AD771 355

Security Classification

**DOCUMENT CONTROL DATA - R & D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Naval Research Laboratory<br>Washington, D.C. 20375 | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

STUDY OF A TITANIUM WIRE ROPE DEVELOPED FOR MARINE APPLICATIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

A final report on one phase of a continuing NRL problem.

5. AUTHOR(S) (First name, middle initial, last name)

Darrell A. Milburn

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| November 2, 1973 | 24 | 9 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>NRL Problem F02-23<br>b. PROJECT NO.<br>RR023-03-45-5806<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>NRL Report 7625<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| | Department of the Navy<br>Office of Naval Research<br>Arlington, Virginia 22217 |

13. ABSTRACT

The mechanical properties and fatigue performance of a titanium wire rope have been experimentally determined. The rope was developed for the Office of Naval Research. It has a nominal diameter of 1/4-in. and is of 7 × 7 structural form. Other salient constructional details of the rope include the use of two titanium alloys and two wire lubricants. Furthermore, lay lengths of the rope and of individual strands were increased over those for similarly constructed steel ropes.

A number of tests were conducted on specimens of the titanium wire rope at the test facilities of the Naval Research Laboratory and The Catholic University of America. The overall test program consisted of two major parts: static tensile tests and axial fatigue tests. For purposes of comparison, stainless-steel and galvanized-steel wire ropes of the same nominal diameter and 7 × 7 form were also subjected to these tests.

Test results indicate that the strength-to-weight ratio and stretch characteristics of the titanium rope are superior to those of the steel ropes. However, the fatigue-life data suggest that it would fail as a part of a marine structure in a significantly shorter period of time than would either of the two less expensive steel ropes.



24

Security Classification

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Wire rope | | | | | | |
| Titanium alloys | | | | | | |
| Titanium wire rope | | | | | | |
| Stainless-steel wire rope | | | | | | |
| Galvanized-steel wire rope | | | | | | |
| Test and evaluation of wire rope | | | | | | |

AD-771 355

# STUDY OF A TITANIUM WIRE ROPE DEVELOPED FOR MARINE APPLICATIONS

NAVAL RESEARCH LABORATORY

NOVEMBER 1973

CONTENTS

## ABSTRACT

The mechanical properties and fatigue performance of a titanium wire rope have been experimentally determined. The rope was developed for the Office of Naval Research. It has a nominal diameter of 1/4-in. and is of 7 × 7 structural form. Other salient constructional details of the rope include the use of two titanium alloys and two wire lubricants. Furthermore, lay lengths of the rope and of individual strands were increased over those for similarly constructed steel ropes.

A number of tests were conducted on specimens of the titanium wire rope at the test facilities of the Naval Research Laboratory and The Catholic University of America. The overall test program consisted of two major parts: static tensile tests and axial fatigue tests. For purposes of comparison, stainless-steel and galvanized-steel wire ropes of the same nominal diameter and 7 × 7 form were also subjected to these tests.

Test results indicate that the strength-to-weight ratio and stretch characteristics of the titanium rope are superior to those of the steel ropes. However, the fatigue-life data suggest that it would fail as a part of a marine structure in a significantly shorter period of time than would either of the two less expensive steel ropes.

Manuscript submitted June 14, 1973.

# STUDY OF A TITANIUM WIRE ROPE DEVELOPED FOR MARINE APPLICATIONS

## INTRODUCTION

Titanium and several titanium alloys are being used in place of traditional materials in a number of marine structures in an effort to improve performance. Titanium alloys have a high strength-to-weight ratio, good fatigue life, excellent corrosion resistance, and nonmagnetic characteristics. Because these properties are desirable, these alloys have been fabricated into wire ropes for marine applications and aircraft use. However, laboratory test and evaluation of these ropes have revealed that they were unacceptable for their particular application because of poor service life (1,2).

Recently a new titanium wire rope was developed for the Office of Naval Research (3). The rope was specially designed to circumvent the poor performance of the previously developed titanium ropes. Salient features of this rope include the use of two different titanium alloys and two different wire lubricants and rope and strand lay lengths that were increased over those of similarly constructed steel ropes.

A 100-ft length of the titanium wire rope was given to NRL for study. The primary objective of the study was to assess the merits and limitations of the rope on the basis of its mechanical properties and fatigue performance. Two types of tests, static tensile and axial fatigue, were devised and conducted on specimens of the titanium rope for this purpose. The study also included comparative tests on stainless-steel and galvanized-steel ropes of the same nominal diameter and structural configuration. This report describes the experimental procedures and provides test data for an evaluation of the titanium wire rope relative to the similarly constructed steel ropes.

## TITANIUM WIRE ROPE

The titanium wire rope has a nominal diameter of 1/4-in. and is of 7 × 7 structural form. Figure 1 is a cross-sectional view of the 7 × 7 configuration. The 7 × 7 nomenclature denotes a rope having seven strands of seven wires per strand. Thus the rope is composed of 49 wires. Only four of these are unique, however, since they are arranged in a centric symmetry. The four wires are designated as A, B, C, and D in Fig. 1.

Two different titanium alloys were used in the manufacture of the wire rope. The seven wires of the core strand and the six center wires of the outer strands of the rope are Ti-13V-11Cr-3Al alloy. The remaining 36 wires that are located in the outer wire layer of the outer rope strands were fabricated from Ti-6Al-4V alloy. Each wire of the rope was treated with a dry-film lubricant. A hard-metal derivative with an acrylic resin was used to lubricate all of the Ti-13V-11Cr-3Al alloy wires, whereas the Ti-6Al-4V alloy wires were coated with graphite. Other distinguishing characteristics of the titanium-alloy wire rope are presented in Table 1. For purposes of comparison, data are also included in Table 1 for stainless-steel and galvanized-steel ropes of the same nominal diameter and 7 × 7 form as that of the titanium rope.

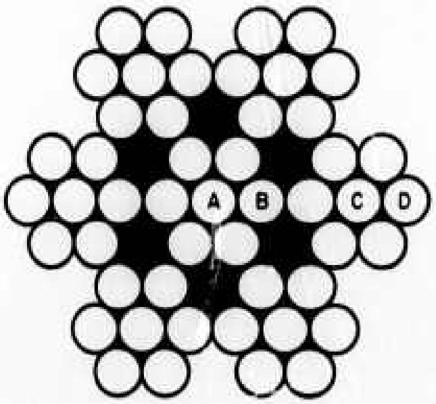


Fig. 1 — Cross-sectional view of the 1/4-in.-diameter, 7 × 7 wire ropes studied. The wires of the rope are arranged in a centric symmetry. They are woven together into strands, and several strands are twisted to form rope according to specific lay patterns. Rope lay is the length of rope corresponding to one revolution of the outer strands. Similarly, strand lay is the length of strand corresponding to a single turn of its external wires. The rope configuration shown consists of two strand components and four wires that are unique in terms of their size and helical form.

Table 1
Constructional Data for 1/4-In.-Diameter (7 × 7 Construction) Titanium, Stainless-Steel and Galvanized-Steel Wire Ropes

| Constructional Data | | Wire Rope | | |
|---|---|---|---|---|
| | | Titanium* | Stainless Steel | Galvanized Steel |
| Rope | Diameter (in.) | 0.291 | 0.265 | 0.268 |
| | Lay Length (in.) | 2.00 | 1.75 | 1.75 |
| | Weight/length (lb/ft) | 0.080 | 0.111 | 0.116 |
| | Metallic area (in.$^2$) | 0.0383 | 0.0316 | 0.0317 |
| | Lubricant | Arcylic resin and graphite | Asphaltic grease | Asphaltic grease |
| Core Strand | Diameter (in.) | 0.102 | 0.094 | 0.096 |
| | Lay length (in.) | 2.30 | 0.94 | 0.94 |
| | Core-wire diameter (in.) | 0.0355† | 0.0340 | 0.0345 |
| | Outer wire diameter (in.) | 0.0330† | 0.0300 | 0.0305 |
| Outer Strand | Diameter (in.) | 0.095 | 0.086 | 0.086 |
| | Lay length (in.) | 1.05 | 0.82 | 0.82 |
| | Core-wire diameter (in.) | 0.0325† | 0.0300 | 0.0300 |
| | Outer wire diameter (in.) | 0.0310‡ | 0.0280 | 0.0280 |

*It should be noted that the rope and strand lay lengths measured for the titanium wire rope are significantly greater than those reported in Ref. 3.
†Ti-13V-11Cr-3Al wires lubricated with an acrylic resin.
‡Ti-6Al-4V wire lubricated with graphite.

It can be seen in Table 1 that the constructional data for the steel ropes are about the same. For the titanium rope, lay lengths of the rope, outer strands, and core strand were increased by about 14%, 28%, and 145% respectively over those of the steel ropes. Furthermore, wire diameters of the titanium rope are somewhat larger than those of the steel ropes. As a consequence of the larger wire diameters, the diameter of the titanium rope and its metallic cross-sectional area are greater. However, because of the lower density of titanium, the steel ropes weigh more per unit length. Figures 2 and 3 are photographs of the titanium, stainless-steel, and galvanized-steel ropes and of their strand and wire components. The results of chemical analyses that were performed on wires from the titanium and steel ropes are provided in Table 2.

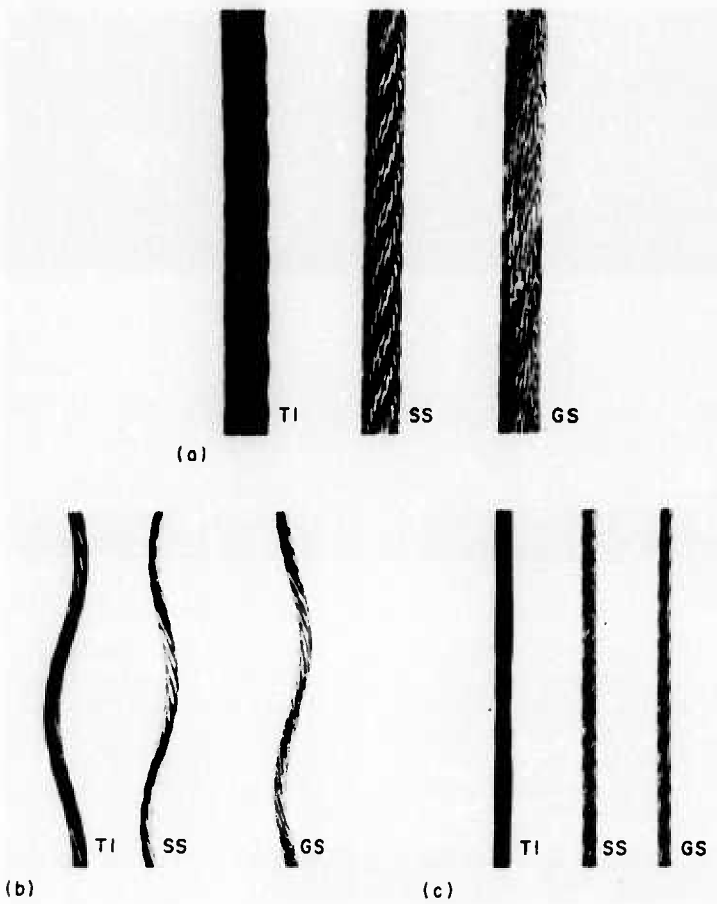


Fig. 2 — Titanium (TI), stainless-steel (SS), and galvanized-steel (GS) wire ropes and strand components. For the titanium wire rope, strand and rope lay lengths were increased over those of the steel ropes, as can be seen in these photographs. (a) The 1/4-in.-diameter, 7 × 7 wire ropes studied. The six outer strands of each rope type (Fig. 2b) were wrapped around their respective center strand (Fig. 2c) in a right lay (4). (b) Outer strands. The exterior wires of these strands (Fig. 3a) were formed around the core wire (Fig. 3b) in a left lay (4). (c) Core strands. The outer wires of these strands (Fig. 3c) were assembled around the center wire (Fig. 3d) in a right lay.

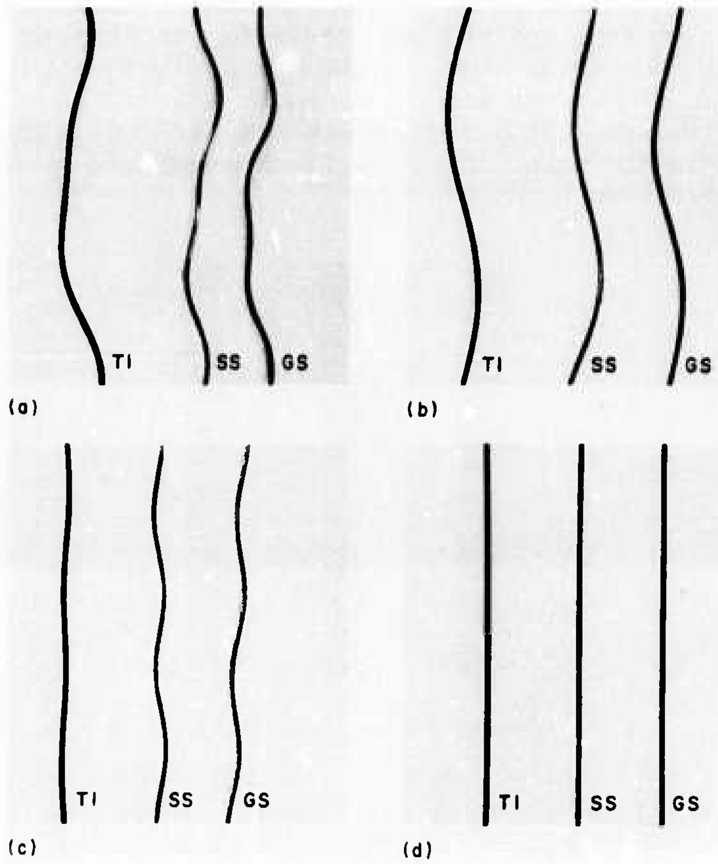


Fig. 3 — The four unique wire components of the titanium (TI), stainless-steel (SS), and galvanized-steel (GS) wire ropes. The disassembled wires and the strands from each type of wire rope maintain their shape as a consequence of being performed (4). (a) Outer wires of the outer strands. (b) Center wires of the outer strands. (c) Outer wires of the core strand. (d) Center wires of the core strand.

Table 2
Chemical Composition of the Titanium, Stainless-Steel and Galvanized-Steel Wires

| Elements (%) | Titanium | | Stainless Steel | Galvanized Steel |
|---|---|---|---|---|
| | A, B, C* | D* | A, B, C, D* | A, B, C, D* |
| Fe | 0.005 – 0.015 | 0.01 – 0.05 | Major constituent | Major constituent |
| Zn | – | – | – | 1 – 3 |
| Cu | 0.0001 – 0.0005 | 0.0001 – 0.0005 | 0.1 – 0.3 | 0.05 – 0.15 |
| Mo | 0.001 – 0.005 | – | 0.3 – 0.5 | 0.1 – 0.3 |
| V | 13.2 | 4.0 | 0.01 – 0.05 | 0.001 – 0.005 |
| Ni | – | – | 8.1 | 0.01 – 0.05 |
| Cr | 10.9 | 0.005 | 17.9 | 0.01 – 0.05 |
| Si | 0.001 – 0.005 | 0.001 – 0.005 | 0.5 – 1.0 | 0.5 – 1.0 |
| Mn | 0.0001 – 0.0005 | 0.001 – 0.005 | 0.5 – 0.9 | 0.3 – 0.7 |
| Al | 3.0 | 6.2 | 0.0001 – 0.0005 | 0.01 – 0.05 |
| Ti | Major constituent | Major constituent | 0.0001 – 0.0005 | 0.0001 – 0.0005 |

*See Fig. 1 for wire nomenclature A, B, C, and D.

## EXPERIMENTAL PROCEDURES

To ascertain the mechanical properties and fatigue performance of the titanium wire rope, several tests were devised and conducted at the test facilities of the Naval Research Laboratory (NRL) and The Catholic University of America. The overall test program consisted of two major parts: static tensile tests and axial fatigue tests. The stainless-steel and galvanized-steel ropes that are described in Table 1 were also subjected to these tests.

### Static Tensile Tests

Tensile tests were conducted on wire-rope specimens and on their individual wires to determine the rope break strength, stretch characteristics of the rope, torque behavior of the ropes, ultimate strength of individual rope wires, and efficiency of the rope construction.

A large testing machine was used to load 7-1/2-ft-long wire-rope specimens. The machine has a single screw drive and applies a load to the specimen at a constant rate of machine cross-head displacement. Specimens from each wire rope were cut and terminated with zinc-pour sockets in accordance to the specimen preparation techniques outlined in Ref. 5. It should be noted that an epoxy was used to terminate the titanium-rope samples instead of zinc, which was used for the steel ropes.

Two different static tensile tests were conducted. Five specimens from each type of wire rope were loaded in the following manner:

Tensile Test 1 — Three specimens were loaded from an initial 100-lb preload to rupture.

Tensile Test 2 — Two specimens were load cycled five times between five different load ranges. The lower end of each load range was 0-lb. The maximum loads were 1000, 2000, 3000, 4000, and 5000-lb. After load cycling the specimens were loaded until they ruptured.

The static load-cycle test (Tensile Test 2) was employed to study the tensile properties of rope specimens for different working loads. A load was continuously applied during both of the tensile tests at a machine-head displacement rate of 0.15 in./min. To measure the torsional properties of the ropes, it was necessary to impede rotation of both ends of the specimens during the test. Longitudinal strain and torque induced by the rope samples were accurately measured by the methods described in Ref. 5. Two XY recorders were used to continuously plot load-versus-strain and torque-versus-load data for each rope specimen.

A Tinius Oleson testing machine was used to tensile test wire samples taken from new specimens of each rope.

### Axial Fatigue Tests

Axial fatigue tests were performed to investigate the effect of repeated loading on the specimens and to make fatigue performance comparisons.

These tests were conducted in the test facilities of The Catholic University of America. They were performed in a 22,000-lb-capacity Amsler high-frequency vibrophore. The vibrophore operates on the resonance principle, that is, its test frequency is dependent on the natural frequency of the test specimen and the mass placed above the specimen. Wire-rope samples, 10-in. in length, were prepared for test according to the techniques mentioned in Ref. 6.

## RESULTS

Results of the tests conducted on the wire-rope specimens and on their individual wires are summarized in Tables 3 through 5 and in Fig. 4.

### Mechanical Properties

The load-versus-strain and torque-versus-load data that were obtained from Tensile Test 1 are shown in Figs. 5 and 6. A summary of the tensile properties for each rope is given in Table 3. It can be seen from this table that:

- The strength-to-weight ratio of the titanium rope is about 24% greater than that of the galvanized rope.

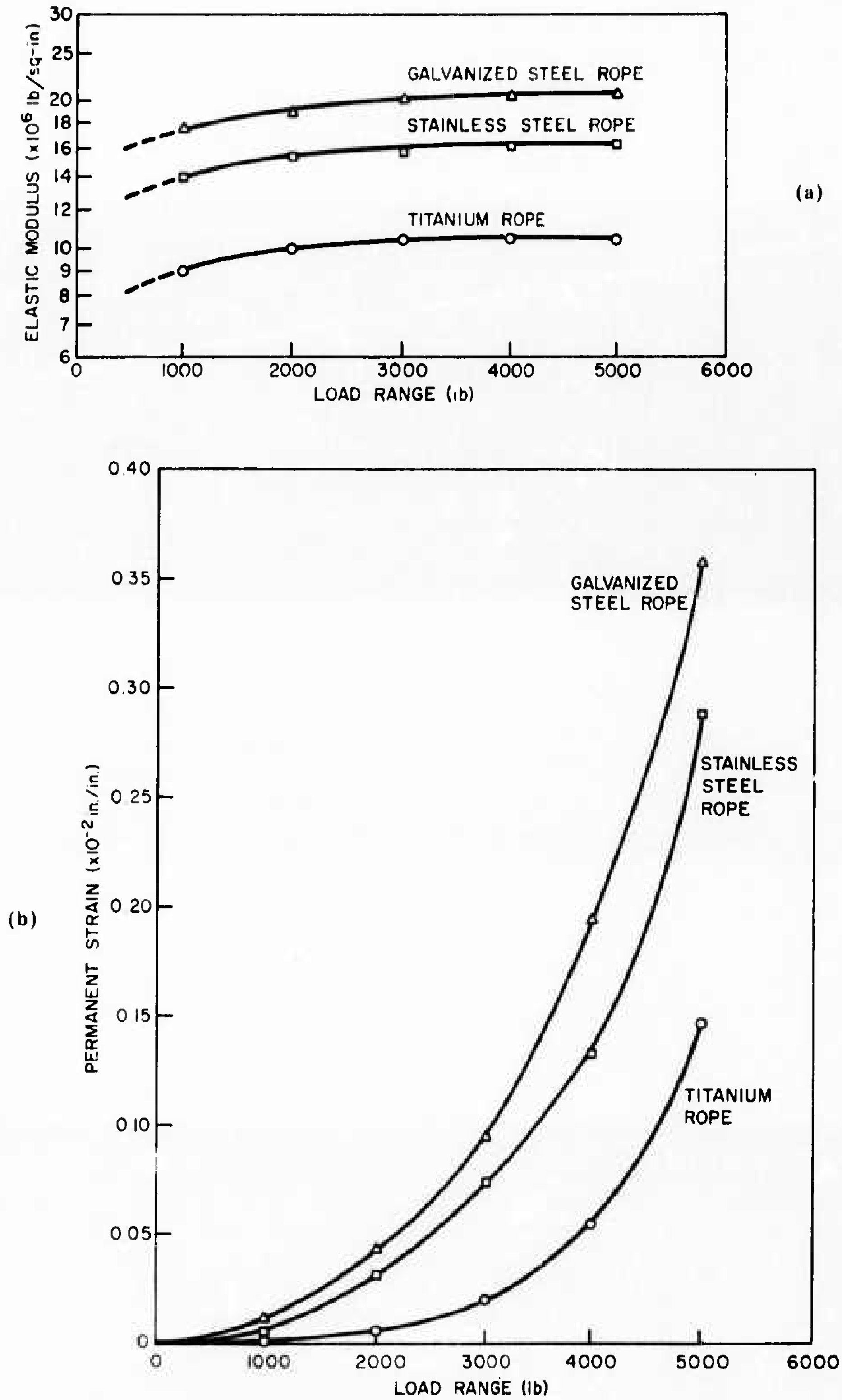


Fig. 4 — Stretch characteristics of the titanium, stainless-steel, and galvanized-steel wire ropes as a function of working load. (a) Elastic modulus vs working load. (b) Permanent strain vs working load.

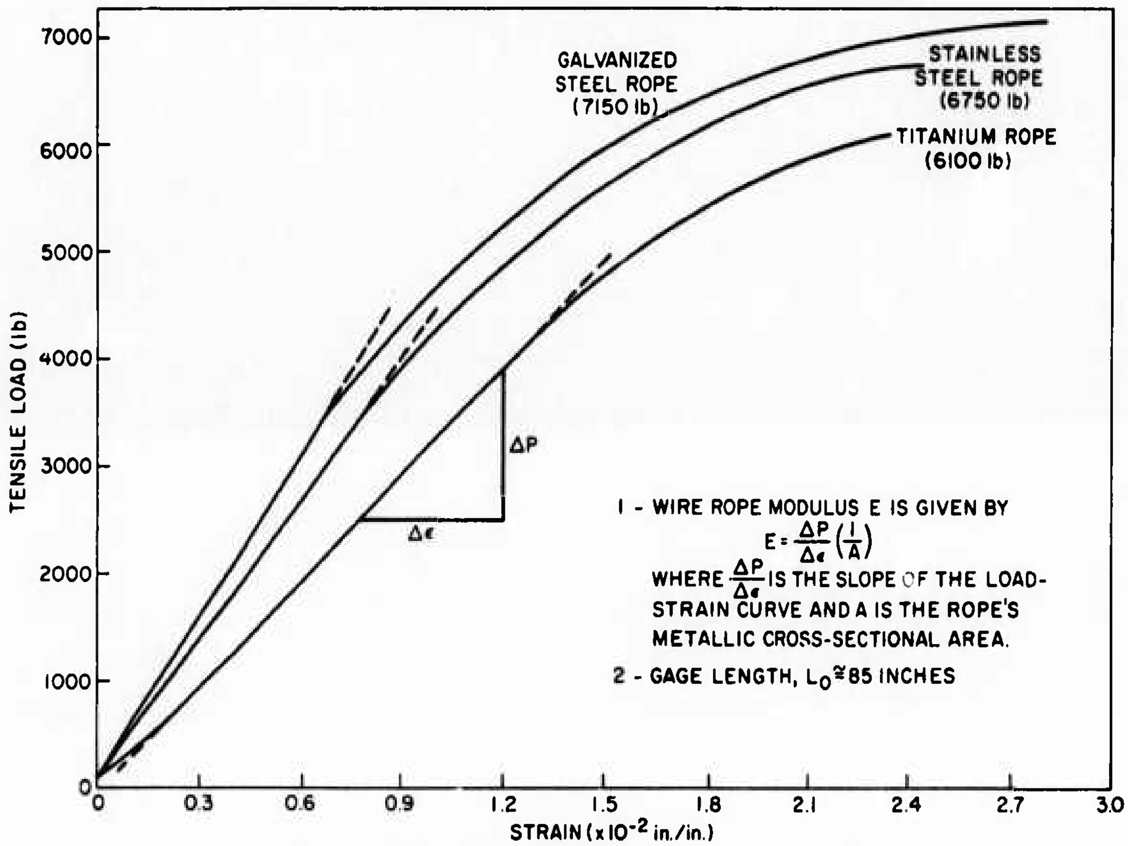


**Fig. 5 — Load vs strain data for the 1/4-in.-diameter titanium, stainless-steel, and galvanized-steel wire ropes. Each specimen was loaded continuously from 100 lb to rupture.**

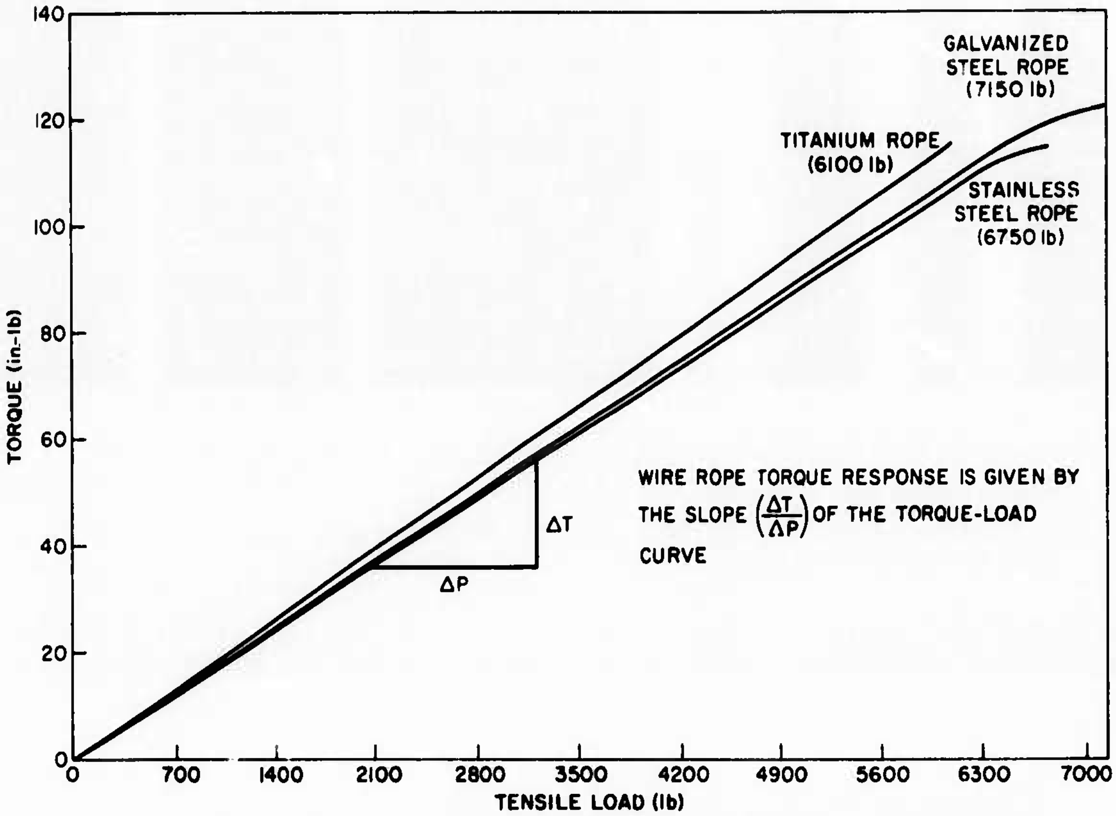


Fig. 6 — Torque vs load data for the 1/4-in.-diameter titanium, stainless-steel, and galvanized-steel wire ropes. Note that the torque generated by each rope is a linear function of the applied load.

Table 3
Tensile Properties of the 1/4-In.-Diameter (7 × 7 Construction)
Titanium, Stainless-Steel, and Galvanized-Steel Wire Ropes

| Wire Rope \ Mechanical Properties | Strength-to-Weight Ratio* (ft) | Strain at Rupture ($10^{-2}$ in./in.) | Energy to Rupture† (in. lb/in.) | Constructional Modulus ($10^6$ psi) | Torque Response (in. lb/lb) |
|---|---|---|---|---|---|
| Titanium | 76,250 | 2.40 | 84 | 8.6 | 0.0189 |
| Stainless Steel | 60,810 | 2.47 | 107 | 13.7 | 0.0175 |
| Galvanized Steel | 61,640 | 2.82 | 140 | 16.0 | 0.0177 |

*Rope break strength divided by rope weight per unit length.
†Area under the load-versus-strain curve (Fig. 4).

- For the titanium rope, strain at rupture is slightly less than that of the stainless-steel rope and is approximately 85% of that of the galvanized rope.
- The titanium rope requires about 21% less energy per unit length to rupture than the stainless-steel rope and about 40% less energy than the galvanized-steel rope.
- The modulus of the titanium rope is approximately 37% less than that of the stainless-steel rope and about 46% less than that of the galvanized-steel rope.
- The torque induced per unit of applied load by the titanium rope is about 7% greater than that of the steel ropes.

The stretch characteristics, that is, elastic modulus and permanent strain, are shown in Fig. 4 as a function of working load. These data were obtained from Tensile Test 2. Figure 7 indicates how the stretch characteristics were determined. The results of Tensile Test 2 are as follows:

- The elastic moduli of the titanium rope are significantly less than those of the steel ropes for all working loads.
- The titanium rope undergoes much less permanent strain than do the steel ropes.
- Break strengths of the rope specimens were within a percent of those obtained from Tensile Test 1.
- The torque response of each rope decreased for increasing increments of load by a small amount which was about the same for each rope. Figure 8 depicts the typical torsional behavior of the ropes.
- The titanium wire rope sustained a number of wire fractures in its core strand prior to its total rupture. The effect of the premature wire breaks on the load-versus-strain data is shown in Fig. 9. Photographs of the fractured core-strand wires are shown in Fig. 10.

The break-strength data for individual wires from new samples of each rope are provided in Table 4. The following results can be seen in Table 4:

- The average tensile strength of the Ti-13V-11Cr-3Al alloy wires is about equal to the average tensile strength of the steel wires.

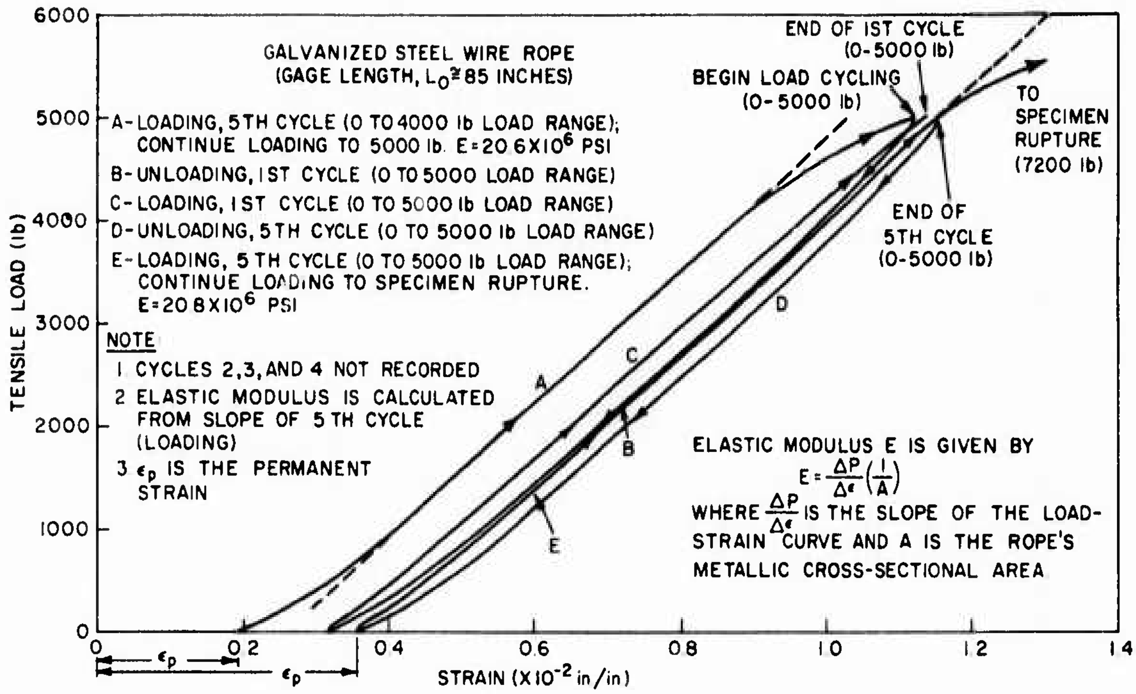


**Fig. 7 — Load vs strain data for the galvanized-steel wire rope. The data were recorded during Tensile Test 2 for the 0-to-5000-lb load range.**

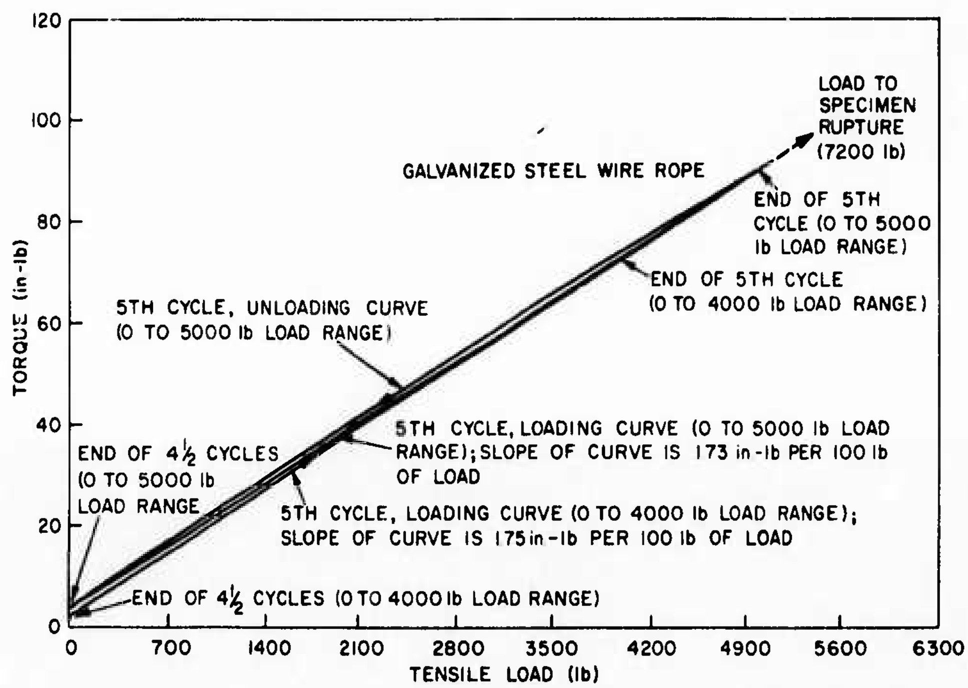


**Fig. 8 — Torque vs load data for the galvanized-steel wire rope. The data were recorded for the 0-to-5000-lb load range of Tensile Test 2. The fifth-cycle loading curve is linear from 0 to 5000 lb. The slope of this curve is only slightly less than the one obtained from Tensile Test 1.**

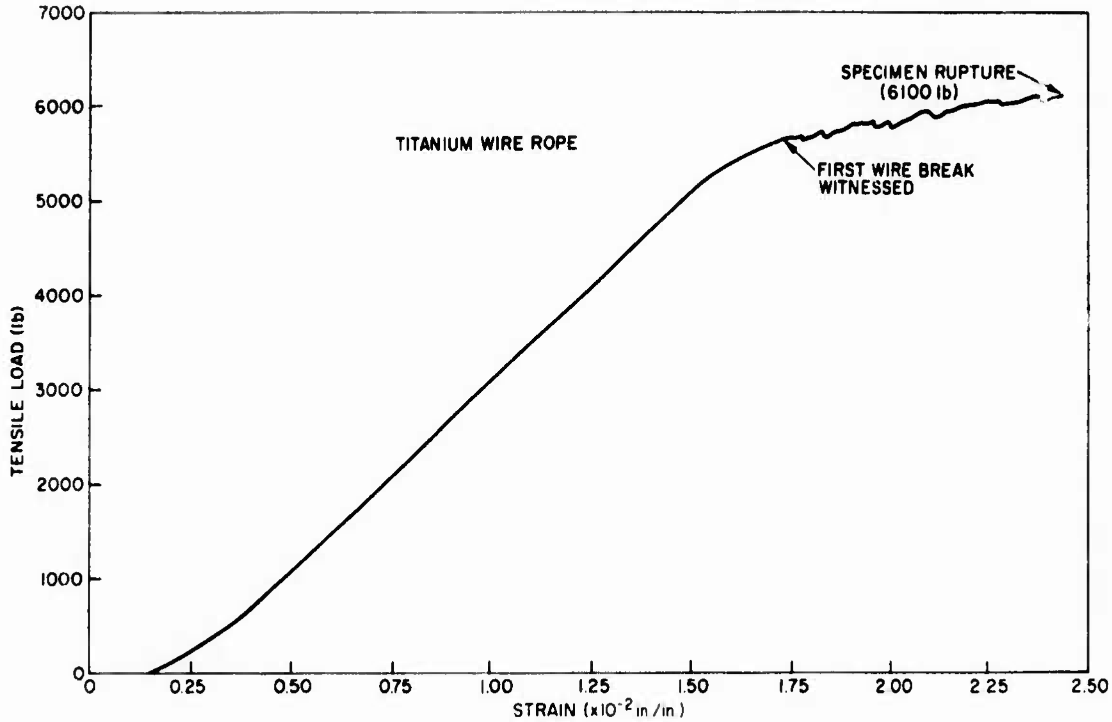


**Fig. 9 — Load vs strain data for the titanium wire rope after it was load cycled. The irregularities are a result of the fracture of the core-strand wires.**

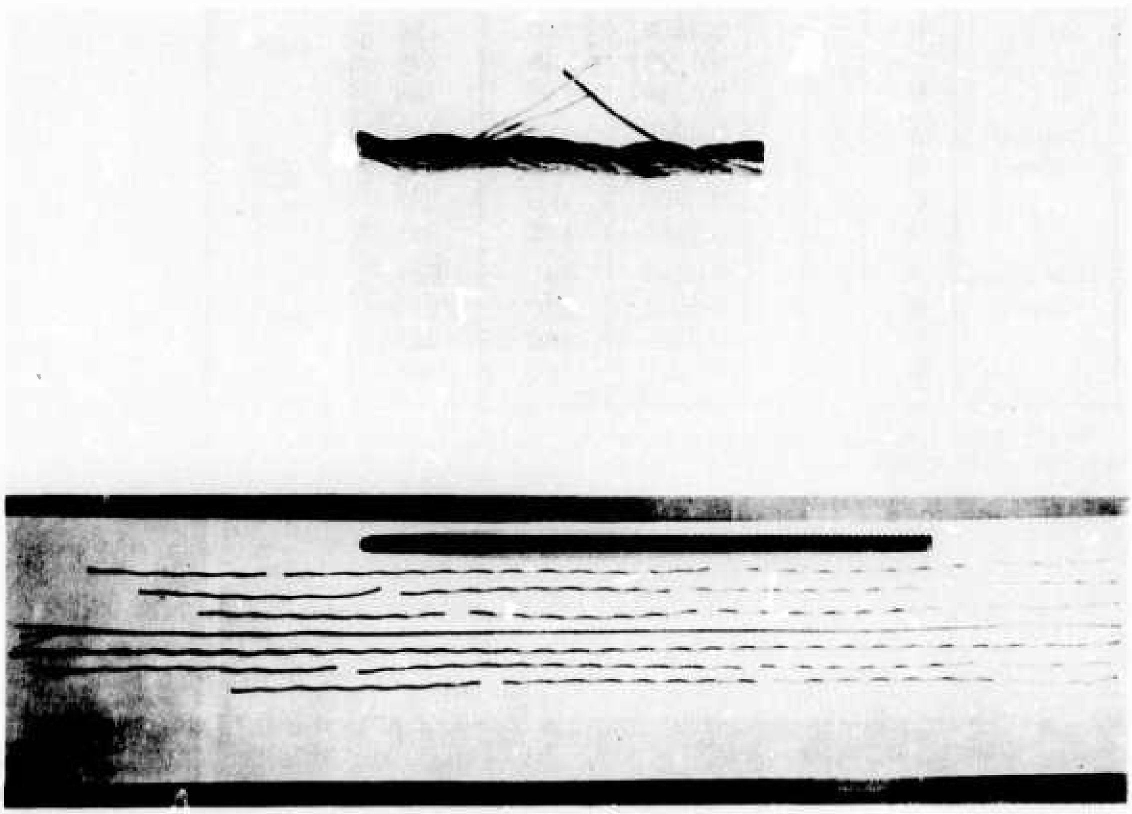

Fig. 10 — Core-strand wire breaks of the titanium wire rope. The photograph at the top shows the broken core-strand wires protruding through the outer strands of the rope. At the bottom is a photograph of the disassembled core strand.

Table 4
Break-Strength Data for Titanium, Stainless-Steel, and Galvanized-Steel Wires

| Wire Rope | Wire* | Number of Wires | Diameter (in.) | Breaking Load (lb) | Tensile Strength ($10^3$ psi) | Aggregate Wire Strength (lb) | Efficiency of the Construction¶ |
|---|---|---|---|---|---|---|---|
| Titanium | A | 1 | 0.0355† | 241 | 244 | 8059 | 0.75 |
| | B | 6 | 0.0330† | 226 | 264 | | |
| | C | 6 | 0.0325† | 225 | 271 | | |
| | D | 36 | 0.0310‡ | 142 | 188 | | |
| Stainless Steel | A | 1 | 0.0340 | 216 | 238 | 7956 | 0.85 |
| | B | 6 | 0.0300 | 193 | 272 | | |
| | C | 6 | 0.0300 | 185 | 262 | | |
| | D | 36 | 0.0280 | 152 | 247 | | |
| Galvanized Steel | A | 1 | 0.0345 | 225 | 241 | 8403 | 0.85 |
| | B | 6 | 0.0305 | 196 | 270 | | |
| | C | 6 | 0.0300 | 189 | 267 | | |
| | D | 36 | 0.0280 | 163 | 265 | | |

*See Fig. 1 for wire nomenclature A, B, C, and D.
†Ti-13V-11Cr-3Al wire.
‡Ti-6Al-4V wire.
¶Ratio of the rope break strength (Fig. 5) to the aggregate strength of the constituent wires.

- The tensile strength of the Ti-6Al-4V alloy wire is approximately 74% of the average tensile strength of the stainless-steel wire and 72% of the average tensile strength of the galvanized-steel wire.
- The efficiency of the construction for the titanium rope is 0.75 compared to 0.85 for the steel ropes.

## Fatigue Performance

Results of the axial fatigue tests are given in Table 5. The data show that:

- The life of the titanium rope in sea water compared to its life in air is about 43% less.
- The life of the stainless-steel rope in sea water compared to its life in air is about 35% less.
- The life of the galvanized-steel rope in sea water compared to its life in air is approximately 60% longer.
- The fatigue lives of the titanium rope compared to those of the steel ropes in both air and sea-water environments are significantly less.

Table 5
Axial Fatigue Life of the 1/4-In.-Diameter (7 X 7 Construction) Titanium, Stainless-Steel, and Galvanized-Steel Wire Ropes in Air and Sea-Water Environments

| Wire Rope | Fatigue Life* | |
|---|---|---|
| | Air ($10^6$ cycles) | Sea Water ($10^6$ cycles) |
| Titanium | 0.148 | 0.084 |
| Stainless Steel | 0.226 | 0.147 |
| Galvanized Steel | 1.058 | 1.688 |

*The experimental procedure required a 1200-lb mean load, an 1800-lb load range, and a 70-Hz test frequency.

An inspection of the wire-rope fatigue specimens was performed after their test to investigate the effect of repeated load on them. Each test specimen was disassembled for this purpose. The core-strand wires of the titanium rope had multiple fractures (Fig. 11), some occurring in wire lengths as small as 1/16 in. long. In contrast, a fractured wire of the steel ropes usually contained only a single break along its length.

## DISCUSSION

Results of the static tensile tests show that the mechanical properties of the titanium rope are more desirable for wire-rope components of marine structures than are those of the steel ropes. A comparison of the break loads for each rope (Fig. 5) showed that the break strength of the titanium rope was the lowest. There are two reasons for this. First, the aggregate strength of the titanium-alloy wires, compared to those of the steel ropes, was less. In Table 4 it can be seen that the total load-carrying capacity of the titanium rope is dominated by the lower tensile strength of its 36 wires made of Ti-6Al-4V alloy. Second, the increased lay length of the titanium rope and of its strand components did not enhance its overall load-carrying capability. The ratio of the break strength of the rope to the aggregate strength of its constituent wires demonstrates this point. This ratio is used to denote the efficiency of the rope construction. As might be expected, this ratio is the same for the steel ropes since they both have the same constructional geometry. The efficiency of the titanium rope's construction was 0.75 compared to 0.85 for the steel ropes. Thus the break strength of the titanium rope could be augmented by increasing its rope and strand lay lengths to those of the steel ropes. However, whether or not such a change would improve the fatigue performance of the titanium rope remains doubtful.

Even though the break strength of the titanium rope was lowest compared to the other two ropes, the titanium rope was superior to the steel ropes in terms of strength-to-weight ratio. This, of course, is a result of the lower density of the titanium alloys.

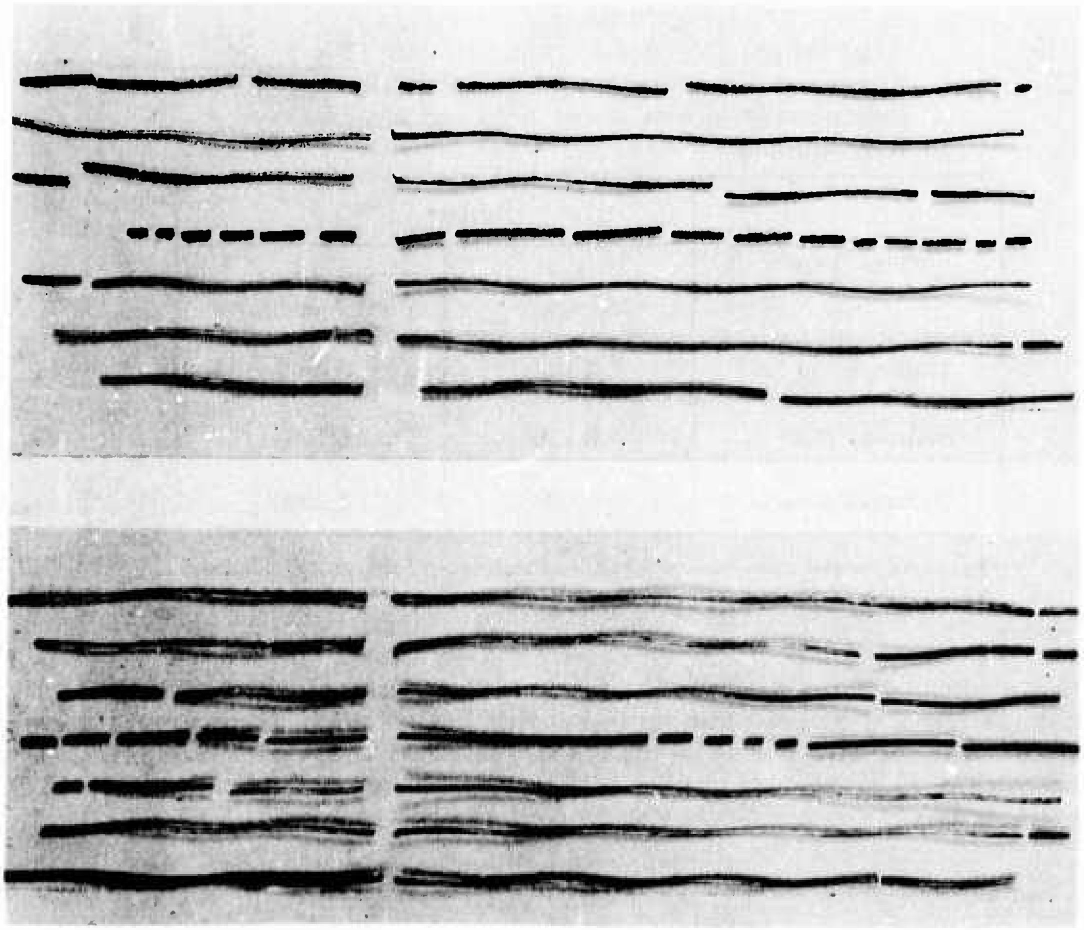

Fig. 11 — Typical fracture appearance of the core-strand wires of the titanium wire rope. The core-strand wires at the top are from a rope that was fatigue tested in air. Those on the bottom are from a rope that was fatigue tested in sea water.

The axial fatigue tests were accelerated laboratory tests. Therefore, an interpretation of the results (Table 5) in terms of actual service life is difficult. It was anticipated that the fatigue life in sea water would be lower than the fatigue life in air for each rope. Except for the galvanized-steel rope, this was the case. The fatigue performance of the galvanized-steel rope in sea water was significantly greater than that in air, possibly as a result of the lubricating properties of the zinc and sea-water combination.

The core-strand wires of the titanium rope, denoted as A and B in Fig. 1, fractured prematurely during Tensile Test 2 (Fig. 10) and also sustained multiple fractures as a result of axial fatigue in air and sea-water environments (Fig. 11). A number of these fractured titanium-wire samples were mounted for examination in the scanning electron microscope (SEM). Wires from Tensile Test 2 specimens appear to have failed as a result of tensile overload. Furthermore, it was noted that over half of the wires from fatigue rope specimens, regardless of location in the rope, appear to have failed as a result of tensile overload also. The balance of the wire failures from the fatigue rope specimens, however, showed evidence of fatigue crack propagation from a pre-existing split in the wire, possibly a drawing defect. Typical examples of these fracture surfaces are shown in Figs. 12 and 13. Figure 12 shows


Fig. 12 — Beach markings of a fatigue crack in a type-B wire of a titanium wire rope that was fatigue tested (Fig. 11)

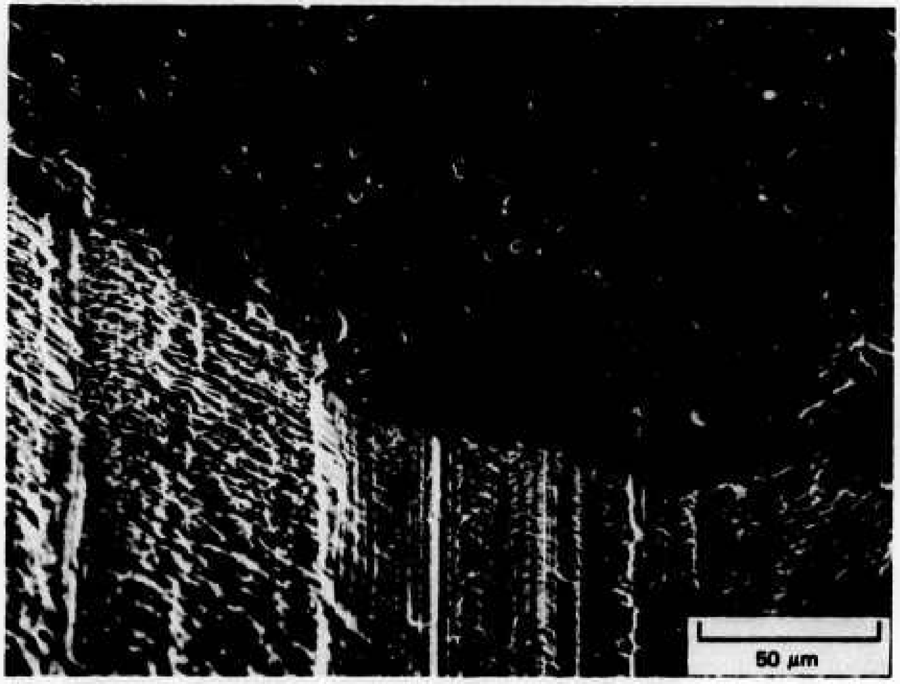


Fig. 13 — Part-through fatigue crack in a type-A wire of a titanium wire rope that was fatigue tested (Fig. 11)

that the progress of the fatigue crack in the type-B, Ti-13V-11Cr-3Al wire to be outlined by a series of "beach" marks denoting transient events in the history of the wire. Figure 13 shows the outline of a part-through crack in a type-A, Ti-13V-11Cr-3Al core wire. Application of the Irwin-Snedded stress-intensity formula for surface cracks (7) indicates that a 3-mil semicircular crack would be required to exceed the fatigue threshold ($\approx$4 ksi $\sqrt{\text{in.}}$ (8)) for the 2100-lb maximum fatigue test load.* This agrees with the measurements in the micrograph, suggesting that a fatigue crack did indeed emanate from a defect of about this size. For this value of fatigue threshold, there is no way in which a crack smaller than this size could have propagated under the test conditions. It is assumed, therefore, that these flaws were formed during the wire drawing process, leading to a defective condition in the new rope.

## CONCLUSIONS

The conclusions reached in regard to the mechanical properties and fatigue performance of the titanium-alloy wire rope, relative to steel ropes of the same nominal diameter and structural form, can be listed as follows:

- Strength-to-weight ratio of the titanium rope is significantly greater.
- Stretch characteristics of the titanium rope are appreciably less.
- Torque generated by the titanium rope is somewhat greater.
- Axial fatigue life of the titanium wire rope, in both air and sea-water test environments, was significantly less.
- Efficiency of the titanium-rope construction is less.

The high strength-to-weight ratio and good stretch characteristics of the titanium rope are desirable properties for wire-rope components of marine structures. However, data on fatigue performance suggest that the titanium rope would fail as a part of a marine structure in a much shorter period of time than would either of the less expensive steel ropes.

## ACKNOWLEDGMENTS

The author expresses his appreciation to Dr. S. R. Heller, Jr., for his permission to use the fatigue test facility of The Catholic University of America, to Mr. J. Metcalf for his time and effort in the conduct of the fatigue tests, and to Dr. W. Cullen for providing the fatigue fracture analysis.

## REFERENCES

1. J. Macco and J. Weiss, "Evaluation of All-Beta (Ti-13V-11Cr-3Al) Titanium and Galvanized Improved Plow Steel Wire Ropes," Technical Memorandum 4, Project 9300-44, Naval Applied Science Laboratory, July 25, 1966.
2. T. Rust and H.B. Jopson, "Evaluation of Titanium Alloy Cables for Aircraft Use," Report NADC-AM-6709, Naval Air Development Center, March 17, 1967.

*The corresponding tensile stress in the wires of the core strand are 62 ksi for the center type-A wire and 61 ksi for the type-B wires (9).

3. Military Consultant Service, "Marine Titanium Cable Test Final Report," Contract N0014-68-C-0361, Office of Naval Research.

4. "Roebling Wire Rope Handbook, U.S. Navy ed.," Colorado Fuel and Iron Steel Corporation, Roebling Wire Rope, Trenton, N.J., 1966.

5. D.A. Milburn and N.J. Rendler, "Methods of Measuring the Mechanical Behavior of Wire Rope," NRL Memorandum Report 2459, July 1972.

6. F. Metanzo, "Axial Fatigue of Wire Rope in Sea Water," OTC 1579, Offshore Technology Conference, 1972.

7. G.R. Irwin, J. Appl. Mech. **29**, 651 (1962).

8. R.J. Bucci, P.C. Paris, R.W. Hesteburg, R.A. Schmidt, and A.F. Anderson, "Fatigue Threshold Crack Propagation in Air and Dry Argon for a Ti-6Al-4V Alloy," in *Stress Analysis and Growth of Cracks*, STP 513, American Society of Testing and Materials, Philadelphia, 1972.

9. F.H. Hruska, "Calculations of Stresses in Wire Rope," Wire and Wire Products **26**, 766, 799 (1951).