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WOODS HOLE OCEANOGRAPHIC INSTITUTION

TECHNICAL MEMORANDUM NO. 2-70

EXPERIMENTAL ANALYSIS OF THE FAILED WIRE ROPES
OF THE SUBMERSIBLE ALVIN HOIST SYSTEM

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Woods Hole, Massachusetts

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EXPERIMENTAL ANALYSIS OF THE FAILED WIRE ROPES
OF THE SUBMERSIBLE ALVIN HOIST SYSTEM

by

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July 1970

This work has been carried out under Contract Nonr 3484(00);
NR 260-107 with the Office of Naval Research.

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Woods Hole Oceanographic Institution

Acknowledgements

The authors express their gratitude for the very helpful cooperation obtained from the Metallurgy Branch of the Naval Applied Science Laboratories, the Engineering Department of the Wire Rope Division of the American Chain and Cable Company, and the Marine Department of the Woods Hole Oceanographic Institution.

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1.0 Introduction

The research submarine ALVIN was carried, launched, and recovered by a platform hoist located between the pontoons of the catamaran support vessel, LULU. (Figure No. 1) On October 16, 1969, the wire ropes of the hoist system failed and the submarine ALVIN was lost. The modes and causes of the failures were subsequently investigated in a comprehensive test program. Methods and results of this experimental analysis are hereafter reviewed.

2.0 Description of hoist system and wire rope failures

2.1 Hoist system

The research submersible ALVIN was hoisted in and out of the water by a platform moving up and down. The submarine during transport, launching, and retrieval was resting in the cradle affixed to the platform. The platform was set in motion when the four wire ropes supporting it were paid out or reeled in from or on the winding drums. (Figure No. 2)

The platform was guided at the four corners down to near the water level by structural members of the mother ship. When not in use, the platform was in the up position and rested on four safety blocks with no tension on the wire ropes. The wire ropes were guided from the platform corners to the winding drums by two single pulleys aft and two double pulleys forward. The length of the wire ropes could be adjusted by a set of turnbuckles. Furthermore, the port and starboard cables were connected together by a pin free to move in a 2 inch slot. Leveling of the platform and equalization of tension in the ropes could thus be achieved.

Figure 1. Catamaran Vessel

Figure 2. Hoist geometry

The wire ropes were stored on two divided and grooved drums (one on each side). These two drums were not mechanically coupled. Simultaneous rotation was provided and controlled by the hydraulic system. Power was transmitted to the drums by a set of reducing gears connected to a worm gear actuated by hydraulic motors.

2.1.1 Wire rope

The wire rope used in the hoist systems was a 3/4 inch diameter, 6 x 25 filler wire construction, aluminized, improved plow steel, right lay regular lay, with a polypropylene core. (Figure No. 3) The approximate tensile strength of the wires was 260,000 psi. The rated breaking strength of the rope was 47,600 lbs., whereas the ultimate breaking strength averaged from actual tests was 51,400 lbs. The modulus of elasticity of the rope was $E = 13 \times 10^6$ psi, and the yield strength 65% of ultimate. The history of the wire rope is detailed in Appendix I.

2.1.2 Terminations

At the platform end the wire ropes were attached to turnbuckles by pins inserted in the turnbuckle jaws and the steel thimbles holding the ropes. The ropes were spliced and the splices reinforced by swaged sleeves in the conventional way.

At the drum ends, the wire rope ends were fastened to the drum flanges by wire rope clips (U bolts).

2.1.3 Sheaves

The tread diameter of the sheaves was 14 inches. The groove diameter was checked with a groove gauge for 3/4 inch rope and was found correct - groove surfaces did not show

Figure 3. Cross Section of 6 x 25 FWPP Wire Rope

much deterioration.

2.1.4. Drums

The drums were cylindrical helically grooved, and of such width that the entire length of rope could be stored on one layer. The tread diameter of the drums was also 14 inches. Grooved surfaces did show a certain amount of deterioration due to abrasion and corrosion.

2.1.5. Fleet angles

The fleet angles, as determined from actual measurements made on the tender, were $1^{\circ} 15'$ for the forward cable and $0^{\circ} 26'$ for the aft cable. These values are conservative and well in line with standard industrial practice.

2.1.6. Loads

The static load supported by the four wire ropes was 42,000 lbs., since the submersible weight was 35,000 lbs. and the platform weight 7,000 lbs. If equally distributed the static load on each wire rope would have been 10,500 lbs.

In addition, dynamic loads due to ship motion (heave) and transient loading during start and stop were present. However, inasmuch as the submarine was lowered only in fair weather the loads due to heave were probably small. Increase of tension due to transient loading was also small, as experimentally determined.

Fatigue loading due to bending over sheaves was rather small, the number of cycles during use being less than 250. The cables had been in service for 18 months at the time of failure.

Figure 4. General View of Bitter Ends

2.2 Wire rope failures

While lowering the submarine, the port forward cable broke, followed immediately by failure of the starboard forward cable. The location of the breaks and the condition of the failed ropes are hereafter reviewed.

2.2.1 Failure locations

Both forward and starboard cables failed at the same location. This location corresponds to the point of tangency of the cables with their winding drums when the hoist system is at rest, i.e. with the platform up and resting on the four arresting blocks. (See figure No. 2) The location of this point was determined by compared measurements of the cable path made on the mother ship and of the cable lengths to the break point.

2.2.2 Wire rope condition at time of failure

The ends of the parted cables which could recoil, i.e. the ends attached to the platform, were opened up (broomed out). The ends on the drum side were constrained and remained closed. (See Figure No. 4)

With the exception of the section close to the bitter ends, the four lengths of wire ropes, when visually inspected were found in relatively good condition. A slight to moderate degree of corrosion had taken place in all parts of the wire ropes in contact with steel (sheaves, drums, fair leads) when the hoist system was at rest. Other parts were in like-new condition with the aluminum coating still apparent. No fishhooks or broken wires were detected in these sections

of the ropes. This indicated that the process of deterioration had taken place in a well defined and unique location close to the broken ends.

The wire ropes at the bitter ends seemed severely deteriorated. Strands were corroded, a number of outer wires in the strands were broken particularly on the drum side of the break, the polypropylene core was crushed, cut, and dry. (See Figures 5 and 6)

3.0 Failure analysis

In order to experimentally evaluate the extent of, and the process for, the deterioration of the failed ropes at the time of failure, a number of mechanical and metallurgical tests were performed. Description of these tests and the derived conclusions are hereafter outlined.

3.1 Description of tests and test results

3.1.1 Tensile tests of ropes

Tensile destruction tests were performed to evaluate the ultimate breaking strength of selected samples of the wire ropes used in the hoist system. Samples were approximately six feet long and terminated at both ends by zinc poured clevis sockets. Actual location in the hoist system of the samples tested is depicted in Figure No. 7. Breaking strength obtained in the different test laboratories are listed in Table No. I: "Tensile Tests of Wire Ropes".

3.1.2 Fatigue tests of ropes

Deterioration of the hoist cables due to bending fatigue evaluated in cyclic sheave tests approximating service conditions. These tests were performed at the Naval Applied Science Laboratories, Brooklyn, New York.

Figure 5. Close-up of Bitter Ends

Figure 6. Close-up of Bitter Ends

Samples of new and used rope were run over 15 inch sheaves under 10,000 lbs. of tension (20% of ultimate breaking strength) at a rate of 10 cycles per minute. The actual location in the hoist system of the samples tested is depicted in Figure No. 7. The number of cycles obtained at failure of at least a complete strand (25 wires) is shown for each tested sample in Table No. II: "Fatigue Test of Wire Ropes."

In addition, two samples of corroded rope were cycled 500 and 1000 times respectively and then tensile tested. The Ultimate Tensile Strength of these samples did not differ markedly from the strength of a comparable corroded section of rope.

Figure 7. Location of Tested Samples

TABLE NO. I

Tensile Tests of Wire Ropes

Sample #	Origin & Condition of Sample	Test Lab.	Breaking Strength (lbs.)
1	Acco - New	Ships rigging & Test	52,705
2	Acco - New	"	51,435
3	Acco - New	Acco	51,100
4	Acco - New	Acco	50,500
5	Starboard aft - Good	Ships Rigging	51,054
6	Starboard aft - Good	"	52,705
7	Starboard aft point of drum tangency - Good	"	45,021
8	Starboard aft from drum - corroded	"	50,927
9	Starboard aft from drum - corroded	"	49,466
10	Starboard fwd - Good	"	49,840
11	Starboard fwd - Good	"	48,577
12	Starboard fwd near break - corroded	"	42,862
13	Starboard fwd on drum - corroded	"	50,482
14	Port aft over platform shoe	NASL	45,800
15	Port aft between sheave & drum - Good	"	51,400
16	Port fwd over platform shoe	"	48,800
17	Port fwd near break - Good	"	48,800

TABLE NO. II

Fatigue Test of Wire Ropes

Sample No.	Origin & Condition of Sample	No. of Cycle @ Failure of a Strand
18	Acco - New	33,457
19	Port aft - Partly corroded	14,284
20	Port aft Tangent to drum - corroded	6,364
21	Port fwd - corroded	7,799

3.1.3 Tensile tests of wires

Tensile destruction tests were performed to evaluate the ultimate breaking strength of new wires and of wires proximate to the broken ends. The distribution of the breaking strengths obtained is presented in the histograms shown in Figures No. 8, 9, and 10.

3.1.4 Visual examination and metallurgical tests

An analysis was made of the deteriorated sections of the port and starboard forward cables near and at the bitter ends and of the individual wires at their locations to determine the nature of the deterioration process and mode of failure.

Examination of the four wire rope sections adjacent to the bitter ends showed that the 12 outer wires of each of the six (6) strands of the wire rope degraded to a much greater extent than the inner wires. In addition to general corrosion which was common to all wires, the outer wires had evidence of wear, some of them being completely broken. Corrosion product in the form of fine debris was present between the strands and between the wires in the strands. Analysis showed this debris to contain iron and aluminum, most likely present as their oxides. No marked difference was noted between the condition of the bitter ends of the portside and of the starboard side cables.

The visual examination of the wires revealed that the pattern of wear and the associated drastic size reduction of the outer wires was systematic in certain discrete areas (See Figure 11) whereas the size reduction, mainly due to corrosion, was moderate and uniform.

Figure 8. Wire Strength Histograms. New Wires

Figure 9. Wire Strength Histograms. Port Side

Figure 10. Wire Strength Histograms. Starboard Side

Figure 11. Pattern of Wire Wear

Furthermore, examination of these discrete areas established that the worn areas were distributed only at the periphery of the rope (See Figure 12) and that this wear was due to the contact of the crown of the outer wires with winding drum and/or with the adjacent turn of rope on the drum. It was also evident that most of the breaks of the outer wires had taken place at these worn areas.

The micro-examination of the wires showed that the wear and flattening of the outer wires were due to abrasion (bright appearance, and ridges). The abrasion was augmented by the use of an aluminized coating on the wire. After corrosion the aluminum is present as aluminum oxide which is a hard abrasive and together with the iron oxide present would rapidly cause damage to the softer steel of the individual wires.

Where identification was clearly evident and had not been masked by corrosion, examination showed that the fracture surfaces were tensile in nature (See Figure 13). No typical fatigue break surface could clearly be identified.

Spectrochemical analysis, microprobe, and metallographic tests were conducted on sections of new wires, used wires, and corrosion debris. No abnormal elements were detected. Carbon content was found to be in agreement with the manufacturers specifications. Aluminum was identified as the coating metal. A standard structure for drawn improved plow steel wire was noted with no structural abnormalities. No cracks were present in the vicinity of the wire break surfaces.

The weight of the lubricant as a percent of the polypropylene core was determined in new and used samples of rope core center and found to be 4.9% in new rope, 3.2% in port side aft cable and 1.6%

Figure 12. Wire Worn Areas Distribution

Figure 13. Close-up of Deteriorated Wire

in port side forward cable.

3.2 Interpretation of test results

3.2.1 Strength of new rope

Tensile testing of unused new sections of rope obtained from the same lot as installed in the ALVIN mother ship showed that the average Ultimate Tensile Strength was 51,435 lbs. As the rated (catalog) breaking strength is given as 47,600 lbs., the actual value obtained is 8.5% higher than rated strength.

The metallurgical tests performed on samples of new rope confirmed that the ropes installed were originally of good quality and within commercial specifications.

3.2.2 Strength of damaged ropes

The strength of the used rope at the point of break and at the time of failure had to be reconstructed from the strength of the wires close to the break.

The agglomerated strength " S_A " of all the wires in the rope is given by:

$$S_A = (72-n) S_O + 36 S_I + 6 S_K + 36 S_F$$

where

S_O = strength of outer wires

S_I = strength of inner wires

S_K = strength of King (center) wires

S_F = strength of the filler wires

n = number of broken outer wires, at the time of failure.

The strength of the wire ropes " S_R " is given by

$$S_R \leq e S_A$$

Where " e " is the efficiency construction factor of the rope, usually

defined as the ratio of the ultimate breaking strength of the new rope to the agglomerated strength of all the individual wires in the new rope. This ratio was experimentally derived and found to be 0.803. Rope strengths obtained for the lowest, the most probable, value and the highest value of individual wire strengths are presented in Table No. III.

TABLE NO. III
"Statistical Rope Strengths"

ROPE LOCATION	Lowest Strength		Most Probable Strength		Highest Strength	
	lbs.	% of New	lbs.	% of New	lbs.	% of New
PORT	18,443	36	23,164	45	29,220	57
STARBOARD	19,166	37	26,152	51	32,094	62

These results indicate that the remaining strength of the deteriorated hoist cables ranged from a minimum of 36% to a maximum of 60% of original strength, (assuming that the efficiency construction factor remained unchanged in the deteriorated condition).

Tensile tests on corroded sections of the port and starboard forward and aft cables showed that the loss in strength due to corrosion (including perhaps some contribution by fatigue due to the few hundreds of operational cycles of the hoist system) showed that the loss was equal to or less than 18% of the ultimate strength of the new rope (10% of the rated strength). Tensile tests performed on uniformly corroded individual wires of the bitter ends with no signs of abrasive wear (inner wires) showed a reduction of 23% compared to the strength of new wires. These tests showed that the damage due to corrosion alone was

moderate and that this process was not the predominant factor for cable deterioration.

Fatigue - The number of cycles at failure, listed in Table No. II range from a high of 33,457 cycles for a new rope to a low of 6,364 cycles for a deteriorated section of the port side aft cable straddling the point of tangency with the storing drum.

The number of cycles obtained with a new lubricated rope was relatively small despite a tensile safety factor of five. However, it is essential to note that the ratio of sheave diameter to rope diameter (20) is much less than the minimum ratio recommended for this particular type of rope (30).

The number of cycles obtained with the corroded and non-lubricated rope is only 18% of the number of cycles obtained with a new lubricated rope. This reduction of fatigue life is due to the changed condition of the rope, i.e., corroded, non-lubricated with presence of abrasive wear particles.

However, 6,364 cycles is approximately 25 times the number of actual cycles attained with this rope. This actual number of cycles was also to be the anticipated number of cycles as the rope was due for routine replacement after completion of the last, unfortunate dive.

These tests confirmed the conclusions derived from a metallurgical investigation of the fracture faces of the wires, that the breaks were not fatigue in nature. It further shows that the effects of fatigue caused by the few hundred cycles of actual service were only a minor contribution to the rope failure.

Wear - The ropes of the hoist system were free of the usual signs of severe abuse, like crushing, flattening, kinks and size reduction. Broken wires, fish hooks and wear of the crown wires were found only near the broken ends. This localized wear constituted a major factor of deterioration, as shown by the large percentage of strength reduction established in the reconstruction of strength at time of failure. The nature of the wear was clearly abrasion.

3.2.4 Causes and modes of Cable Failures.

Maximum tension and therefore maximum pressure on the wires occurred at and near the point of tangency of the ropes with the winding drums (point of lift). When raising the platform a few inches to clear the resting blocks, the ropes were stressed to their maximum operative stress levels and high friction occurred between rope and drum as the ropes adjusted themselves to the stressed condition. The accumulation of abrasive corrosion products at this location and the repeated immersion of the forward cables resulted in a localized and accelerated deterioration of the ropes.

Results from the hoist system operational tests performed at Woods Hole did show that no appreciable transient loads were present in the hoist cables during normal stops and starts.

The analytical derivation of the combined tensile and bending stresses shows that the load at the location and time of failure could have been as high as 19,136 lbs. in the forward cables (Appendix No. 5.2). This force value falls within the statistical distribution of the remaining strengths previously established, thus confirming that the port cable failed under normal operating conditions.

After failure of the port forward cable the submarine and the cradle were free to fall a distance equal at most to the width of the centering slot (2 inches). At the end of the fall the forward starboard cable was forced to absorb the impact load.

Tests simulating this event have shown that this impact load could be as high as twice the static load, and therefore was certainly sufficient to break the deteriorated and weakened starboard forward wire rope.

4.0 Conclusions

The port forward cable parted under normal operating conditions. The starboard forward cable parted due to impact load subsequent to the rupture of the port cable. After 18 months of use the strength of both forward cables was reduced to a level close to the operating loads in these cables. The deterioration of both cables was strictly located at the point of lift. The mechanism of deterioration was essentially wear due to high friction of the dry ropes on their winding drums. Corrosion accelerated the abrasion and deteriorating process. Fatigue was not an appreciable contributing factor to the ropes degradation. No defects could be observed in the ropes which were of good commercial grade.

5.0 Appendices

5.1 Wire Rope History. (See Figure No. 14.)

5.2 Analysis of the loads in the cables of the hoist system (H.O. Berteaux)

1. Static loads

The static load in the cables is a function of the space location of the center of gravity of the submarine and platform system. To reduce the complexity of the general statically indeterminate problem, the reasonable assumption is made that the C.G. of the submarine is on the longitudinal center line of the platform. (See sketch).

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TO :File (T & E, ALVIN Salvops)

DATE: 6 November 1968

FROM :J. Leiby, H. Berteaux

SUBJECT: ALVIN Hoist System - Wire rope history

1. Manufacturer:
Hazzard Wire Rope Div. of American Chain & Cable Co.
Wilkes-Barre, Penna.
(Agent is Philip A. Rand Co., Newton, Mass.)
2. Type:
3/4-inch diameter, 6 x 25 filler wire construction
with polypropylene rope center core, ALUMINIZED
improved plow steel. Mfg. Card #66466.
3. Rating: (Mfg. Catalogue) 47,600#
Actual ultimate rope strength
in Mfg. test Nov. 1966..... 51,100#
4. Dates:
Manufactured - Wilkes-Barre Oct. 31, 1966
Tested Wilkes-Barre Nov. 1966
WHOI P.O. #18224 Feb. 24, 1967
To Philip A. Rand Co., Newton, Mass.
Rand P.O. #6592
Rec'd. at WHOI March 21, 1967
Installed April, 1967
System load tested @ Miami June, 1967
Wire broke Oct. 16, 1968

Jonathan Leiby
J. Leiby

gbc

cc: Director
Dr. Maxwell
Mr. Stanbrough
Mr. Berteaux
Dr. Daubin

Fiber Core

6 x 25 FW Elevator Rope

Figure 14. Wire Rope History

The equilibrium conditions are then:

$$F_1 + F_2 + F_3 + F_4 = W_c + W_s$$

$$(F_3 + F_4) b = W_c \left(\frac{b}{2}\right) + W_s y$$

$$(F_2 + F_3) a = (W_c + W_s) \frac{a}{2}$$

Where:

F_i ($i=1,2,3,4$)	is the tension force in cable
W_c	is the weight of the platform
W_s	is the weight of the submarine
a	is the width of the platform
b	is the length of the platform
y	is the location of the submarine
G.G. on the longitudinal center line	

The assumption on the location of the submarine C.G. yields two additional equations

$$F_3 = F_4$$

$$F_2 = F_1$$

The solutions of this set of equations are:

$$F_1 = F_2 = \frac{Wc}{4} + \frac{Ws}{2} \left(1 - \frac{y}{b}\right)$$

$$F_3 = F_4 = \frac{Wc}{4} + \frac{Ws}{2} \left(\frac{y}{b}\right)$$

It can be seen that the sum

$$\sum_{i=1}^4 F_i = Wc + Ws \quad \text{as it should}$$

and that for the case $y = \frac{b}{2}$ the forces are equal and given by

$$F_i = \frac{Wc + Ws}{4} \quad \text{as it should.}$$

The maximum distance between the C.G. of the submarine and the C.G. of the platform has been observed to be approximately one tenth of the platform length. In this condition

$$y = \frac{3}{5} b$$

and the tensions are

$$F_1 = F_2 = 0.25 Wc + 0.2 Ws \text{ in the aft cables}$$

$$F_3 = F_4 = 0.25 Wc + 0.3 Ws \text{ in the forward cables}$$

The additional tension due to friction in the sheaves (head line factor) is neglected (low speed and small number of sheaves).

2. Dynamic loads

The platform was not operated in bad weather and therefore additional loading due to heave acceleration was never severe.

In simple harmonic motion the heave acceleration "a" is given by

$$a = A\omega^2$$

where $A = \frac{1}{2}$ wave amplitude from crest to trough

and $\omega = 2 \frac{\pi}{T}$ with T the wave period.

In a moderate sea condition with 4 ft. wave amplitude and 4 sec. wave period the maximum acceleration is

$$a \approx \text{ft./sec.}^2 \approx \frac{1}{6} g \text{ approximately}$$

(where $g = 32 \text{ ft./sec.}^2$)

3. Tension including dynamic loads

The maximum weight of the platform and the submarine under these dynamic conditions is given by

$$W_c^v = 1.17 W_c$$

$$W_s^v = 1.17 W_s$$

and the maximum tension in the cables are:

$$F_1 = F_2 = 0.293 W_c + 0.234 W_s$$

$$F_3 = F_4 = 0.293 W_c + 0.351 W_s$$

The weight of the cradle being 7,000 lbs. and the weight of the submarine being 35,000 lbs., the tension in the cables is therefore

$$F_1 = F_2 = 0.293(7000) + 0.234(35,000) = 10,241 \text{ lbs.}$$

$$\text{and } F_3 = F_4 = 0.293(7000) + 0.351(35,000) = 14,336 \text{ lbs.}$$

4. Bending loads

Stresses induced in the wires of a rope passing over a sheave must be added to the stresses due to pure tension. One way to account for these bending stresses is to derive a fictitious tensile force

inducing equivalent stresses in the wires*. A standard and simple approach to the solution of this complex problem is to assume that the wire rope is made of a bundle of parallel circular beams of equal cross section and all bent to the same radius.

With this assumption the bending stress " σ " in a fiber of any beam is given by

$$\sigma = \pm \frac{E y}{R}$$

where

"E" is the modulus of elasticity of the wire, "y" is the distance to the neutral axis, and "R" is the bending radius. The maximum stress in the wire would then be given by:

$$\sigma_{\max} = \frac{E d}{D}$$

where d is the wire diameter

D is the sheave diameter

The equivalent force is often obtained by multiplying this maximum bending stress by the total metallic area of the rope. This leads to very high forces, the stresses in each wire being either tensile or compressive, and not constantly equal to the maximum stress.

Instead of following this course, why not derive the tensile force F_{BW} per wire and multiply the result by the number of wires? The tensile force due to bending, " F_{BW} ", in each wire is given by:

$$F_{BW} = \int \sigma dA = \frac{2E}{D} \int_0^{\pi} \int_0^{d/2} r^2 \sin \phi d\phi dr$$

$$F_{BW} = \frac{E d^3}{6D}$$

*Ref: Faires, Design of Machine Elements, 4th Edition. MacMillan Company (Page 471 & following).

and the equivalent force for the whole rope " F_B " would then be

$$F_B = N F_{BW}$$

where N =numbers of wires in the rope.

For the rope studied in this report,

$$d = 0.05 \text{ in. (average value)}$$

$$D = 15 \text{ in. (average value)}$$

$$E = 30 \times 10^6 \text{ lb/in}^2$$

$$N = 6 \times 19 = 114 \text{ (neglecting filler wires)}$$

The equivalent force is then found to be:

$$F_B = 4,800 \text{ lbs.}$$

5. Total loads

The total load in the cables is the sum of the tensile and bending loads and is:

$$10,241 + 4,800 = 15,041 \text{ lbs. for the aft cable}$$

$$14,338 + 4,800 = 19,136 \text{ lbs. for the forward cable.}$$