break Test

Figure 8.19 MQIQ 4 Wear of Outer Cover at Point Where Rope First Makes Contact with Spool (Tangent Point) Fixed End Eye

Figure 8.20 MQIQ 4 Wear of Outer Cover at Point Where Rope First Makes Contact with Spool (Tangent Point) Moving End Eye

9 CLOSING REMARKS

As stated earlier in the report, part way through the revised programme the 30 MN machine (after suffering a major failure) was permanently taken out of service, which meant that the test programme was terminated at NEL. Since the test work is not complete, it is difficult to draw overall conclusions. Stress Engineering Services will draw final conclusions once they have completed the test programme.

One result is significant, however, even though the test programme is not complete. As a result of data evaluation and comparison of retained strengths of the first six tests (MQDE series), it was found that subrope cutting (damage application) in the middle of the test sample was reducing the splice efficiency. Further there was no correlation between severity of damage and retained strength. Nor was there good repeatability between tests with the same severity of damage.

As a result of this finding, Marlow Ropes Limited took the decision to change their traditional splice design (for large mooring ropes only) to an improved design. The final test series (MQIQ) produced results for this improved, more damage resistance splice design.

APPENDIX BB

Results of Analysis to Determine Percent Rope Cut By Counting Cut Strands

1. Cutting Experiments on Old DeepStar Rope Recovered from Gulf of Mexico. This rope is identical in design to the new rope samples we tested.

0.5-Inch Cut

DS 1 (Deepstar Rope)		% dam			% Undamaged	%Area
CUT	SUBROPE	EL 1	EL2	EL3		
0.5	SR1	5	0	0	0.983	
	SR2	90	75	0	0.450	
	SR3	100	70	5	0.417	
	SR4	100	95	45	0.200	
	SR5	25	15	0	0.867	
	SR6	25	0	0	0.917	
No. Subropes Cut =					2.167	7.738095

0.4-Inch Cut

DS 2 (Deepstar Rope)		% dam			% Undamaged	%Area
CUT	SUBROPE	EL 1	EL2	EL3	Total	
0.4	SR1	5	2	0	0.977	
	SR2	95	60	0	0.483	
	SR3	25	15	0	0.867	
	SR4	80	35	0	0.617	
	SR5	2	0	0	0.993	
No. Subropes Cut					1.063	3.797619

0.7-Inch Cut

DS 3 (Deepstar Sample)		% dam			% Undamaged	%Area
CUT	SUBROPE	EL 1	EL2	EL3		
0.7	SR1	100	100	100	0.000	
	SR2	100	100	100	0.000	
	SR3	99	88	85	0.093	
	SR4	40	60	0	0.667	
	SR5	100	100	99	0.003	
	SR6	5	50	0	0.817	
	SR7	11	0	0	0.963	
	SR8	100	67	17	0.387	
Number of Subropes Cut =					4.070	14.53571

0.7-Inch Cut on DS 3. Determination of Cut % By Weight, Rather than by Counting.

By Weight	
Total Weight	1535
Jacket, etc.	387
Undamaged Subropes	952
Damaged Subropes	196
Total Weight (Rope)	1148
	17.0731707

Conclusion: % area cut by weight was 17, as compared with 14.5 by count. Therefore counting method is satisfactory.

Summary of Three DS Cuts

For DS 1, DS 2 and DS 3		
Cut Depth	Equiv. Subropes Cut	%Area
0.4	1.06	3.77
0.5	2.15	7.68
0.7	2.75	14.53

0.7-Inch Cut on SES 2

Sample SES 002		% dam			Total	
0.7	SR1	100	50	50	0.333	
	SR2	0	10	20	0.900	
	SR3	80	0	10	0.700	
	SR4	0	50	10	0.800	
	SR5	100	50	90	0.200	
	SR6	100	100	100	0.000	
	SR7	100	100	99	0.003	
Number of Subropes Cut =					4.064	14.51429

0.7-Inch Cut on SES 3

SES #003		% dam			Total	
CUT	SUBROPE	EL 1	EL2	EL3		
0.7	SR1	50	0	0	0.833	
	SR2	100	70	60	0.233	
	SR3	100	99	60	0.137	
	SR4	100	60	20	0.400	
	SR5	80	10	8	0.673	
	SR6	5	0	0	0.983	
	SR7	5	0	0	0.983	
Number of Subropes Cut =					2.757	***9.845238***

0.5-Inch Cut on SES 4

BP Marlow SES-004		PERCENT DAMAGED				%AREA
CUT	SUBROPE	EL 1	EL2	EL3		
0.5	SR1	100	35	8	0.523	
	SR2	99	55	0	0.487	
	SR3	100	66	8	0.420	
	SR4	22	15	0	0.877	
	SR5	5	0	0	0.983	
					1.710	6.107143

0.5-Inch Cut on SES 5

BP Marlow SES-005		PERCENT DAMAGED				%AREA
CUT	SUBROPE	EL 1	EL2	EL3		
0.5	SR1	100	100	40	0.200	
	SR2	20	0	0	0.933	
	SR3	100	95	85	0.067	
	SR4	100	100	73	0.090	
	SR5	5	0	0	0.983	
	SR6	10	0	0	0.967	
	SR7	33	11	0	0.853	
					2.907	10.38095

0.5 Inch Cut on SES 6

(Surgical Cuts With Scissors to Identically Match SES 4. No Knife Cut Used)

BP Marlow SES-006		PERCENT DAMAGED				%AREA
CUT	SUBROPE	EL 1	EL2	EL3		
0.5	SR1	100	33	11	0.520	
	SR2	100	55	0	0.483	
	SR3	100	66	11	0.410	
	SR4	22	22	0	0.853	
	SR5	11	0	0	0.963	
					1.770	6.321429
					0.115	

Note: Damage was inflicted by cutting individual elements of each subrope.
If the damage % was less than 100% it was inflicted by cutting the appropriate number of parts of each element.

Each subrobe contains 3 elements.
Each element contains 9 parts.

The subropes were picked based on what was damaged for SES-004
SR1 - SR4 were in close proximity to each other and generally on the outer layer. (the layer next to the jacket) There was one subrope between SR1 - SR4 and SR5.