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on

A STUDY OF PARAMETERS THAT INFLUENCE WIRE-ROPE FATIGUE LIFE

to

NAVAL SHIP SYSTEMS COMMAND

October 31, 1974

by

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The objective of this research program was to investigate the influence of various parameters on the fatigue life of wire rope through well controlled and statistically planned laboratory bend-over-sheave fatigue experiments. Parameters studied included three rope constructions, two rope sizes, three sheave sizes, and three operating loads for ropes subjected to both simple single-sheave bending and two-sheave reverse bending. A total of 288 rope specimens were cycled to failure, and the results were analyzed statistically to determine which parameters had a significant influence on rope life.

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P. T. Gibson, F. G. White, L. A. Schalit,
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INTRODUCTION

Wire rope is an essential component of many Navy systems. This versatile machine element is used in a wide variety of applications and represents an annual investment of many millions of dollars.

Because of the importance of wire rope to the successful performance of many Navy missions, a research effort spanning several years has been underway to provide a better understanding of wire-rope behavior. This work will result in improved methods for designing wire-rope systems, selecting wire-rope constructions and materials, and retiring wire rope from service before operational safety is jeopardized.

One current Navy program has as its objective the compilation of a comprehensive wire-rope handbook. The work reported herein, as well as the results of previous experimental programs, will provide some of the basic fatigue data needed to augment this handbook and extend its scope and usefulness beyond that of wire-rope engineering handbooks previously available.

Specifically, the objective of this research program was to investigate the influence of various parameters on the fatigue life of wire rope through well controlled and statistically planned laboratory bend-over-sheave fatigue experiments. Parameters studied included three rope constructions, two rope sizes, three sheave sizes, and three operating loads for ropes subjected to both simple single-sheave bending and two-sheave reverse bending.

SUMMARY AND CONCLUSIONS

The wire-rope constructions selected for evaluation were 6 x 36 Warrington-Seale with an independent wire-rope core (IWRC), 6 x 24 Warrington-Seale with a fiber core, and 6 x 26 Warrington-Seale with an IWRC. All ropes were preformed and were of right regular lay construction. The 6 x 24 Warrington rope was manufactured from galvanized improved plow steel, and the others were manufactured from bright improved plow steel. Both 1/2-inch and 3/4-inch diameter ropes of all three constructions were subjected to the bend-over-sheave fatigue experiments.

Experiments were conducted with sheave-to-rope diameter ratios of 10, 20, and 30 and at rope tensions of 20, 40, and 60 percent of the catalog rated breaking strength. Four rope specimens were cycled to failure under each unique test condition; a total of 288 specimens were broken during the program. Care was taken to hold constant all extraneous factors which might have influenced rope fatigue life such as sheave throat shape and hardness, cycling speed, tension settings, and environmental conditions.

The statistical plan for the experiments included randomization of the test sequence with respect to rope diameter and construction, tension load, and sheave-to-rope diameter ratio. In addition, the rope specimens themselves were randomized with respect to the location at which they were cut from the manufactured lengths. Initially, two specimens were cycled simultaneously for each test condition (thereby providing an original and a repeat experiment) and then all experiments were conducted a second time with a new randomized sequence (thereby providing a replication of the experiments). This procedure was first followed for single-sheave bending and was than repeated for reverse bending.

The experimental data were analyzed statistically to determine which parameters yielded significant changes in rope life. The results of the experiments revealed that the 6 x 36 and 6 x 26 rope constructions provided nearly identical fatigue performance; however, the 6 x 24 rope was significantly poorer than the others under all test conditions. This result was as expected since the 6 x 24 construction is intended for applications such as mooring where a low elastic modulus is desired, and it is not usually recommended for applications requiring good bending-fatigue life.

An important result was that the 1/2-inch and 3/4-inch diameter ropes of each construction displayed quite similar fatigue behavior. When rope life was plotted as a function of test load (expressed as a percent of actual rope breaking strength) the data points for both rope sizes fell essentially on the same curves for all sheave-to-rope diameter ratios. This observation suggests that the results of experiments on ropes of one diameter may be extrapolated to ropes of a different diameter, at least over a limited range of diameter difference. It also indicates that future laboratory experiments may be limited to a single rope size to reduce costs without seriously jeopardizing the value of the results.

Reverse-bend experiments, which were conducted at a single sheave-to-rope diameter ratio of 20 and a sheave spacing equal to four lays, resulted in a rope life approximately 60 percent of that obtained in the absence of the reverse bend. In other words, a rope system with two sheaves may be expected to provide significantly better rope life (by approximately 67 percent) if the sheaves are arranged so as to avoid a reverse bend situation.

The results of the experiments also provided a quantitative evaluation of the striking influence of rope tension and sheave-to-rope diameter ratio on rope life. The extremes of the test conditions produced rope lives ranging from only 44 bending cycles to a maximum of 487,580 bending cycles. Examination of the specimens during and after the experiments revealed the existence of several rope failure modes, the dominant mode being determined by the particular test condition. For the least severe conditions, many broken wires were observed long before rope failure occurred. However, with increasingly severe conditions, fewer broken wires were observed, and for the most severe conditions, no broken wires could be detected within just a few cycles of rope failure. Thus, the use of broken-wire accumulation as an accurate rope retirement criterion should be limited to certain ranges of operating conditions.

A similar conclusion can be drawn regarding the use of rope elongation behavior as a retirement criterion. The less severe test conditions typically produced significant initial rope elongation followed by a long period of slight, constant elongation. Then, prior to failure, the rate of rope elongation again increased. Thus, this last change in stretch rate could be used as a signal to retire the rope. However, the more severe test conditions resulted in a more-or-less high rope elongation rate until total failure, without a detectable late-life rate change to use as a retirement criterion.

Several methods were used to present the fatigue data including use of a dimensionless parameter, the bearing pressure ratio, originally proposed about thirty years ago. It was verified that this parameter is indeed useful for presenting and normalizing fatigue data obtained over a wide range of tension loads and sheave sizes and for different rope diameters. A plot of bearing pressure ratio versus rope life for each rope construction produced a fairly well-defined curve with a surprisingly small amount of data scatter.

An unexpected result was that for the reverse-bend experiments (and only these experiments) a factor influencing rope life was the location of the test specimen on the fatigue machine. The sample on the part of the machine which included the tensioning sheave had a slightly shorter life than the sample on the opposite end of the machine, even though the two samples were connected together and the machine was symmetrical with regard to sheave location, spacing, groove shape, and bearing type. It is believed that this result was due to a very slight tension difference between the specimens caused by the drive force required to produce cycling. The significance of this observation is that very accurate tension control is required during laboratory experiments to minimize data scatter and avoid the possibility of drawing inaccurate conclusions about the results.

It is also important that future experimenters select test loads on the basis of a percent of <u>actual</u> rope breaking strength rather than on a percent of rated or catalog rope strength. The reason for this choice is that the actual strength values may vary significantly from the rated values. A comparison of the relative performance of any two different wire ropes can be done accurately only if the actual strengths are considered. If test loads are selected on the basis of rated strengths, and if the strength margins of the two ropes are significantly different, then the results can be misleading. For example, the 6 x 36 and 6 x 26 constructions evaluated during this program performed about the same when compared on the basis of test loads expressed as a percent of <u>actual</u> rope strength. However, when compared on the basis of test loads expressed as a percent of <u>rated</u> rope strength, it appeared that the 6 x 36 construction was superior.

RECOMMENDATIONS

The results of the experiments provide basic data on how several important parameters affect the bending-fatigue life of wire ropes. Although only a limited number of rope sizes and constructions, sheave sizes, and rope tensions were evaluated, the information that has been developed should be quite valuable to wire-rope users and system designers.

Presentation of the fatigue data in terms of the dimensionless bearing pressure ratio revealed the value of this parameter for ordering and normalizing the results obtained from a wide range of experiment variable combinations. However, this method of data analysis was shown to have significant shortcomings since it does not account for changes in wire-rope failure modes with the severity of the test conditions.

With the knowledge available regarding rope failure modes and with the methods of wire-rope load and stress analysis that have been developed during recent years, it should now be possible to develop a more accurate and useful method of data analysis and presentation. Additional effort put forth in this area could lead to improved methods for predicting rope life and the development of improved wire-rope retirement criteria. An additional benefit of evolving an improved data analysis technique would be to minimize the number of specimens and test conditions that would have to be included in future experimental programs. Experiment results obtained with selected combinations of variables could then be extrapolated with confidence to other conditions, thereby eliminating the need for conducting a large number of experiments.

For the experiments reported herein, as for nearly all published wire-rope bending fatigue data, the results are presented in terms of cycles to failure. This is a convenient method for conducting the experiments, and the results allow comparisons of the effects of various parameters. However, for the less severe test conditions, wire breaks occur in such large numbers long before total rope failure that no wire rope in actual service would be allowed to continue functioning in that condition. Possibly a more meaningful method would be to stop the fatigue cycling at certain critical numbers of cycles or when certain numbers of broken wires have been accumulated, and then determine the remaining rope strength through tensile tests. This procedure would allow curves to be developed indicating remaining rope strength versus bending cycles or remaining rope strength versus number of observable broken wires. Thus, the wire-rope user could better determine when to retire a wire rope to assure that its strength had not dropped below some acceptable minimum value.

Certain parameters which have a large effect on rope life but which were not included in this program include sheave throat shape and hardness, fleet angles, and rope wrap angles around the sheaves. Limited data are available suggesting the importance of these parameters, but a well-controlled set of experiments is needed to quantify their effects. For example, published data (which have been qualitatively confirmed through recent experiments at Battelle) indicate that rope wrap angles providing less than one rope lay length of sheave contact will result in poorer fatigue life than larger wrap angles. This trend is contrary to certain published handbook information and has an important impact on rope system design. It is not uncommon to find systems which use very small deflection sheaves or even flat rollers where rope wrap angles are small. It is highly likely that certain combinations of sheave-to-rope diameter ratios and wrap angles are producing serious rope damage and short rope life.

Hopefully, the results of this program will help to direct the efforts of future investigations so that duplication of effort can be avoided and attention can be focused on those studies which will be most fruitful to increasing the understanding of wire-rope behavior.

EQUIPMENT

Bend-Over-Sheave Fatigue Machine

The experiments were conducted on a multipurpose bend-over-sheave wire rope fatigue machine. The machine, shown in Figure 1, has a useable area of 4 by 18 feet and can accommodate a number of sheaves arranged in a variety of ways. It has a maximum rope load capacity of 40,000 pounds, an adjustable specimen cycling stroke of up to 15 feet, and an adjustable stroking speed with a practical limit of 200 feet per minute.

The load is applied to the wire-rope specimens by displacing a movable sheave which is attached to a hydraulic cylinder (lower left in Figure 1). Tension is controlled by adjusting the setting on a hydraulic pressure relief valve; a pressure gage is used to monitor the load. The tension system is calibrated using a strain gage load cell which itself has a calibration traceable to the National Bureau of Standards.

A chain-drive and slipper-block arrangement (shown in Figure 2) performs the specimen stroking action. The stroke is adjusted by changing the length of the drive chain and the spacing of the drive sprockets.

Machine Configurations

Machine layouts for both single-sheave and reverse-bend experiments are shown in Figures 3, 4, and 5. Two wire-rope specimens are cycled on the machine simultaneously during each run. After failure of one specimen a dummy rope is used to allow continued cycling of the other specimen. Both ends of each specimen are restrained from rotating so that changes in the torque characteristics of one sample do not cause twisting of the other sample. For the reverse-bend configuration, Figures 4 and 5, only the smaller sheaves

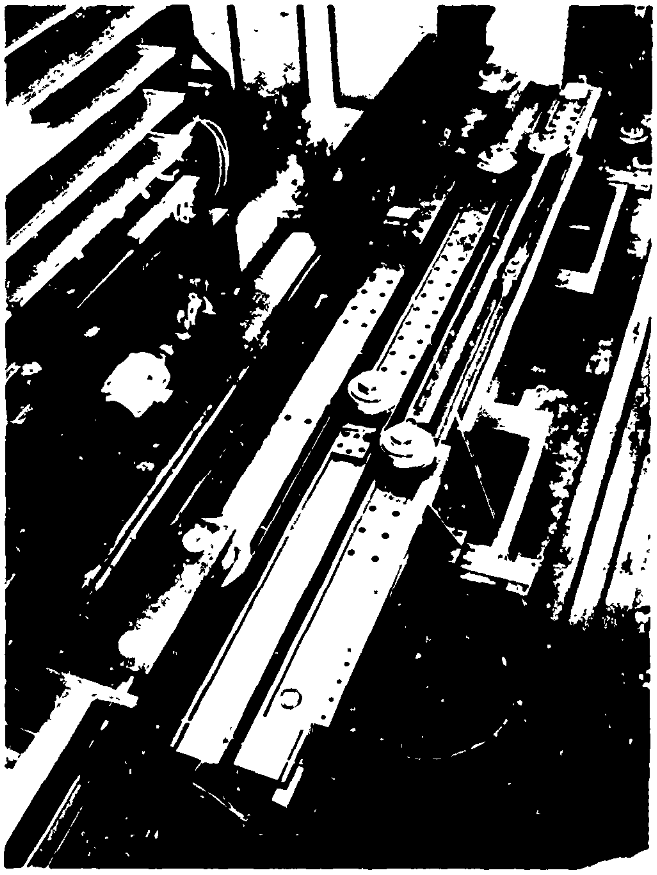


Figure 1. Wire Rope Fatigue Machine

(Overarms which support upper ends of sheave axles removed for clarity.)

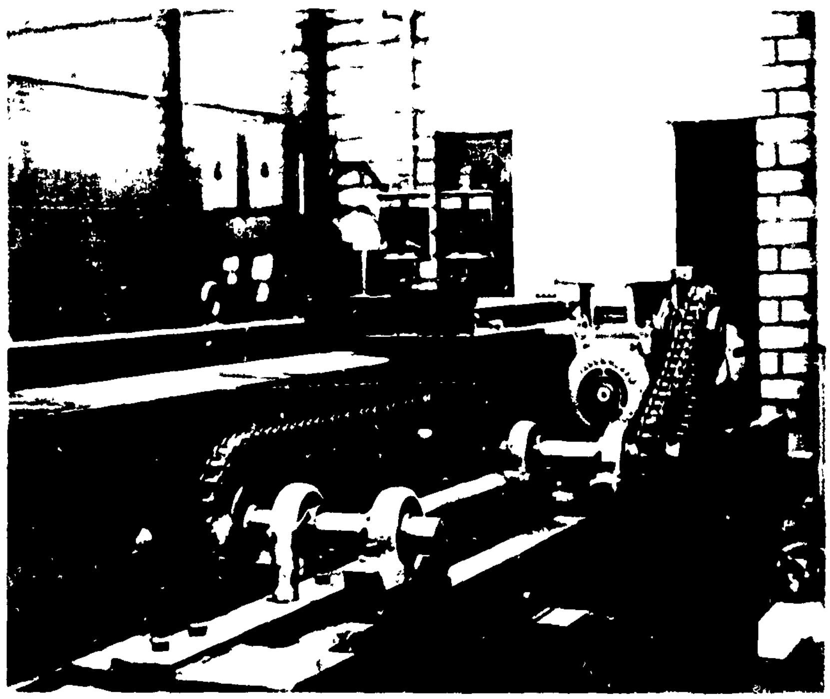
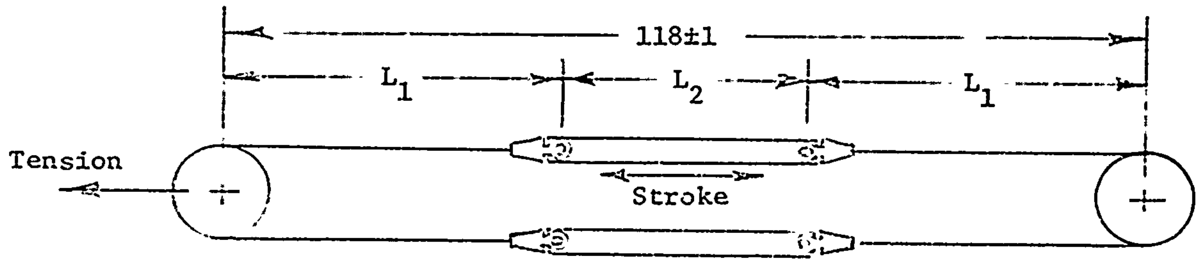


Figure 2. Fatigue Machine Drive System

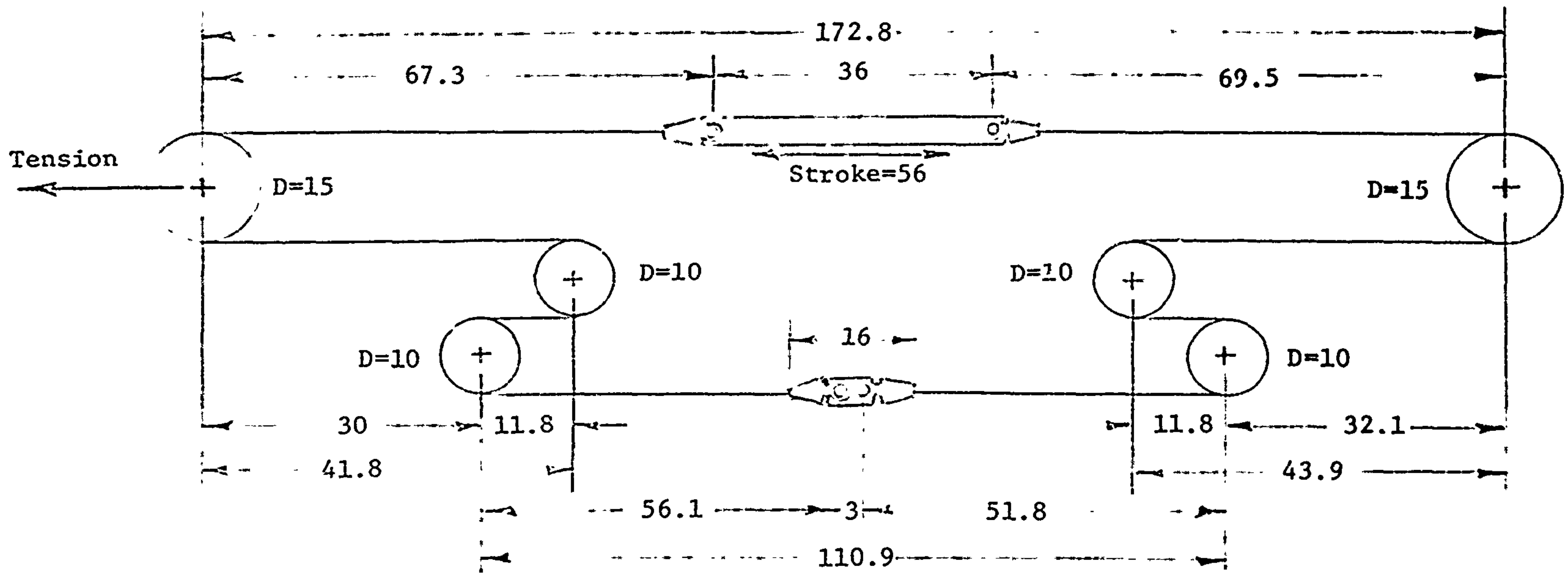


d, Rope Diameter, in.	D/d	D, Sheave Pitch Diameter, in.	L_2, in.	Specimen Length, in.*	Stroke, in.
1/2	10	5	65	61	20
1/2	20	10	57	76	28
1/2	30	15	49	92	36
3/4	10	7.5	36	94	31
3/4	20	15	24	117	43
3/4	30	22.5	13	141	54

*Eye-to-eye length

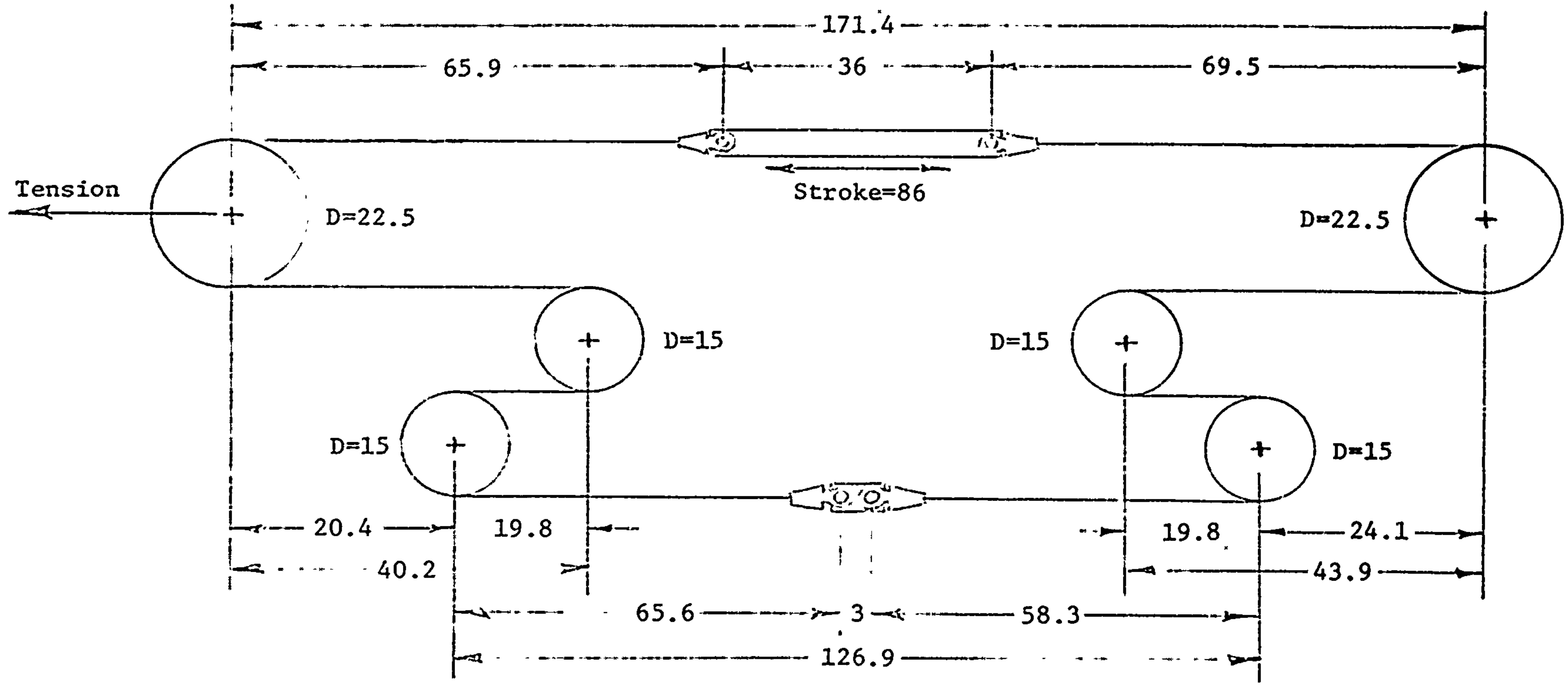
Note: All dimensions at zero tension.

FIGURE 3. MACHINE LAYOUTS FOR PHASE I EXPERIMENTS



All dimensions at zero tension
Rope diameter = 1/2 inch
Rope cut length = 226 inches
Specimen length, eye-to-eye = 232 inches

FIGURE 4. MACHINE LAYOUT FOR PHASE II EXPERIMENTS WITH 1/2-INCH WIRE ROPE



All dimensions at zero tension
Rope diameter = 3/4 inch
Rope cut length = 268 inches
Specimen length, eye-to-eye = 274 inches

FIGURE 5. MACHINE LAYOUT FOR PHASE II EXPERIMENTS WITH 3/4-INCH WIRE ROPE

are involved in the actual experiment; the larger sheaves are used only to bring the ends of the specimens into the drive position.

Stroke and Test-Section Lengths

Note that different portions of the rope specimens receive different numbers of bend cycles for each machine cycle. (One bend cycle is defined as the passing of a portion of the specimen onto and off of the sheave; straight-bent-straight.) The part of each specimen receiving the greatest number of bends is designated the "test section" of that specimen. For these experiments, the test-section length was chosen to be approximately four times the lay length of the rope, or approximately 12 inches for 1/2-inch rope and 18 inches for 3/4-inch rope. For the reverse-bend experiments the spacing of the two test sheaves was also chosen to be approximately four rope lays.

For all single-sheave experiments, then, the required cycling stroke length was one-half the sheave circumference, measured at the pitch line, plus four rope lays. In the single-sheave configuration each machine cycle produced two rope bend cycles. For the reverse-bend experiments, the required cycling stroke was equal to one sheave circumference plus eight rope lays. In this latter case, four rope bend cycles resulted from each machine cycle.

For the reverse-bend experiments, the large "turn around" sheaves were spaced well away from the test sheaves so that no secondary test section would be produced by the passage of a length of rope completely around both the large sheave and the nearest test sheave. For all experiments, the rope specimen length was chosen so that the sockets were never closer to the sheaves than approximately four rope lay lengths.

Rope Speed

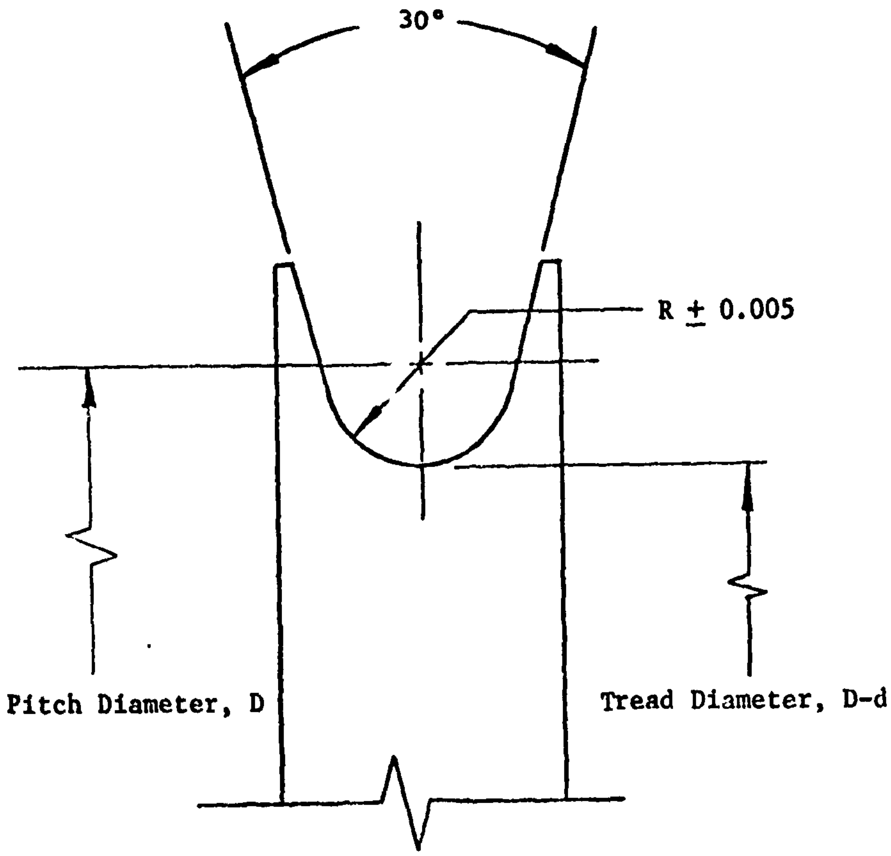
Preliminary fatigue tests were performed to determine how far temperatures would rise at a rope speed of 150 feet per minute. Results showed that under extreme conditions (low D/d ratios, high loads), there was indeed a rapid temperature rise. However, the number of cycles to failure was so low (around 200) that it is doubtful the temperature rose high enough to have an influence other than causing some loss of lubricant. At less extreme conditions, the temperature rose less rapidly and stabilized well below the level where rope life might have been affected. A rope speed of 150 feet per minute was therefore used, in accordance with the contract specification.

Sheave Design and Material

The sheaves used in this program were made of mild carbon steel; the grooves were carburized to a minimum case depth of 0.040 inches and heat treated to a hardness of R_c 58 to 64. A diagram of the sheave groove profile is shown in Figure 6.

It should be noted that sheave groove shape and hardness are factors which influence wire-rope life. References 1 through 5 recommend groove shapes. It is generally recognized that grooves which are too small have a pinching effect on the rope which increases the contact stresses between the rope and the groove surface and between adjacent wires within the rope. On the other hand, grooves which are too large do not properly support the rope. Future work should include an investigation of the effects of improperly grooved sheaves since there are instances where mismatches can occur in Navy systems.

d = Nominal rope diameter



d, Rope Diameter, inch	R, Groove Radius, inch
1/2	0.265
3/4	0.390

Material: Mild steel carburized to minimum case depth of 0.040 in. heat treated to Rockwell C 58-64.

FIGURE 6. SHEAVE GROOVE CONFIGURATION AND MATERIAL

There are some apparent contradictions in published literature concerning the desirability of hard versus soft sheave grooves. Although Drucker and Tachau(6)* reported that use of softer sheaves would lengthen rope life, their conclusion was probably based on the historical methods using wood, leather, or other fibrous materials as a groove lining. When soft metal sheaves are used, wearing or permanent deformation of the sheave throat may lead to improper support of the rope by the sheave, and may produce rapid rope wear. S. C. Gambrell(7) reported that for high loads and relatively small sheave diameters, tool-steel (Rockwell C60) sheaves provide better rope fatigue life than do sheaves manufactured from aluminum bronze, aluminum alloy, cast iron, or ductile steel. Case hardened sheaves were chosen for this investigation to minimize sheave wear or roughening which might have influenced the experimental results. In fact, at the conclusion of all experiments the sheave grooves were very smooth and polished and showed no signs of deterioration.

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*Numbers in parenthesis refer to similarly numbered items in the "References" section.

WIRE-ROPE SPECIMENS

Wire-Rope Construction

Wire ropes for this program were manufactured in conformance with Federal Specification RR-W-410[8]. Three types of wire-rope construction were investigated:

Construction 1: Type I, Class 3 -- 6 x 37 Warrington Seale, preformed, right-regular lay, IWRC rope with each strand consisting of 36 wires of which 14 were outer-layer wires. This rope was manufactured from uncoated improved plow steel.

Construction 2: Type III, Class 3 -- 6 x 24 Warrington, preformed, right-regular lay rope with each strand consisting of 24 wires of which 16 were outer-layer wires. This rope was manufactured from galvanized improved plow steel and had a natural fiber core.

Construction 3: Type I, Class 2 -- 6 x 19 Warrington Seale, preformed, right-regular lay, IWRC rope with each strand consisting of 26 wires of which 10 were inner-layer and 10 were outer-layer wires. This rope was manufactured from uncoated improved plow steel.

All ropes studied in the program were manufactured from the same heat of steel, and all rope specimens of the same construction and diameter came from a single reel.

Notable is the fact that wire ropes of Constructions 1 and 3 are generally used for applications requiring bending over sheaves, such as hoisting; while Construction 2 is used more commonly for mooring and other applications requiring increased elasticity. This fact is reflected in the experiment results: the performance of Construction 2 was inferior to that of the other two.

The actual measured breaking strengths of the rope specimens are shown in Table 1 together with the rated minimum breaking strengths as indicated in Federal Specification RR-W-410. Typical tensile strength and torsion data for the individual rope wires are included in Appendix A.

Rope Diameter

Two rope diameters, 1/2-inch and 3/4-inch, were subjected to bending-fatigue experiments during this program. The results of earlier experiments[9] suggested that small-diameter rope performs better than larger-diameter rope under moderate conditions, i.e. low loads and large sheaves; while the opposite is true under severe conditions, i.e. high loads and small sheaves. The reason for this anomaly was not clear, although it was recognized that the physical properties of rope wires are a function of wire diameter. (Typically, smaller wires may be manufactured with higher tensile strengths while retaining adequate ductility to be fabricated into satisfactory wire rope - or, to say it another way, for large and small wires of a given strength, the smaller wires are likely to display the better ductility.) To further investigate the influence of rope diameter on wire-rope behavior, two rope diameters were compared in this study.

Type of End Fitting

Open spelter sockets were used to secure the ends of all wire-rope specimens. A description of the socketing procedure is found in Appendix B. Care was taken to align the sockets properly

TABLE 1. WIRE ROPE BREAKING STRENGTHS

Rope Diameter, Inch	Rope Construction[a]	Breaking Strength, Pounds RR-W-410[b]	Breaking Strength, Pounds Test Specimen[c]	Actual Strength Margin, Percent[d]
1/2	1	22,000	27,450	24.8
1/2	2	16,800	19,400	15.5
1/2	3	23,000	25,600	11.3
3/4	1	48,600	60,500	24.5
3/4	2	37,200	45,930	23.5
3/4	3	51,200	58,950	15.1

(a) Refer to Text, "Wire-Rope Construction".
(b) Minimum Rated Breaking Strength.
(c) Actual Measured Breaking Strength
(d) $\frac{\text{Actual Strength} - \text{Rated Strength}}{\text{Rated Strength}}$ (100%)

during their installation on the rope and during installation of the specimens on the fatigue machine, for any twisting or unlaying of the rope might have adversely affected the fatigue results.

PROCEDURE

Wire ropes were cycled to failure on the wire-rope bend-fatigue machine under various experimental conditions. Two ropes were cycled during each machine run; and when the first rope failed a dummy specimen, cut from the same spool of rope as the test specimen, was installed and the second rope was cycled to failure. Wire-rope elongation was monitored by means of a dial indicator attached to the sheave tensioning apparatus. The resultant measurements were of average wire-rope elongation for each of the pair of specimens. The machine was stopped periodically in order to count broken wires.

The machine automatically stopped cycling in response to sudden elongation of a wire-rope specimen, corresponding to the failure of at least one complete strand.

The following aspects of wire-rope behavior were investigated:

(a) The effect of wire-rope design and construction on rope life.

(b) The effect of rope diameter on rope life.

(c) The effect of tensile load on rope life.

(d) The effect of sheave-to-rope diameter ratio on rope life.

(e) The interaction effects among the above conditions and rope life.

(f) The effects of the above conditions on secondary phenomena such as rope elongation and wire breakage.

The investigation took place in two phases. Phase I examined the effects of the above parameters in single-bend fatigue tests. Phase II examined the effects in reverse-bend fatigue tests.

To lend credence to the results of the experiments, the investigation was organized to allow statistical analysis of the data.

Statistical Basis of Experimental Configuration

As previously stated, this program investigated the effects of four major parameters on rope life: wire-rope design, rope diameter, tensile load, and sheave-to-rope-diameter ratio. Consider what the rope user might want to know regarding these parameters. Perhaps he is interested in the effect of a specific parameter on rope life; for instance, whether rope design A will provide longer life than design B. But chances are that the user's problem is more complex than that. For example, suppose the user has discovered that for a tensile load of X percent of the rated breaking strength, design A performs better than design B. Can he extend this relationship to a load of Y percent? What happens to the relationship if the user changes to smaller-sized sheaves?

Statistical analysis can aid in answering these kinds of questions. Statistical confirmation of trends in experimental results provides a level of quantification of conclusions beyond the capabilities of the "eyeball" method. It is a standardized and universally accepted decision-making procedure, firmly based in the theories of mathematics and probability. Statistical analysis may aid the experimenter in determining whether he has gathered enough data to draw the conclusions he does. Statistical methods may also help unearth certain trends or relationships not obvious to the researcher at first glance. Statistics is certainly not "magic", but it is a recognized procedure for scientific elucidation and verification.

A statistical method called "factorial experimentation" was used in the design of experiments and the analysis of results in this program. The factorial method is a subset of the group of statistical methods called "analysis of variance". The term "factorial" applies to both the statistical tests used to analyze the results and to the experimental design. Suppose there are n parameters to be varied in a series of experiments. Parameter A_1 is to be examined at a_1 different points (e.g. the parameter "tensile strength" examined at 20, 40, and 60 percent rated breaking strength), parameter A_2 and a_2 different points, and so on. Then there are $a_1 \times a_2 \times .. \times a_n$ possible combinations of all the experimental conditions. The set of all these combinations is called a "factorial block", from the fact that each set of "factors" is represented once in the block. A factorial block is usually portrayed as a large box, divided into ever smaller boxes corresponding to the variations in each parameter. To complete a factorial block, each set of conditions is tested once, resulting in $a_1 \times a_2 \times \ldots \times a_n$ experiments. For example, if three parameters are under study, and each parameter is tested at three levels, the resultant factorial block would appear as shown in Figure 7. Notice that there are 3 x 3 x 3 = 27 different results, each corresponding to a different set of conditions. Each set of conditions corresponds to a "cell" in the block.

To find out how much of the variation in results is due to data scatter, the whole set of experiments is often repeated. Each set of results conforming to a factorial block is called a "replicate".

In this program, there were two factorial block configurations: one for single-sheave and one for reverse-bend experiments. Two replicates were made based on each block. Since the fatigue machine ran two ropes at a time, there are two results corresponding to each cell of each replicate. Figures 8 and 9 show these factorial blocks.

Parameter A_1	a_{11}									a_{12}									a_{13}								
Parameter A_2	a_{21}			a_{22}			a_{23}			a_{21}			a_{22}			a_{23}			a_{21}			a_{22}			a_{23}		
Parameter A_3	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}	a_{31}	a_{32}	a_{33}
Results	y_{111}	y_{112}	y_{113}	y_{121}	y_{122}	y_{123}	y_{131}	y_{132}	y_{133}	y_{211}	y_{212}	y_{213}	y_{221}	y_{222}	y_{223}	y_{231}	y_{232}	y_{233}	y_{311}	y_{312}	y_{313}	y_{321}	y_{322}	y_{323}	y_{331}	y_{332}	y_{333}

FIGURE 7. A 3^3 FACTORIAL BLOCK

FACTOR	LEVEL																	
Rope Diameter (inches)	1/2									3/4								
Rope Construction	1			2			3			1			2			3		
Load (% R.B.S.)	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60
D/d Ratio	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Side of Machine (Left vs. Right)	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Results	y_1	y_7	y_{13}	y_{19}	y_{25}	y_{31}	y_{37}	y_{43}	y_{49}	y_{55}	y_{61}	y_{67}	y_{73}	y_{79}	y_{85}	y_{91}	y_{97}	y_{103}
	y_2	y_8	y_{14}	y_{20}	y_{26}	y_{32}	y_{38}	y_{44}	y_{50}	y_{56}	y_{62}	y_{68}	y_{74}	y_{80}	y_{86}	y_{92}	y_{98}	y_{104}
	y_3	y_9	y_{15}	y_{21}	y_{27}	y_{33}	y_{39}	y_{45}	y_{51}	y_{57}	y_{63}	y_{69}	y_{75}	y_{81}	y_{87}	y_{93}	y_{99}	y_{105}
	y_4	y_{10}	y_{16}	y_{22}	y_{28}	y_{34}	y_{40}	y_{46}	y_{52}	y_{58}	y_{64}	y_{70}	y_{76}	y_{82}	y_{88}	y_{94}	y_{100}	y_{106}
	y_5	y_{11}	y_{17}	y_{23}	y_{29}	y_{35}	y_{41}	y_{47}	y_{53}	y_{59}	y_{65}	y_{71}	y_{77}	y_{83}	y_{89}	y_{95}	y_{101}	y_{107}
	y_6	y_{12}	y_{18}	y_{24}	y_{30}	y_{36}	y_{42}	y_{48}	y_{54}	y_{60}	y_{66}	y_{72}	y_{78}	y_{84}	y_{90}	y_{96}	y_{102}	y_{108}

FIGURE 8. FACTORIAL BLOCK FOR PHASE I EXPERIMENTS

FACTOR	LEVEL																	
Rope Diameter (inches)	1/2									3/4								
Rope Construction	1			2			3			1			2			3		
Load (% R.B.S.)	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60
Side of Machine (Left vs. Right)	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Results	y_1	y_3	y_5	y_7	y_9	y_{11}	y_{13}	y_{15}	y_{17}	y_{19}	y_{21}	y_{23}	y_{25}	y_{27}	y_{29}	y_{31}	y_{33}	y_{35}
	y_2	y_4	y_6	y_8	y_{10}	y_{12}	y_{14}	y_{16}	y_{18}	y_{20}	y_{22}	y_{24}	y_{26}	y_{28}	y_{30}	y_{32}	y_{34}	y_{36}

NOTE: All experiments conducted at D/d=20.

FIGURE 9. FACTORIAL BLOCK FOR PHASE II EXPERIMENTS

In the case of reverse-bending, the side of the machine on which the rope was cycled affected its life, and so side-of-machine was made a separate parameter for analysis. Statistical analysis of the effect of side-of-machine on rope life in the single-sheave experiments showed no significant effect; therefore in the latter case the two values for each cell were considered repeats of the same experiment. So for reverse-bend experiments there were two replicates, while for single-sheave experiments there were in effect four replicates (two repeats and two replicates).

The presence of inconstant, hard-to-predict factors such as climate, sheave wear, etc. may bias the results of wire-rope fatigue experiments if their effects are strong enough. Although it is generally assumed that the effects of such conditions are weak, the validity of the results can be furthered by a damping-out process known as "randomization". In this process, a testing order is assigned to the experiments from a random number table or generator. Since the extraneous conditions affect each cell in a random way, the effects can be treated as random error.

The order of the experiments in this program was randomized as shown in Appendix C. Specifically, all planned experiments were listed by rope diameter, construction, load, and sheave-to-rope diameter ratio. Then, a random number table was used to determine a new order -- the "Test Number" shown in the appendix.

Since rope manufacturing conditions might have varied with time, the order of cutting the specimens from the reels was also randomized. First the two specimens to be used for each experiment were assigned numbers corresponding to the testing order (e.g., Test 1 used Specimens 1 and 2, Test 2 used Specimens 3 and 4, and so forth). Included at the end of the list of specimens for each replicate were two additional specimens for each rope size and construction. These extra samples were spares to be used in case some problem caused an experiment to be invalidated, and, thus, repeated. A random number table was again used to determine a new order, the "cutting order", for all specimens including spares. The result was a list of randomized specimen numbers which included all rope sizes and constructions.

To simplify the cutting procedure, all specimens to be taken from a single reel were cut as a group. The resulting order of specimen cuts is indicated in Appendix C ("Cutting Order"). For example, the first test samples for Phase I, Replicate 1 cut from Reel 1 was Specimen 48, followed by Specimen 7, and so forth. After all twenty samples (18 test specimens and 2 spares) were cut from Reel 1, cutting proceeded on Reels 2 through 6. This procedure was repeated for each replicate. In all tables of Appendix C, those sequential numbers missing from the "cutting order" were either unused spares or samples which were discarded during the course of the program because of a machine malfunction. (There was a total of six discarded specimens.)

Since dummy ropes of the appropriate constructions and lengths were required to complete all experiments, they were cut from the reels at convenient intervals, but were not included in the randomization process. The first set of dummies required for the Phase I, Replicate 1 experiments was cut prior to cutting the test specimens. This procedure insured that any anomalies in rope geometry at the extreme ends of the reels would be removed and would not influence the experiment results. The three dummies cut from the beginning of each reel required approximately 18 feet of 1/2-inch diameter rope and approximately 28 feet of 3/4-inch diameter rope.

The dummy ropes required for the Phase I, Replicate 2 experiments were cut after cutting the corresponding test specimens.

Similarly, the dummies for Phase II, Replicates 1 and 2 were cut after cutting the test specimens for each replicate.

It should be noted that the randomization of the experiment is not complete. First, it was necessary to cycle the left and right specimens on the machine at the same time. A visual scan of the data reveals a closer correlation between the number of cycles to failure of the first-failing and second-failing ropes of each replicate than between the results of the two replicates. It is not known whether this result is due to similar conditions at the time of the fatigue test or to some effect of the failure of one rope on the remaining fatigue life of the other rope. Second, although each replicate of each factorial block was randomized, an entire replicate was always completed before the next replicate was begun. Third, Phase I of the program was completed before Phase II began.

The importance of considering the macroscopic order of the program is illustrated in the fact that Phase I, Replicate 1 ran from February 1973 to August 1973 (winter, spring, summer) and Replicate 2 ran from September 1973, to January 1974 (summer, fall, and winter). Although all experiments were conducted indoors and the marine enviroment at the Long Beach Research Facility minimizes seasonal variation, it is difficult to predict what the seasonal effect might have been. Daily, weekly, or seasonal variations in temperature, humidity, smog content, etc. of the air may have affected rope life. However, an effort was made to "damp out" the effects of enviromental factors by randomizing the order in which the fatigue tests were performed under each set of conditions.

Rope Tension

When rope bending fatigue life is plotted as a function of rope tension, the result is a curve with a well defined knee or change in slope. This nonlinearity is due to the relative importance of the various kinds of stresses and failure modes which occur at various loads. The knees in the curves result from transitions between failure modes. For very low loads (and small sheaves), bending stresses are the most important cause of rope deterioration. At high loads, the major deterioration factor is contact stress between the wires within the construction; at moderate loads it is the contact stress between the wires and the sheave throat. The interactions of these modes over the range of loads also vary with the sheave diameter.

In this investigation, wire ropes were evaluated at three different loads: 20, 40 and 60 percent of the ropes' rated breaking strength (RBS). The knees in the rope-life curves fall somewhere within these values for the sheave sizes evaluated. To determine the exact shape of the curve, experiments including more intermediate load values would be required.

Sheave-to-Rope Diameter Ratio

The ratio of sheave diameter to rope diameter also exerts a significant effect on wire rope life and mode(s) of failure; since sheave size determines the relative magnitudes of the tensile, bending, and comprehensive contact stresses developed within the rope. References (1) through (4) recommend an "average" sheave-to-rope diameter (D/d) ratio of 27 and a "minimum" of 18 for 6 x 37 classification wire rope under "general" operating conditions. However, due to space or weight limitations, wire-rope systems often use sheaves of much smaller size.

To investigate the influence of sheave size on rope life, three D/d ratios were investigated during the Phase I experiments: D/d = 10, 20 and 30. Since a more restricted program was desired for the Phase II reverse-bend experiments, a single D/d ratio of 20 was used. A ratio of 20 is a typical sheave size used in many Navy systems.

Definition of Specimen Failure

It is often difficult for a wire rope user to determine when a rope has deteriorated to the extent that replacement becomes necessary. A wire rope operating at moderate loads with recommended sheave sizes will experience considerable crown wire breakage long before it becomes sufficiently worn or fatigued to necessitate replacement. However, rope operating under severe conditions (high loads and small sheaves) may show little or no visible wear before actual tensile failure occurs, and the same is true for ropes operating at very low loads over very small sheaves.

This difference in rope behavior is due to the kinds of failure modes which dominate under each condition. In general, three major factors combine to produce fatigue degradation in wire ropes: tensile stress, bending stress, and contact stress. Under very severe conditions (high loads and small sheaves), failure usually occurs at locations of cross-wire notching. Strand-to-strand and strand-to-core contact forces produce severe wire deformation, and when the deformation reaches a certain critical point, multiaxial stresses produce wire breaks. When the effective metallic area of the rope is reduced sufficiently by means of individual wire breakage, the entire rope fails. Little or no crown wire breakage may be visible.

Under low-load, small-sheave-diameter conditions, the major factor is bending stress. The outer wires in each strand experience the greatest bending stress, and that stress is greatest where the wires pass close to the rope core. In the kind of wire failure which results, a fatigue crack appears at the point of maximum bending stress, and propagates across the wire cross-section with each pass of the rope around the sheave. Thus, a great number of the outer wires in the rope strands may break or crack, significantly reducing the metallic area of the rope. Since the outer wires break first near the core, total wire rope failure may occur with no visible indication of wire deterioration.

Under moderate conditions (low to moderate loads and recommended sheave sizes), most of the wire breakage is caused by wire contact with the sheave throat. Thus, in this case, many wire breaks may be visible before metallic area reduction causes rope failure.

For purposes of this investigation, specimen failure was defined to be the parting of at least one complete rope strand. Thus the problem of defining rope failure was somewhat simplified in choosing for the definition an event which nearly always signalled the imminent tensile failure of the entire rope. Obviously this criterion should not be used in the field, nor should the fatigue-life data presented in this report be used as an ultimate quantitative authority on how long to use a wire rope. Rather, the relationships and trends which the data suggest should be used to estimate or predict the behavior of wire rope in the field, taking into account the particulars of the situation at hand.

Although total strand failure was used as the rope failure criterion, records were also maintained regarding the accumulation of broken wires. Thus, one of the results of this program is an indication of whether a count of broken wires is a practical rope retirement criterion for various operating conditions.

ANALYSIS OF EXPERIMENT RESULTS

The results of all bend-over-sheave fatigue experiments are presented in Appendix D. It should be emphasized that all data are in terms of rope bending cycles, not machine cycles. A rope bending cycle is defined as a straight-bend-straight flexure of the rope test section. During the Phase I, single-sheave bending experiments, each machine cycle produced two rope bending cycles; during the Phase II, two-sheave reverse bending experiments, each machine cycle produced four rope bending cycles.

The Bearing Pressure Ratio

One method used to present the results of this study involves plotting the data as a function of a dimensionless variable called the "bearing pressure ratio". This parameter, put forth in 1945 by Drucker and Tachau[6], is the result of an attempt to simplify the relationship between wire-rope fatigue life and the parameters which affect it. The variable is written in the following form:

$$B = \frac{2T}{UDd} ,$$

where B = bearing pressure ratio
T = load on rope, units of force
U = ultimate strength of the wire material, force per unit area
d = rope diameter, length
D = sheave pitch diameter, length.

The original curves presented by Drucker and Tachau are repeated in Figure 10 for convenience. Research since 1945 has so far borne out the assertion that B is a convenient simplification of the relationship among the factors affecting wire-rope fatigue life.

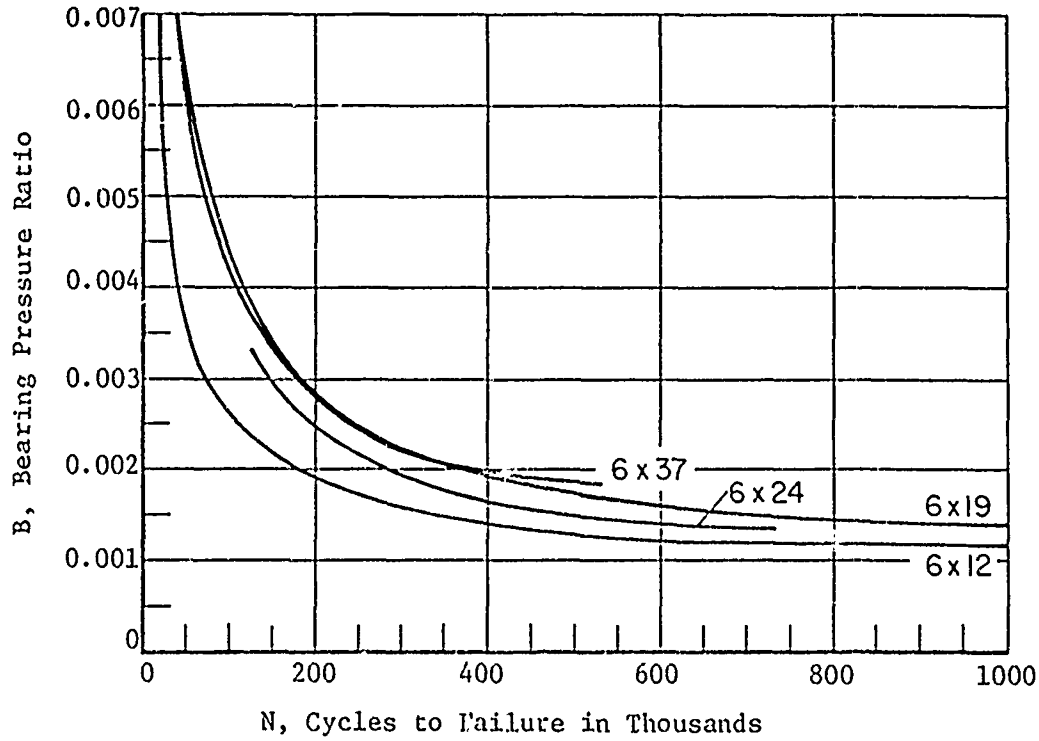

FIGURE 10. ORIGINAL DRUCKER AND TACHAU CURVES OF AVERAGE BEARING PRESSURE RATIO VERSUS FATIGUE LIFE

The bearing pressure ratio also may be written in terms of the parameters evaluated in this program. The load, L_{tbs}, when expressed as a percent of the rope true breaking strength, is proportional to the tension on the rope, T, divided by the ultimate breaking strength of the rope. The ultimate breaking strength may be expressed as

$$Ud^2K_1,$$

where K_1 is a constant accounting both for the fact that not all of the cross-sectional area of the rope is actually wire material, and for the fact that there is some strength loss in stranding the wires to form a rope. Thus, L_{tbs} is directly proportional to T/Ud^2, and

$$B = \frac{2T}{UDd} = \frac{2T}{Ud^2 D/d} = K \frac{L_{tbs}}{D/d}$$

where L_{tbs} = load, percent of true breaking strength

K = a constant.

Thus, in terms of the bearing pressure ratio (which is inversely related to rope life), the life of a wire rope passing over a sheave is directly proportional to rope strength and sheave-to-rope diameter ratio, and inversely proportional to load.

It should be emphasized that when the bearing pressure ratio is used for the graphical interpretation of fatigue data, all results are in effect presented in terms of actual rope breaking strength. Thus, differences in material properties among a number of rope samples are accounted for. Experience has shown that actual rope breaking strength is usually at least as great as the rated breaking strength (to insure meeting a minimum standard), but can be as much as 40 percent higher.

Since the wire-rope user usually does not have knowledge of actual rope breaking strength or wire material strength, the design of rope systems and the selection of design factors (factors of safety) must be based on catalog values of rated rope breaking strength. Indeed, it was this factor which led to the selection of test loads for this program (20, 40, and 60 percent of <u>rated</u> breaking strength, RBS).

Some of the graphical presentations of fatigue data which follow are in terms of RBS, while others are in terms of bearing pressure ratio (or actual rope breaking strength). Generally, the two methods of data presentation indicate the same trends; however, some minor adjustments in curve positions are to be expected depending on which method is used. Table 2 expresses the test loads both as a percent of rated breaking strength and as a percent of actual breaking strength.

The values of bearing pressure ratio, B, used for the data analysis are given in Table 3. These values were computed using the values of average wire ultimate tensile strength also shown in this table. The method used to determine the average wire strength for each rope construction was to compute the aggregate wire breaking load, in pounds, based on the data given in Appendix A and then to divide this value by the aggregate wire metallic area. All wires in each rope construction, including the IWRC when applicable, were considered in this calculation.

The results of the fatigue experiments are presented graphically in Figures 11, 12, and 13 in terms of the bearing pressure ratio. The method of data presentation used in these figures, B versus log N, corresponds to the conventional method of displaying fatigue data for various engineering materials and machine components. In the portions of this report dealing with the statistical analysis of the data, other methods of data presentation are also used as appropriate to the discussion.

Figures 11 and 12 reveal the superiority of Constructions 1 and 3 over Construction 2 for the specified test conditions. Figure 13 shows that for $D/d = 20$, reverse-bend cycling produced a wire-rope fatigue life approximately 60 percent of that obtained without the reverse bend. This result is consistent with data obtained during previous studies[9].

TABLE 2. TEST LOADS

Rope Diameter, inch	Rope Construction	Test Load, pounds	Percent Rated Breaking Strength	Percent Actual Breaking Strength
1/2	1	4,400	20	16.0
		8,800	40	32.1
		13,200	60	48.1
	2	3,360	20	17.3
		6,720	40	34.6
		10,080	60	52.0
	3	4,600	20	18.0
		9,200	40	35.9
		13,800	60	53.9
3/4	1	9,720	20	16.1
		19,440	40	32.1
		29,160	60	48.2
	2	7,440	20	16.2
		14,880	40	32.4
		22,320	60	48.6
	3	10,240	20	17.4
		20,480	40	34.7
		30,720	60	52.1

TABLE 3. VALUES OF BEARING PRESSURE RATIO

d, in.[a]	C[b]	Wire UTS, psi[c]	D/d	B		
				T = 20% RBS	T = 40% RBS	T = 60% RBS
1/2	1	275,000	10	.0128	.0256	.0384
			20	.0064	.0128	.0192
			30	.0043	.0085	.0128
	2	259,100	10	.0104	.0207	.0311
			20	.0052	.0104	.0156
			30	.0035	.0069	.0104
	3	275,200	10	.0134	.0268	.0401
			20	.0067	.0134	.0200
			30	.0045	.0089	.0134
3/4	1	270,700	10	.0128	.0256	.0384
			20	.0064	.0128	.0192
			30	.0043	.0085	.0128
	2	253,300	10	.0104	.0208	.0313
			20	.0052	.0104	.0157
			30	.0035	.0070	.0104
	3	269,900	10	.0134	.0268	.0403
			20	.0067	.0134	.0201
			30	.0045	.0090	.0134

(a) Rope diameter
(b) Rope construction
(c) Average wire ultimate tensile strength

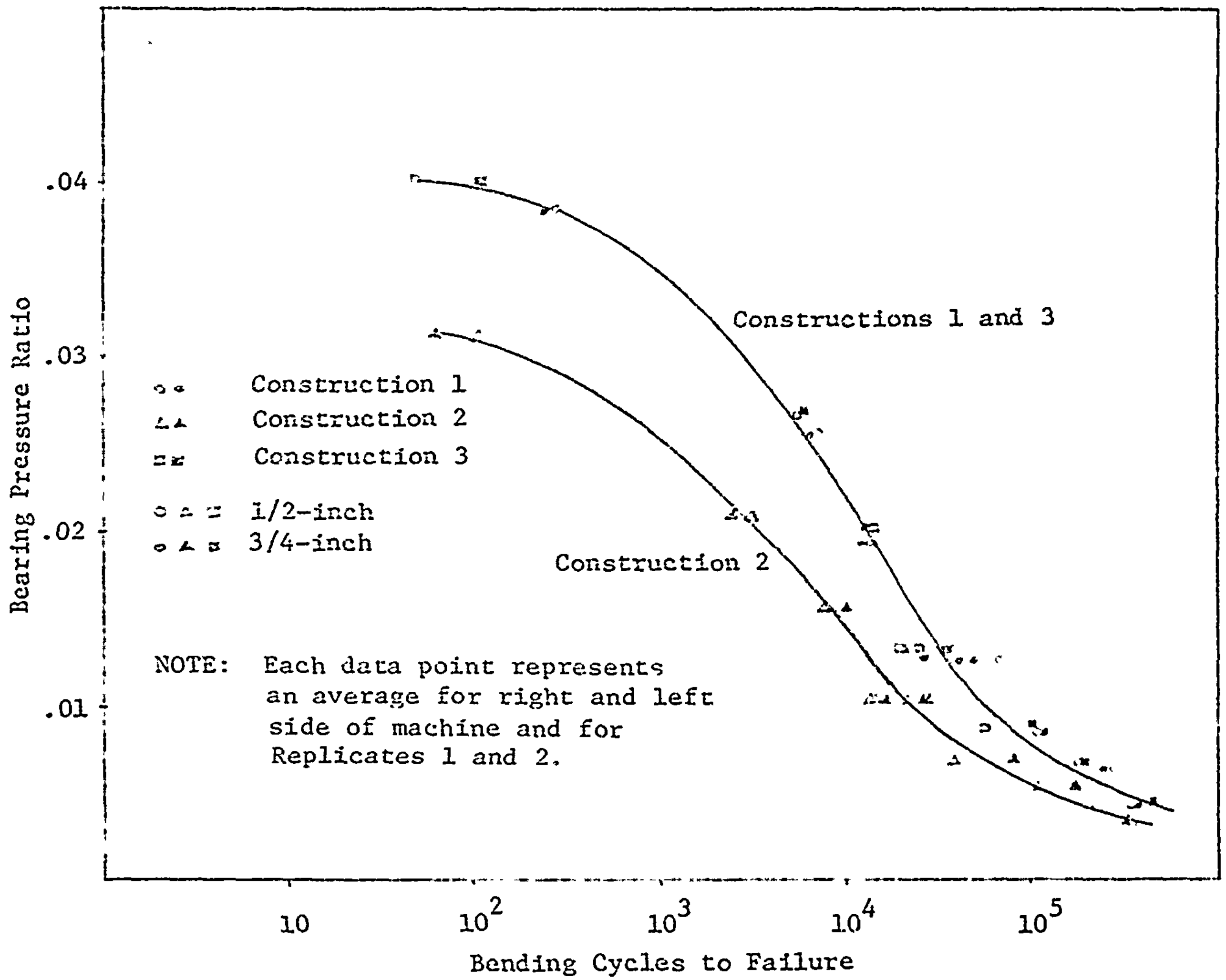

FIGURE 11. PHASE I RESULTS, EXPRESSED AS A FUNCTION OF THE BEARING PRESSURE RATIO

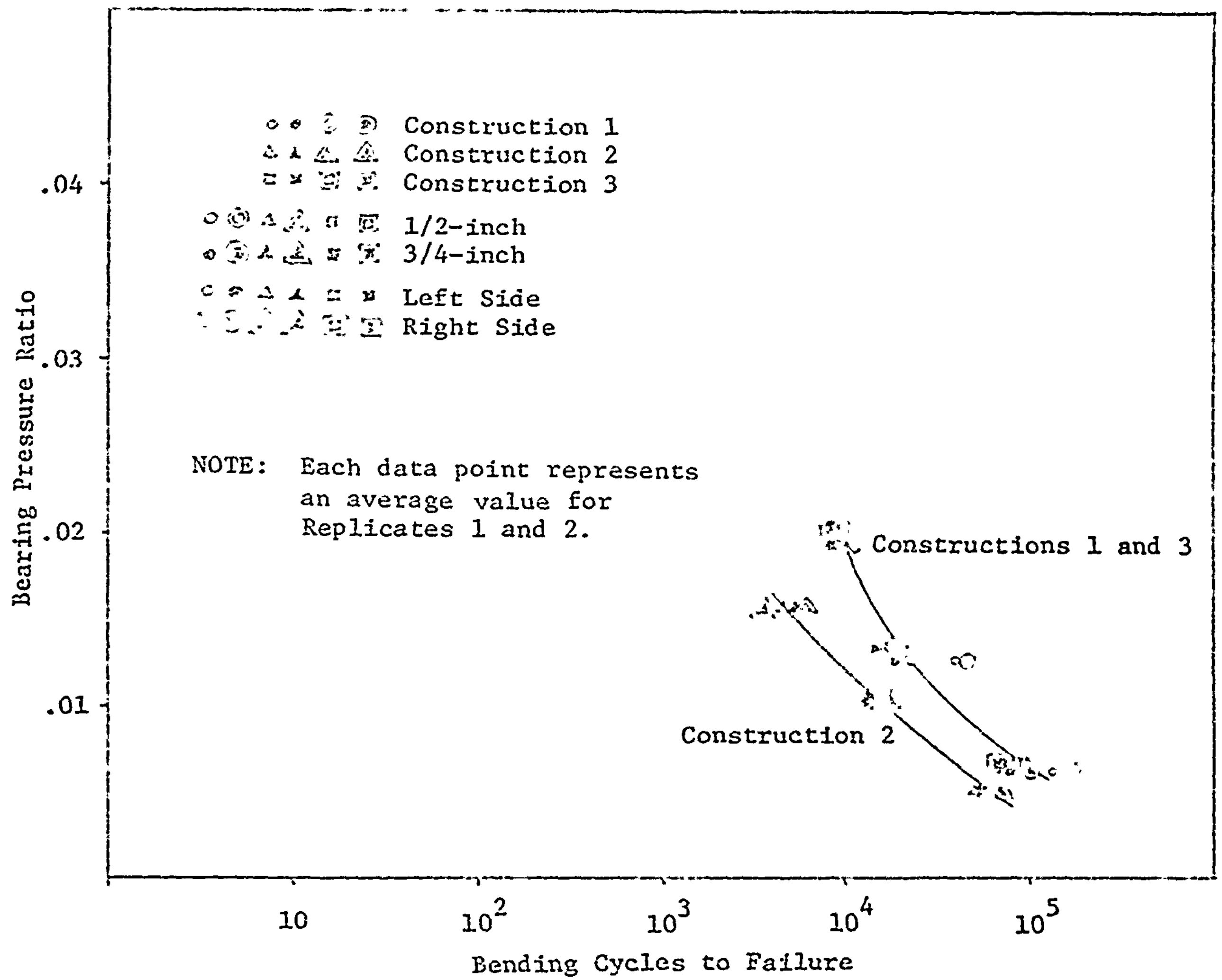

FIGURE 12. PHASE II RESULTS, EXPRESSED AS A FUNCTION OF THE BEARING PRESSURE RATIO

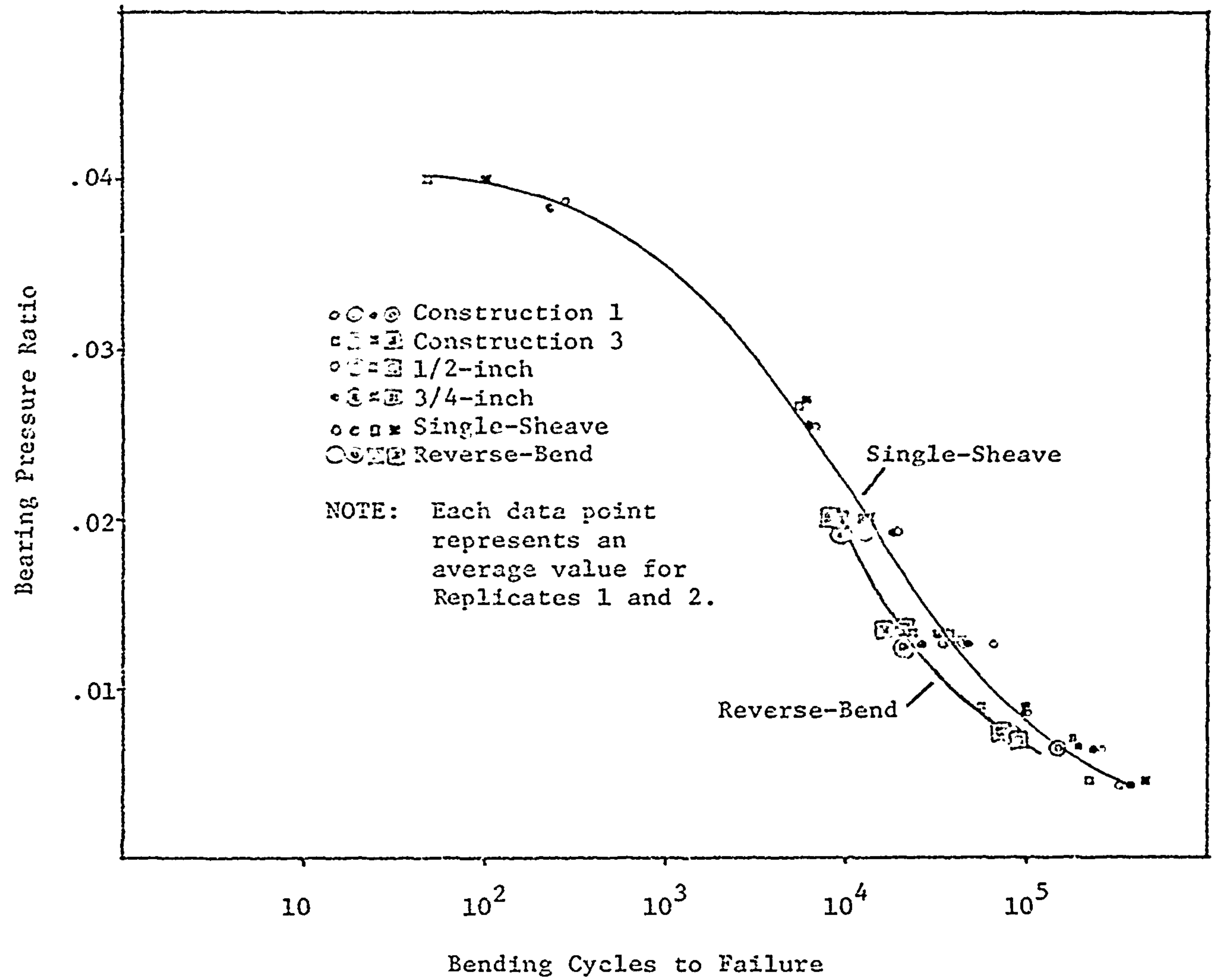

FIGURE 13. COMPARISON OF PHASE I AND PHASE II RESULTS FOR D/d = 20 AND ROPE CONSTRUCTIONS 1 AND 3

In Figure 14, the Phase I, single-sheave fatigue data for Constructions 1 and 3 are plotted in terms of rope tension versus cycles to failure for various D/d ratios. This figure reveals more clearly how changes in load and sheave size influence rope life. Note that for D/d= 10, at the highest tension loads the fatigue curve departs from the trend established by the other D/d ratios. This unusually short rope life produced by the most severe test condition is a result of a change in the mode of rope failure.

It is also important to note that in Figure 14 rope tension is expressed as a percent of <u>actual</u> rope breaking strength, not <u>rated</u> rope breaking strength (RBS). The result is a reduction in the apparent differences between lives of rope Constructions 1 and 3. For example, consider the data points corresponding to the highest rope tension loads for all D/d ratios. These points are quite close to the assumed straight line curves. If this figure had been drawn with rope tension expressed in terms of <u>rated</u> rope breaking strength, all high-load data points would have appeared on the same horizontal line (at 60 percent RBS) and the fit would have been much poorer.

The significance of this observation is that in Figure 14 (as in Figures 11 through 13) no large difference is obvious between Constructions 1 and 3. However, if the data are compared on the basis of percent RBS, Construction 1 appears to be superior to Construction 3. Thus, when analyzing the comparative performance of various wire ropes or wire-rope systems, it is important that the actual rope breaking strengths be taken into consideration. Large differences between actual and rated strengths can lead to different interpretations of the data, depending on which basis is used for the comparison.

In the following report sections which present the results of the statistical analysis of the fatigue data, all graphs and bar charts are

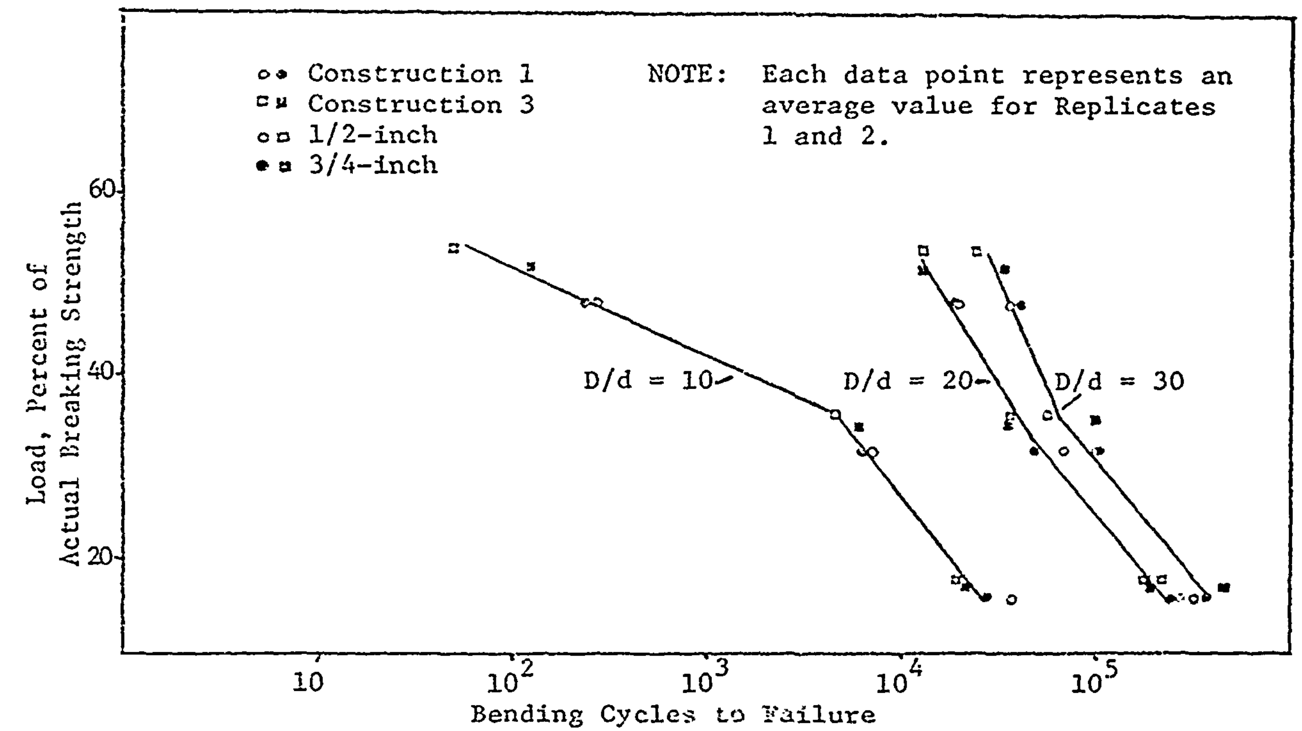

FIGURE 14. PHASE I RESULTS EXPRESSED IN TERMS OF ROPE TENSION AND D/d RATIO

predicated on the test results derived from experiments conducted with rope tensions based on rated rope breaking strength.

Presentation of ANOVA Tables

Analysis of variance was performed on the data to study the influence of the experiment variables on wire-rope fatigue life. As previously stated, each factorial block was replicated to yield two machine cycling experiments per cell; and for each experiment both a left-sheave specimen and a right-sheave specimen were cycled to failure.

A visual scan of the fatigue data suggested that in the case of reverse bending, the side of the machine on which a specimen was cycled affected rope life. (Possible reasons for this result are discussed later in the report.) Therefore, the analysis of variance was performed in more than one way to investigate the various possible roles which side-of-machine played in the outcomes of the experiments.

A statistical test called an "F-test" was performed on the data to distinguish those parameters, and those combinations of parameters in interaction with one another, which significantly affected the outcomes of the experiments. To perform an F-test on a set of experimental outcomes, a number called the "F-statistic" is computed from the data. A different F-statistic may be computed for each parameter or set of parameters to be evaluated. If an F-value is larger than its corresponding "critical value" found in a table of such numbers, the effect of the parameter or set of parameters corresponding to that F-statistic is determined to be "statistically significant". The term "significance", applied to a parameter, A_1 , means that the value of the result, Y, changes with the value of A_1 by an amount too large to be ascribed to chance factors alone. "Statistical significance in interaction" of two variables, A and A_2, means that the relationship of A_1 to the result, Y, changes with the value of A_2, and vice versa. (There can be more than two parameters interacting.) Graphic interpretations of "statistical significance" are shown in Figure 15.

In the ANOVA tables which follow, F-values are included for each parameter and combination of parameters. F-values corresponding to statistically significant relationships are marked with an asterisk (*). Degrees of freedom for each parameter combination are also listed. The fact that the number of degrees of freedom is large reflects the sizeable number of experiments performed; and hence, the high accuracy of the results.

Anaylsis of Phase I Experiments

The Phase I single-sheave experiments involved parameters d, C, L, D/d, and S (rope diameter, rope construction, load, sheave-to-rope diameter ratio, and side-of-machine); these parameters had corresponding numbers of levels 2, 3, 3, 3, and 2, yielding 108 fatigue measurements for each of the two replicates. The ANOVA results of these experiments are presented in Tables 4, 5, and 6. The asterisks (*) beside the main effects and interaction symbols indicate statistical significance at the 99 percent level or better. The corresponding tables of cell means are presented in Appendix E.

The first ANOVA deals with Phase I data, with S treated as a design variable (Table 4). All main effects except S are significant. Some of the interactions are also significant, but, with one exception, none of the parameters involving S showed significant effects; for the d-D/d-S relationship the F-value was so low as to be borderline.

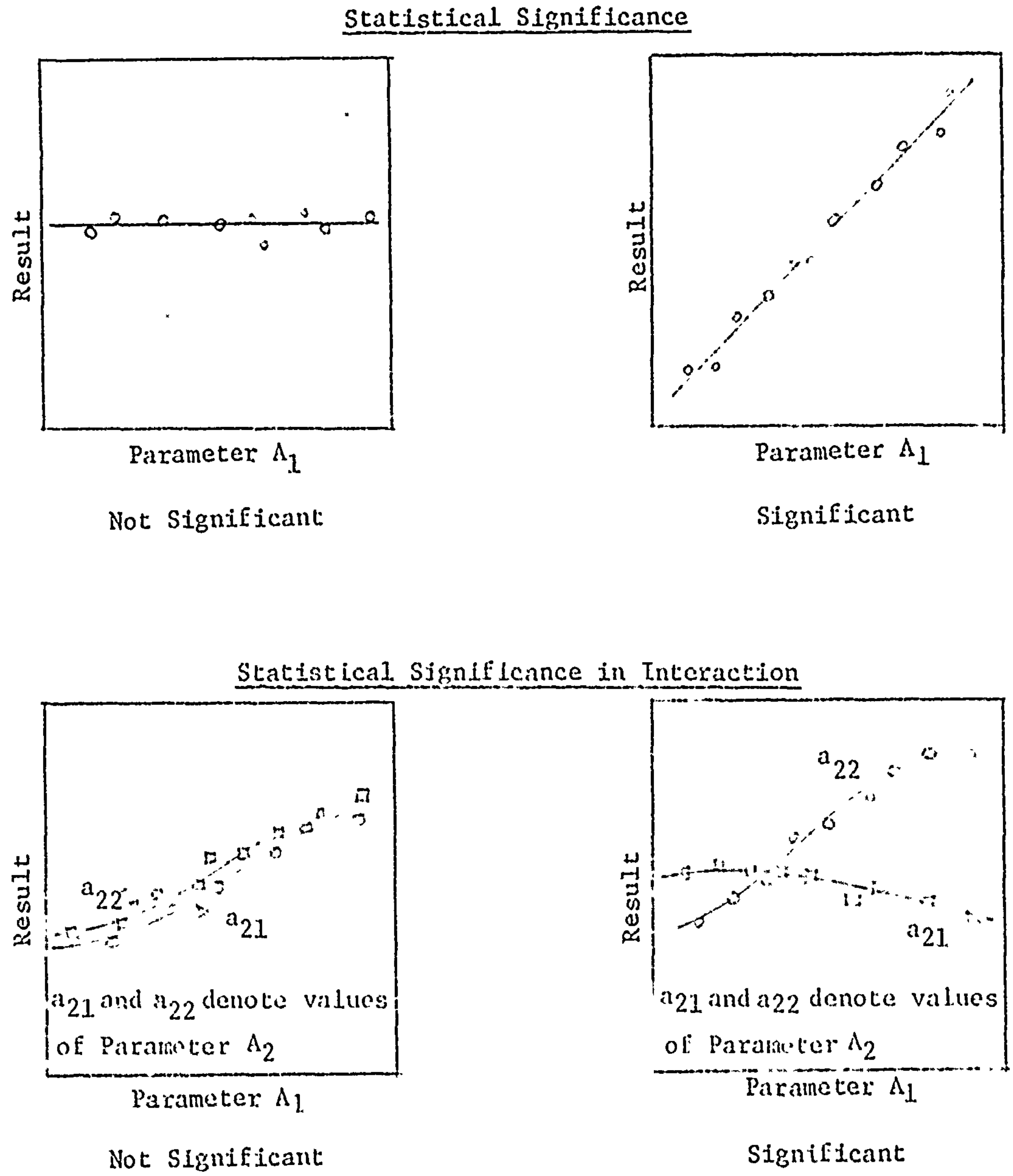

FIGURE 15. GRAPHIC INTERPRETATIONS OF STATISTICAL SIGNIFICANCE

TABLE 4. FIVE-WAY ANOVA FOR SINGLE-SHEAVE FATIGUE EXPERIMENTS

Parameter	Degrees of Freedom	F	Significance
d	1	67.04	*
C	2	531.13	*
L	2	12,339.38	*
D/d	2	15,620.97	*
S	1	0.06	
dC	2	36.46	*
dL	2	1.06	
CL	4	22.97	*
dD/d	2	43.07	*
CD/d	4	23.54	*
LD/d	4	1,048.82	*
dS	1	1.36	
CS	2	0.06	
LS	2	2.26	
D/dS	2	1.27	
dCL	4	1.27	
dCD/d	4	20.98	*
dLD/d	4	4.20	
CLD/d	8	13.28	*
dCS	2	0.06	
dLS	2	1.75	
CLS	4	0.00	
dD/dS	2	5.28	*†
CD/dS	4	0.27	
LD/dS	4	0.24	
dCLD/d	8	15.79	*
dCLS	4	1.27	
dCD/dS	4	0.57	
dLD/dS	4	0.33	
CLD/dS	8	0.36	
dCLD/dS	8	1.02	
R(dCLD/dS)	108	--	

† Of Borderline Significance

TABLE 5. FOUR-WAY ANOVA FOR SINGLE-SHEAVE FATIGUE EXPERIMENTS

Parameter	Degrees of Freedom	F	Significance
d	1	71.19	*
C	2	564.02	*
L	2	13,103.57	*
D/d	2	16,588.40	*
dC	2	38.72	*
dL	2	1.12	
CL	4	24.39	*
dD/d	2	45.74	*
CD/d	4	25.00	*
LD/d	4	1,113.77	*
dCL	4	1.35	
dCD/d	4	22.28	*
dLD/d	4	4.46	*
CLD/d	8	14.10	*
dCLD/d	8	16.76	*
R(dCLD/d)	162	--	

TABLE 6. COMPARISON OF FOUR-WAY ANOVA FOR FIRST-FAILING SPECIMENS WITH FOUR-WAY ANOVA FOR SECOND-FAILING SPECIMENS, FOR SINGLE-SHEAVE FATIGUE EXPERIMENTS

Parameter	Degrees of Freedom	First-Failing Group F	First-Failing Group Significance	Second-Failing Group F	Second-Failing Group Significance
d	1	57.26	*	30.48	*
C	2	379.42	*	296.06	*
L	2	8,510.22	*	7,128.38	*
D/d	2	10,944.10	*	8,882.48	*
dC	2	22.28	*	23.59	*
dL	2	1.09		0.43	
CL	4	16.02	*	14.23	*
dD/d	2	31.21	*	23.66	*
CD/d	4	14.15	*	15.66	*
LD/d	4	754.66	*	580.43	*
dCL	4	1.04		0.66	
dCD/d	4	12.19	*	14.34	*
dLD/d	4	2.88		2.75	
CLD/d	8	7.34	*	9.57	*
dCLD/d	8	10.77	*	9.43	*
R(dCLD/d)	54	--		--	

Although the factor S does not strictly constitute replication, its behavior in the full model suggested that S should be combined with the replication to produce a four-way factorial (design parameters d, C, L, and D/d) with four observations per cell. Table 5 presents the ANOVA for this model. The tests of significance for the effects common to this and the previous model yield virtually identical results.

To examine whether the occurrence of the first specimen failure in a pair of wire-rope specimens affects the remaining life of the unbroken specimen, a third experimental model was considered. This model consisted of two four-way factorials: one made up of the experiments involving all first-failing specimens and the other made up of the corresponding experiments for the second-failing specimens.

Table 6 compares the ANOVAs for these two models. These tables indicate that the first and second breaks yield practically identical ANOVA results.

Analysis of Phase II Experiments

In Phase II of the program, D/d was not a design variable since it was considered at only one value, 20. The first model considered for Phase II treats S as a design variable as in the case of the first model considered for Phase I. For Phase II results, however, S is a significant factor affecting wire-rope longevity, as shown in Table 7.

Table 8 contains the ANOVAs for the first-failing and the second-failing specimens. Again, these two ANOVAs are practically identical.

TABLE 7. FOUR-WAY ANOVA FOR REVERSE-BEND FATIGUE EXPERIMENTS

Parameter	Degrees of Freedom	F	Significance
d	1	26.61	*
C	2	149.66	*
L	2	1,430.39	*
S	1	19.19	*
dC	2	18.22	*
dL	2	1.43	
CL	4	5.48	*
dS	1	1.34	
CS	2	0.33	
LS	2	0.04	
dCL	4	1.96	
dCS	2	1.96	
dLS	2	2.73	
CLS	4	0.51	
dCLS	4	2.31	
R(dCLS)	36	--	

TABLE 8. COMPARISON OF THREE-WAY ANOVA FOR FIRST-FAILING SPECIMENS WITH THREE-WAY ANOVA FOR SECOND-FAILING SPECIMENS, FOR REVERSE-BEND FATIGUE EXPERIMENTS

Parameter	Degrees of Freedom	First-Failing Group		Second-Failing Group	
		F	Significance	F	Significance
d	1	35.76	*	18.54	*
C	2	225.80	*	96.25	*
L	2	2,437.88	*	814.78	*
dC	2	32.65	*	9.92	*
dL	2	2.11		0.99	
CL	4	3.74		6.84	*
dCL	4	3.11		1.28	
R(dCL)	18	--			

Interactions Among Phase I Experiment Variables

The two-way interaction effects of various combinations of experiment variables are displayed graphically in Figures 16 through 21. In each case, data for all experimental conditions have been lumped together except as specifically identified in the figures.

The interaction effect of rope diameter and rope construction are shown in Figure 16. This figure indicates that Construction 3 shows the greatest performance difference between 1/2-inch and 3/4-inch ropes and Construction 1 behaves most nearly the same for both diameters.

The interaction of rope diameter and rope tension load is shown in Figure 17. Note that the two curves are nearly parallel, indicating similar behavior of both rope diameters to changes in operating load, with the 3/4-inch rope giving slightly superior fatigue life.

Figure 18 illustrates the interaction effect of rope diameter and sheave-to-rope diameter ratio. The graph shows that a difference between 1/2-inch and 3/4-inch rope exists only at a D/d of 30. At the largest sheave size, 3/4-inch rope lasted significantly longer than 1/2-inch rope. At the other sheave sizes there is very little difference between 1/2-inch and 3/4-inch rope behavior.

The interaction between rope construction and tension load is shown in Figure 19. Construction 1 indicates superior performance followed by Constructions 3 and 2.

The interaction effect of rope construction and sheave-to-rope diameter ratio is plotted in Figure 20. The three curves corresponding to the three rope constructions are essentially parallel, suggesting similar behavior of all constructions under a changing D/d.

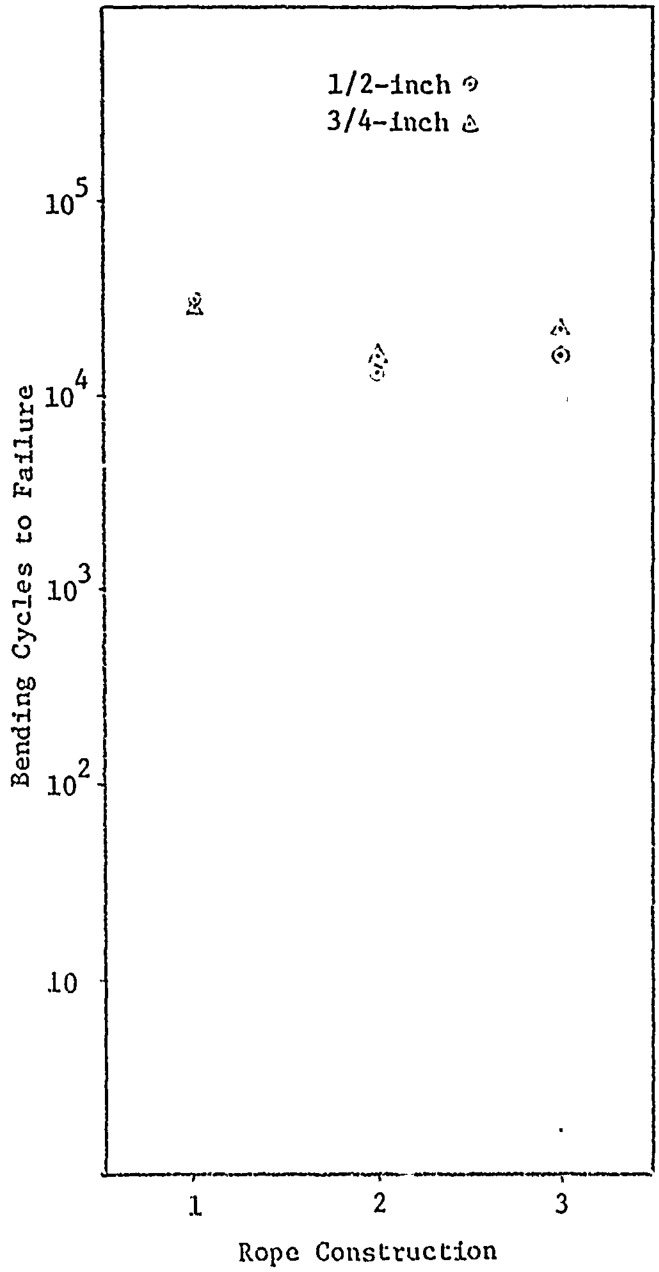

FIGURE 16. INTERACTION OF ROPE DIAMETER AND ROPE CONSTRUCTION

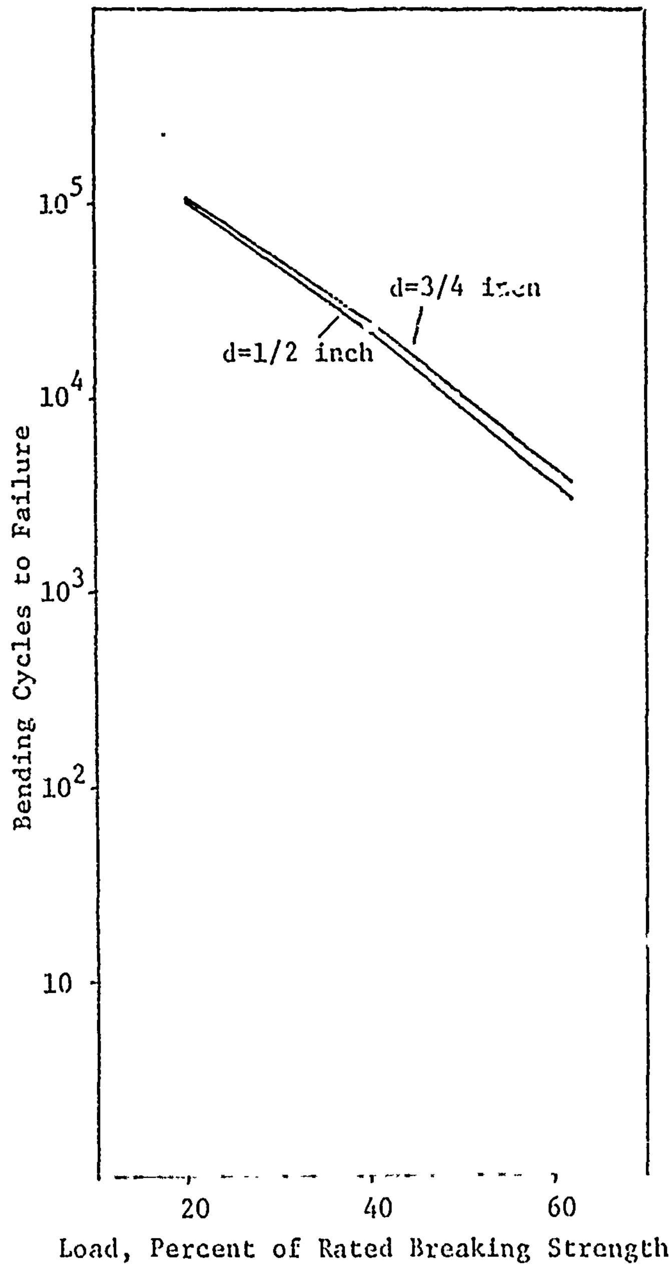

FIGURE 17. INTERACTION OF ROPE DIAMETER AND ROPE TENSION

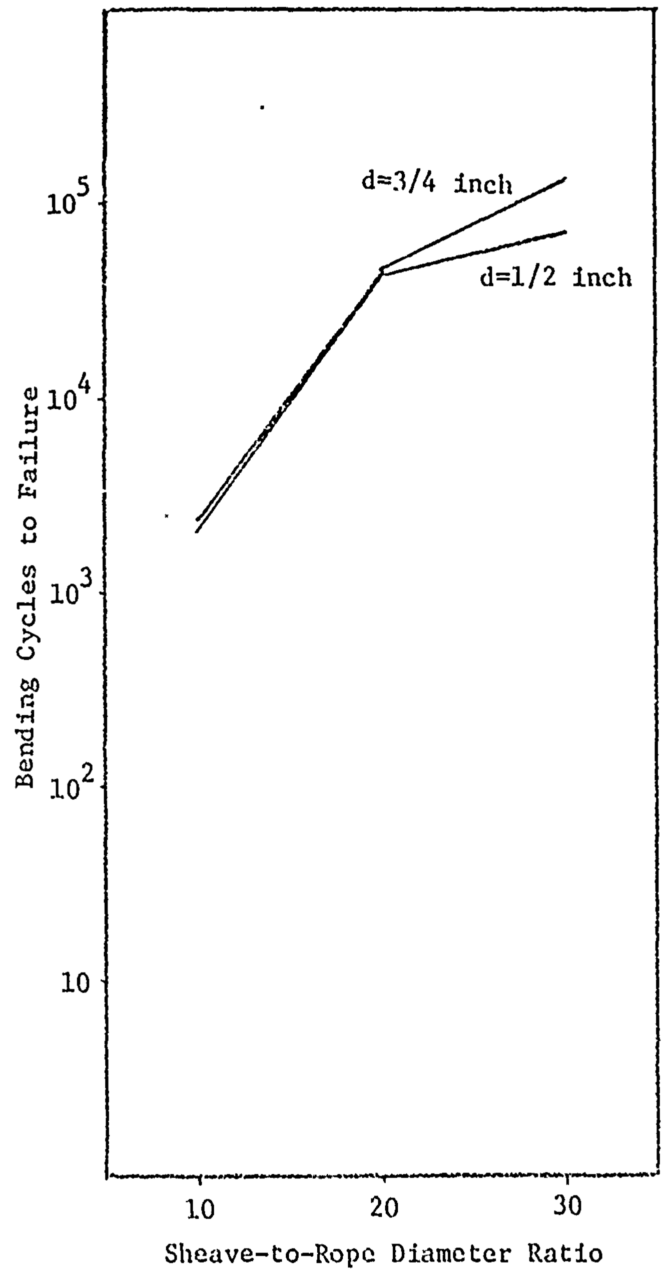

FIGURE 18. INTERACTION OF ROPE DIAMETER AND SHEAVE-TO-ROPE DIAMETER RATIO

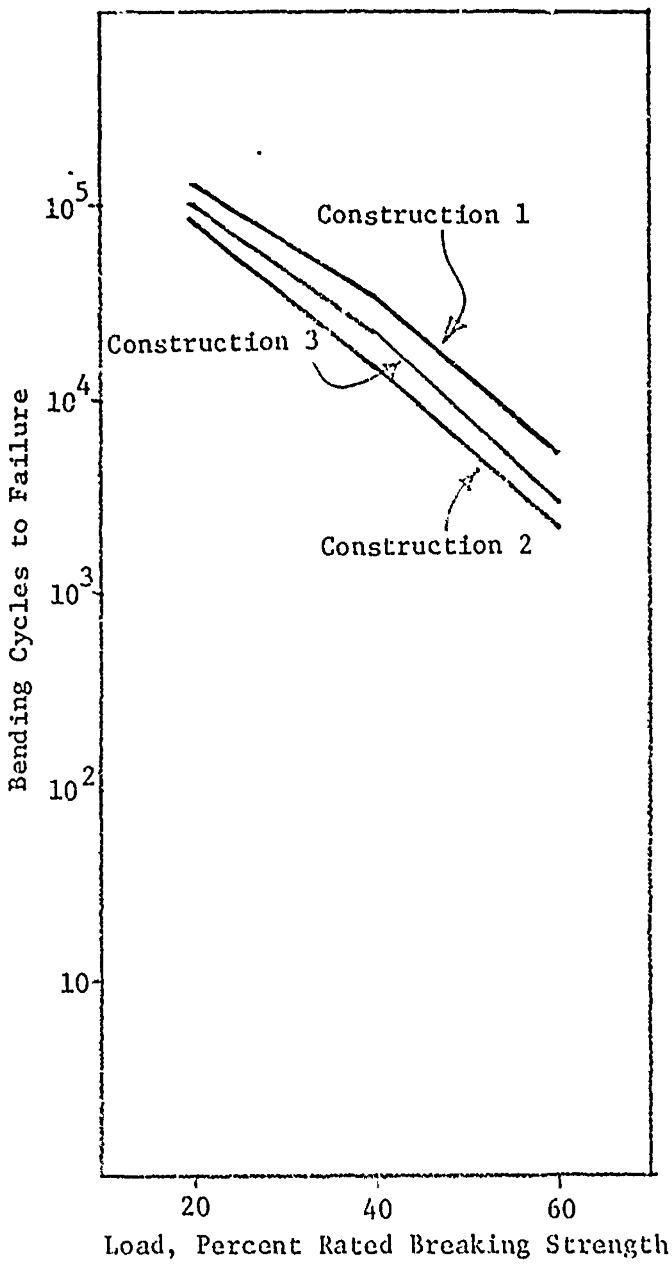

FIGURE 19. INTERACTION OF ROPE CONSTRUCTION AND LOAD

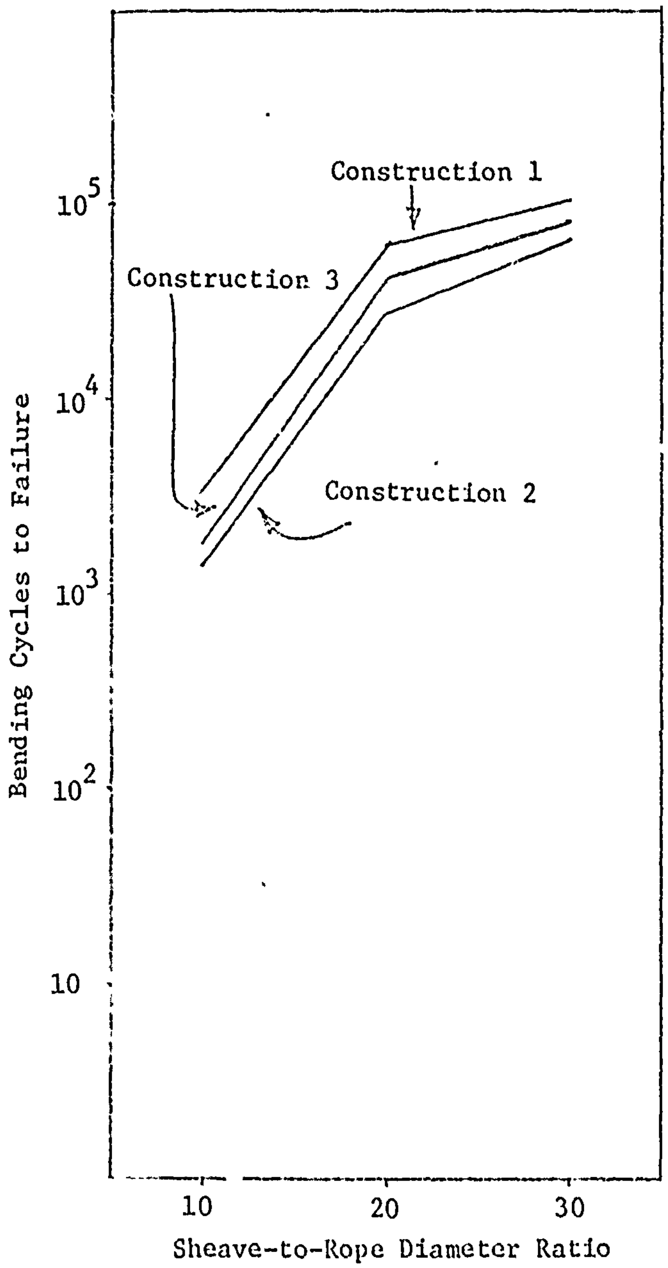

FIGURE 20. INTERACTION OF ROPE CONSTRUCTION AND SHEAVE-TO-ROPE DIAMETER RATIO

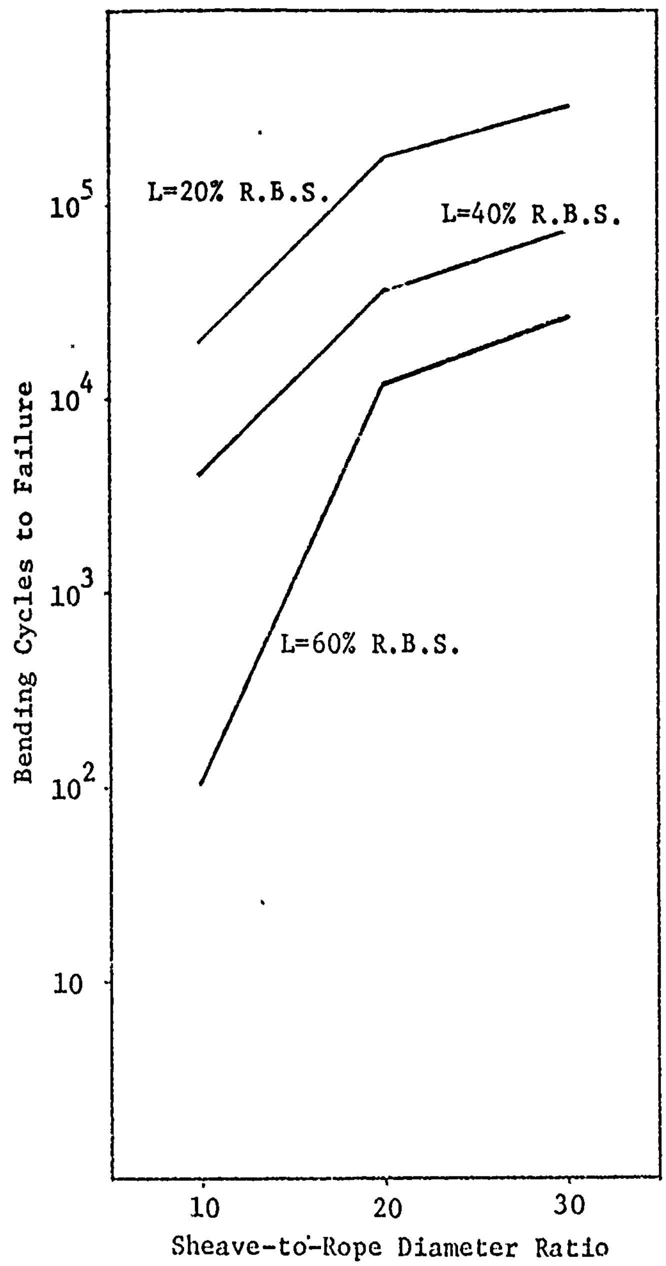

FIGURE 21. INTERACTION OF LOAD AND SHEAVE-TO-ROPE DIAMETER RATIO

Rope load and sheave-to-rope diameter ratio were the parameters displaying the strongest two-way interaction. Figure 21 shows D/d versus log N for the three values of L. If the D/d = 10, L = 60% R.B.S. data point is omitted, the remaining points describe parallel curves. This deviation of the most severe test condition (highest load and smallest sheave) from the trends established by the other test conditions is consistent with the results of numerous other wire-rope bending fatigue studies. It is known that a number of different failure modes cause wire-rope deterioration, and the dominant mode is determined by the service conditions. Typically, very severe operating conditions result in rope failure due to interstrand cross-wire notching. This mode of failure is accompanied by very short rope life.

Changes in failure modes with the severity of operating conditions were noted during the experiments and representative photographs are presented later. The statistically significant three-way interactions among experiment variables are shown in Figures 22 through 24.

Discussion of Phase II Results

With two exceptions, Phase II results were similar to Phase I results. The first exception is the relationship of wire-rope diameter to rope life, and the second is the significance of the side-of-machine factor in influencing wire-rope longevity.

If the parameters involving D/d (D/d being a design variable in Phase I but not in Phase II) and S are left out of the examination, the remaining parameters show the same relative significance in each Phase. Phase I had four times the sample size of Phase II and as a result the significant F-values are much higher than for Phase II, but proportionately the values are all comparable. The same parameters show significance in each Phase.

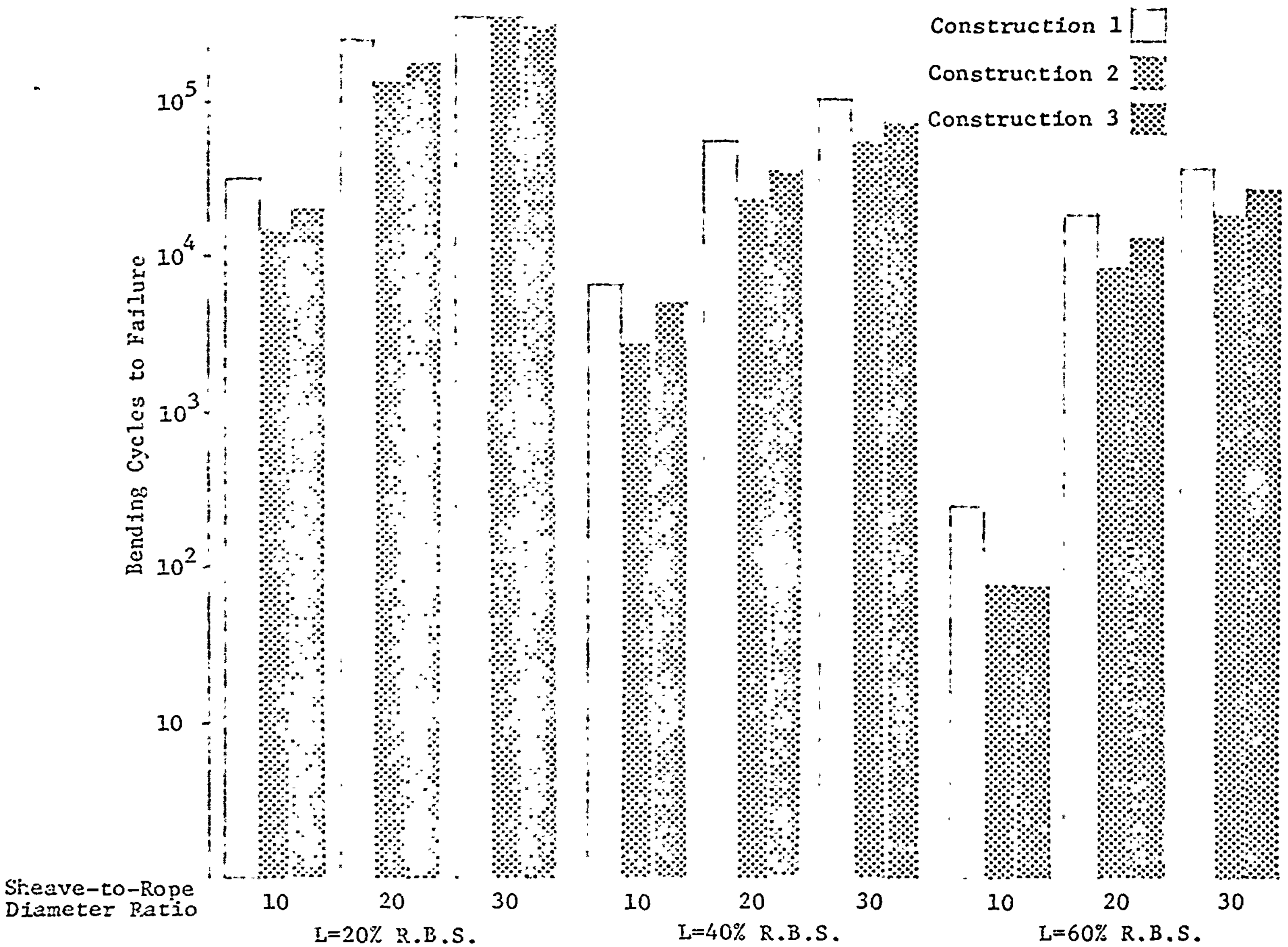

FIGURE 22. INTERACTION OF ROPE CONSTRUCTION, ROPE LOAD, AND SHEAVE-TO-ROPE DIAMETER RATIO

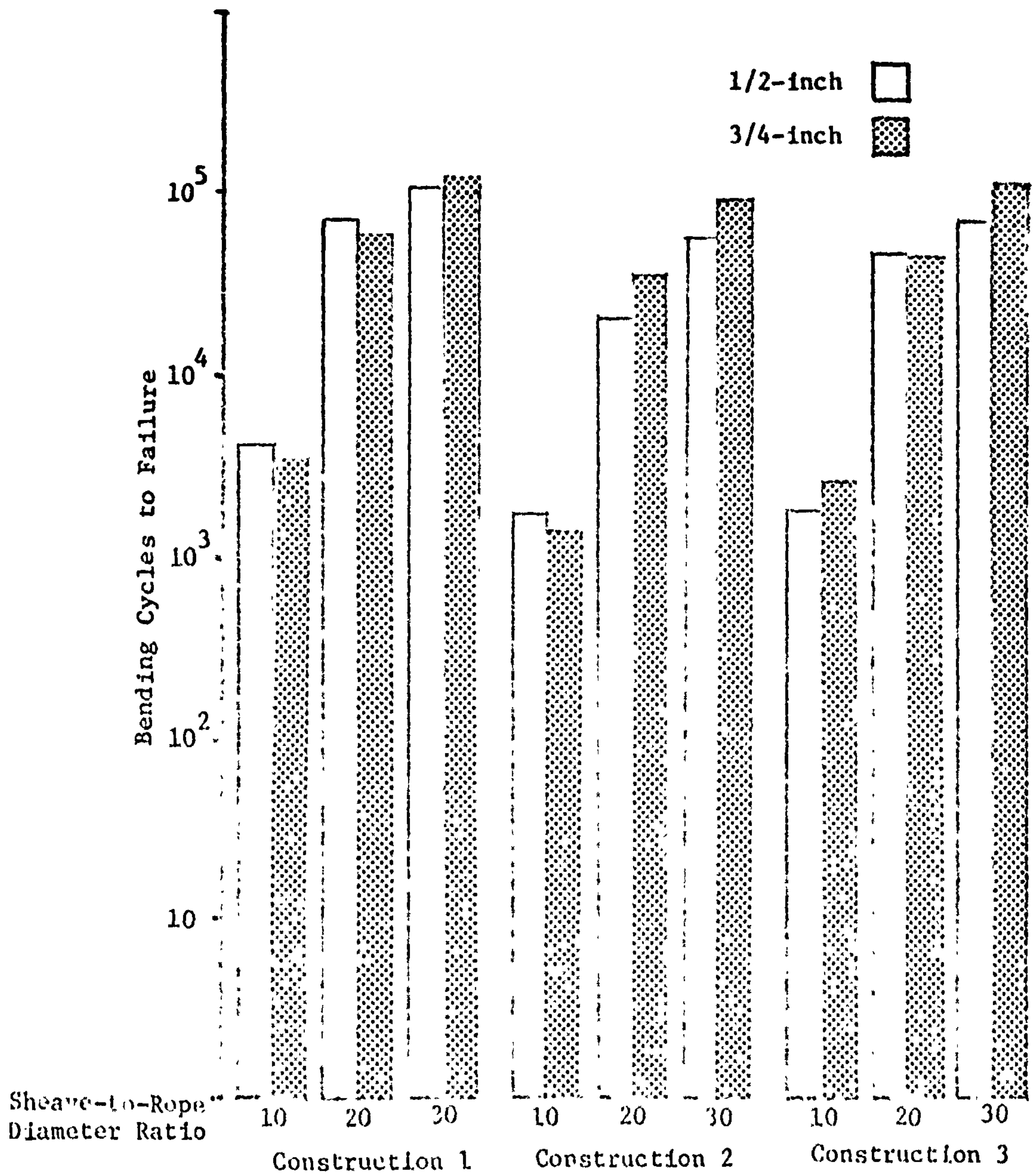

FIGURE 23. INTERACTION OF ROPE DIAMETER, ROPE CONSTRUCTION, AND SHEAVE-TO-ROPE DIAMETER RATIO

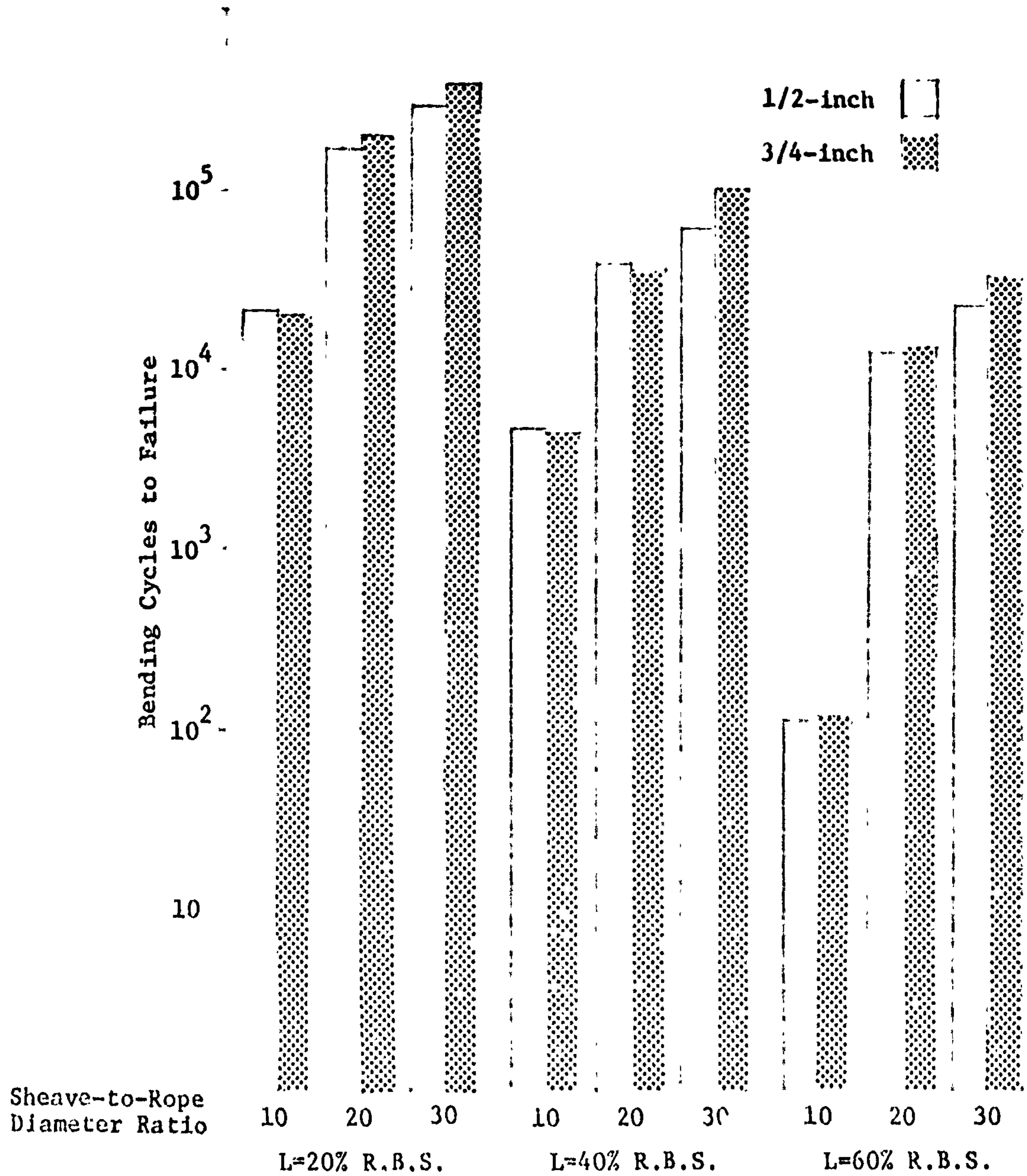

FIGURE 24. INTERACTION OF ROPE DIAMETER, ROPE LOAD, AND SHEAVE-TO-ROPE DIAMETER RATIO

Rope Diameter

In contrast to the behavior of wire rope in Phase I, in Phase II the 1/2-inch rope slightly outperformed the 3/4-inch rope. Phase I specimens tested at D/d = 20 showed the 3/4-inch rope to last slightly longer.

Side-of-Machine Factor

The other major behavioral difference between ropes cycled over single sheaves and those cycled through reverse bends is the effect of the factor S on rope life. The value for average fatigue life in reverse-bend cycling was approximately 20 percent higher for the right-sheave specimen than for the left-sheave specimen.

The most likely reason for this difference is that the tension in the left specimen stayed more nearly constant than that in the right specimen. This asymmetry was more pronounced in reverse-bending experiments than in single-sheave experiments for reasons discussed below. It is suspected that small fluctuations in rope load, such as occurred in the reverse-bend experiments, result in longer rope life.

The machine configuration for the Phase II reverse-bend fatigue experiments (Figures 4 and 5) had a total of six sheaves, whereas the configuration for the Phase I single-sheave bend experiments had only two sheaves (Figure 3). The presence of these additional sheaves required that the drive force be approximately three times higher for the reverse-bend experiments. Depending on the direction of rope travel, the drive force augmented or diminished the preset rope tension value, resulting in a total load which fluctuated from slightly above to slightly below the nominal value. Since the drive force was three times larger for reverse-bend experiments, the variation was also three times larger.

Although the exact drive force was not measured during these experiments, estimates of its value based on work by Hind(11) suggest that it was approximately as follows:

D/d	Drive Force Per Sheave, Percent of Rope Tension
10	2.1
20	0.8
30	0.5

As previously described, tension was applied to the rope specimens by means of a hydraulic cylinder which was attached to the moveable sheave assembly on the left side of the machine. The standard operating procedure was to establish the desired rope tension (prior to initiating specimen cycling) by adjusting a pressure relief valve which controlled the output of a continuously running pump. Thus, the initial load in the cylinder rod was equal to twice the desired rope tension.

When the drive system was then turned on, the required drive force acted to increase or decrease the cylinder rod tension depending on whether the drive trolley was moving toward or away from the tensioning sheave. The hydraulic control system acted to maintain a constant cylinder rod tension (constant pressure). As the drive trolley began moving toward the tensioning sheave, the cylinder rod tension momentarily dropped by one-half of the drive force. The hydraulic system then compensated for this change by returning the cylinder pressure to the preset value. The result was that the section of rope wrapped around the tensioning sheave was subjected to the nominal preset tension for a major part of its cycling stroke. However, the section of rope wrapped around the turn-around sheave at the opposite end of the machine was subjected to a tension equal to the nominal value <u>plus</u> the required drive force.

Exactly the opposite situation occurred as the drive trolley moved away from the tensioning sheave. The hydraulic control system acted to maintain the preset rope tension at the tensioning sheave, while the rope tension at the opposite end of the machine dropped to a value equal to the nominal tension minus the drive force.

During the Phase I experiments the drive force was quite low and, as a result, rope tension variations tended to be small. Also, the cycling stroke was rather short (20 to 54 inches depending upon sheave and rope diameters) and the response of the hydraulic control system may have been slow enough that complete tension adjustment may not have been achieved during the brief period of each machine stroke. These factors probably account for the observed results that side-of-machine was not a significant parameter during the Phase I experiments. The first-failing rope was equally likely to be on the left or right sides of the machine.

However, for the Phase II experiments, the higher drive force resulted in larger tension variations, and the longer stroke allowed more time for tension adjustment. Thus, the left specimen tended to remain at approximately the preset tension while the right specimen tended to see a slightly higher load during one half of each machine cycle and a slightly lower load during the other half of each cycle.

Experience has shown that ropes exposed to a fluctuating load may exhibit longer life. The reason for this behavior may be that the rope wires deform at high-stress locations during the high-load portion of the cycle. The deformation is caused when local contact stresses exceed the yield stress of the material; the rope deforms to maintain the stress acting on the new shape at the yield-stress value. Thus, during periods of high load, the wire stress at certain locations is approximately the material yield stress, while during periods of reduced load, the wire stress at these critical locations is below the material yield stress. On the other hand, a rope subjected to a constant load experiences local stresses close to the yield stress for greater intervals in the bending cycle. Thus, the rope loaded to a constant tension may display earlier fatigue crack initiation and more rapid crack propagation. (It should be noted that the above argument may not apply to widely fluctuating loads, where failure mode changes may result in early failure at the high-load condition.)

The strong effect of a relatively minor parameter (i.e. small load fluctuations) on wire-rope behavior (i.e. a 20 percent increase in rope life) should serve to illustrate to the reader that caution must be used in interpreting wire-rope fatigue data. It has been empirically shown that fatigue-testing results vary widely with the machine used, the rope tested, and with other hard-to-control factors. Thus, these data are best used as indicators of trends in wire-rope behavior rather than as a guide for estimating the exact service life that might be expected for an operating wire rope in the field.

Comments Regarding the Bearing Pressure Ratio

The ANOVA results indicate a strong interaction between L, D/d, and rope-life. The bearing pressure ratio, which can be expressed as a function of L and D/d, may be viewed as an attempt to account for this two-way interaction with a single variable.

An indication of a shortcoming in the bearing pressure ratio is that for equal values of B, rope life varied widely. For example, for each wire-rope construction, a single value of B applied to T = 20, D/d = 10; T = 40, D/d = 20; and T = 60, D/d = 30. But each condition yielded a different rope-life value as shown in Table 9. The bearing pressure ratio failed to account for the factors which produced this result.

It is likely that the observed inconsistencies in the bearing pressure ratio are related to the various wire-rope failure mechanisms

TABLE 9. VARIATION IN ROPE FATIGUE LIFE FOR COMMON VALUES OF BEARING PRESSURE RATIO

Rope Construction	d, in.	T, % RBS	D/d	B	Cycles to Failure[(a)]
1	1/2	20	10	.0128	37,266
		40	20	.0128	67,627
		60	30	.0128	34,621
1	3/4	20	10	.0128	26,336
		40	20	.0128	49,800
		60	30	.0128	24,112
2	1/2	20	10	.0104	14,060
		40	20	.0104	21,975
		60	30	.0104	13,391
2	3/4	20	10	.0104	16,553
		40	20	.0104	25,987
		60	30	.0104	27,174
3	1/2	20	10	.0134	19,564
		40	20	.0134	38,788
		60	30	.0134	24,213
3	3/4	20	10	.0134	20,878
		40	20	.0134	34,510
		60	30	.0134	32,801

(a) Average of four data points from Phase I experiments.

produced by different service conditions. Depending on the rope load, rope construction, wire material, and sheave size, rope failure is initiated by a certain critical combination of wire stresses (tension stress, bending stress, interstrand contact stress and rope/sheave contact stress).

If rope life is plotted as a function of rope tension with all other parameters held constant, the resulting curve can be considered to be a series of connected curves, each corresponding to a unique failure mode regime. These individual curves are likely to have different slopes, thus giving rise to "knees" in the total wire-rope load/life curve in areas of failure mode transition.

Since a given value of bearing pressure ratio can represent a wide range of rope-tension and sheave-size combinations, it can also correspond to a variety of rope failure modes. Thus, it is to be expected that rope life differences will exist among the various failure types.

It is possible that the shortcomings of the bearing pressure ratio may be overcome through development of an improved parameter which takes into consideration the important phenomena which influence wire-rope fatigue behavior. Laboratory fatigue experiments and rope failure analyses, together with detailed stress analysis, may allow such a parameter to be developed.

Wire Breakage

Many wire-rope users count wire breaks to estimate the remaining strength of a wire rope. A critical average or maximum number of wire breaks per lay is the signal to retire the rope.

Figures 25 through 28 show average and maximum wire breaks per lay versus percent rope life for wire ropes cycled under several different conditions. Percent of rope life is defined to be the number of cycles at which the measurement was taken, divided by the number of cycles to failure of that wire-rope specimen, all multiplied by 100 percent.

Among specimens showing wire breakage, the number of breaks at a certain percentage of rope life varied widely. At low B-values (big sheaves and low loads), the ropes tended to exhibit a large number of wire breaks prior to rope failure. As the B-value increased, (increasing severity of conditions), the number of observable wire breaks exhibited by the specimens lessened. At high loads and D/d = 10, many ropes failed before wire breakage could be identified by visual observation.

The data scatter displayed in Figures 25 through 28 suggests that the broken-wire criterion of rope retirement may result in rope replacement at widely varying values of percent rope life. Also, the broken-wire criterion becomes less useful as the service becomes more severe. Since rope retirement is usually desirable when rope strength has been reduced to some acceptable portion of the new rope breaking strength, future experiments should include a determination of remaining rope breaking strength versus number of fatigue cycles and number of broken wires. Although the required number of test specimens would be quite large, the results would be of tremendous value in establishing more accurate rope retirement criteria.

Figures 29 through 36 illustrate the appearance of typical ropes under the various conditions very late in the rope life. Each of these photographs depicts the test section of a reverse-bend specimen just after failure of its mate on the opposite side of the machine. Note wires broken from cross-wire notching which have "popped out" and become visible in Figures 31 through 33. Note the wire flattening due to sheave-throat contact in Figures 35 and 36.

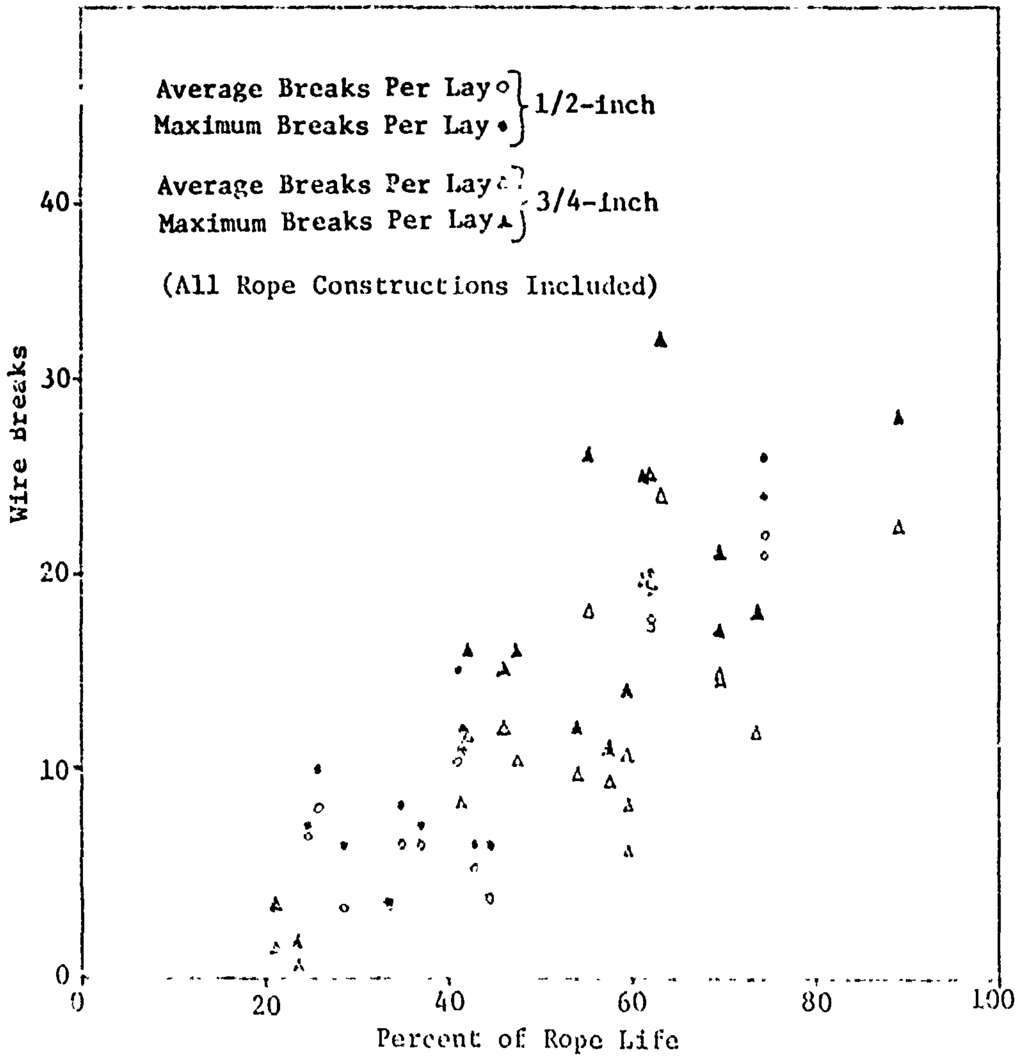

FIGURE 25. OBSERVED WIRE BREAKS
FOR D/d = 30, L = 20% RBS

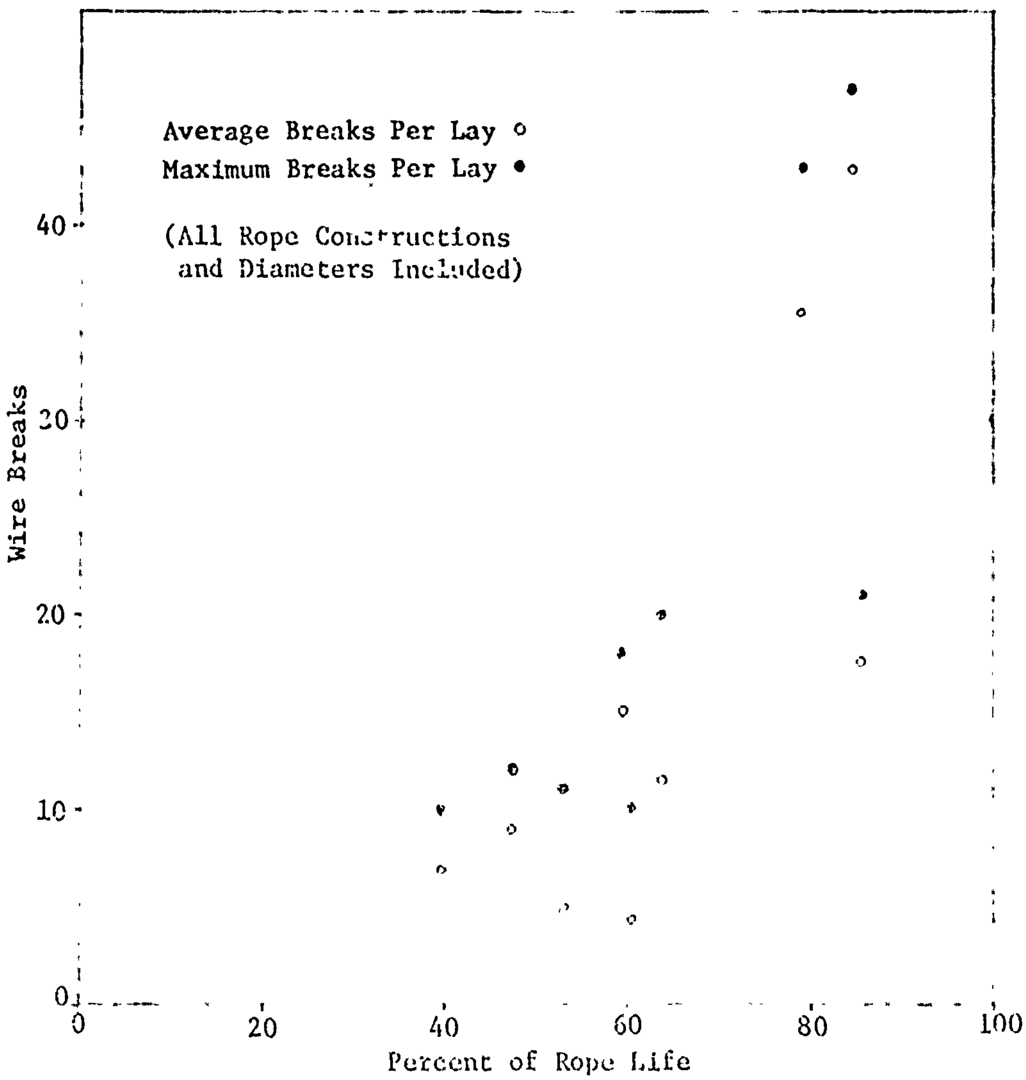

FIGURE 26. OBSERVED WIRE BREAKS
FOR D/d = 20, L = 20% RBS

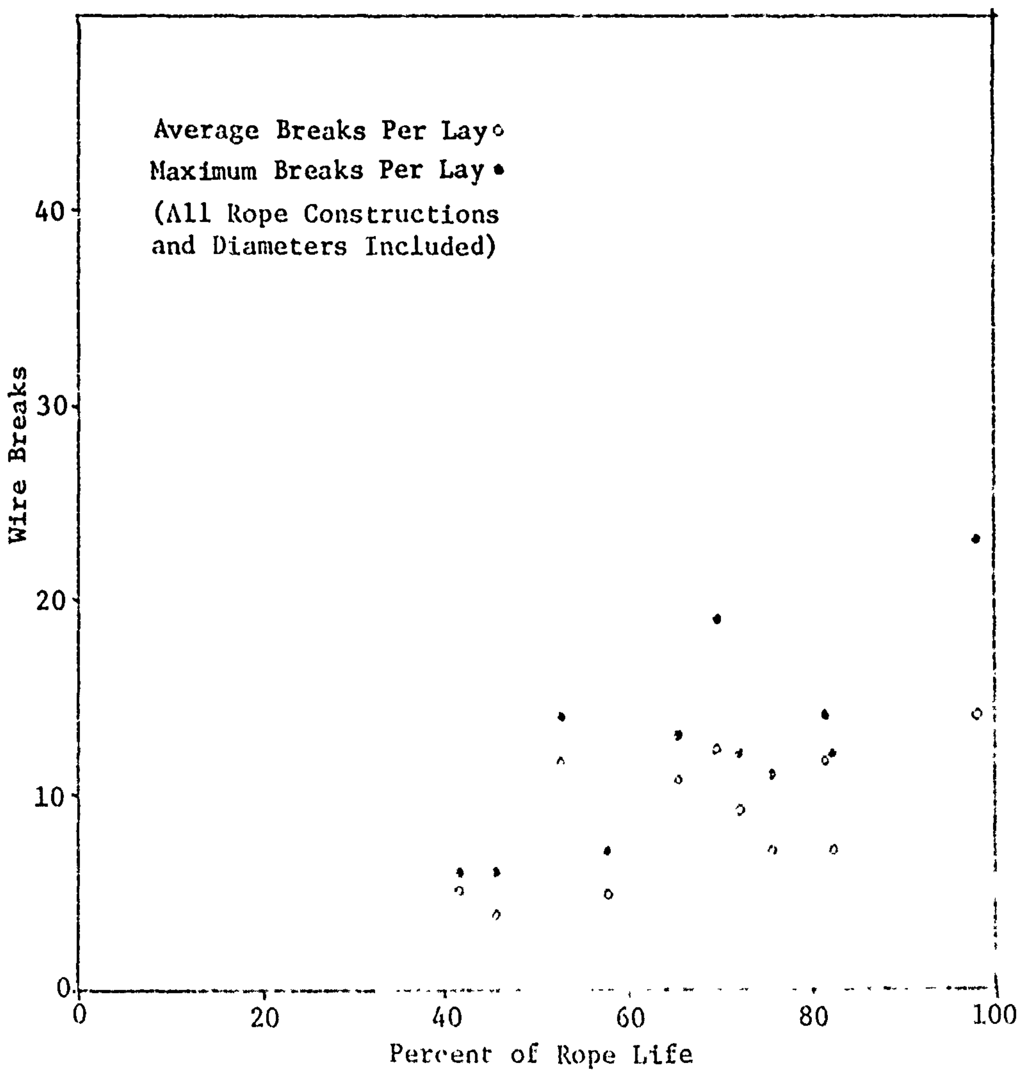

FIGURE 27. OBSERVED WIRE BREAKS FOR D/d = 30, L = 40% RBS

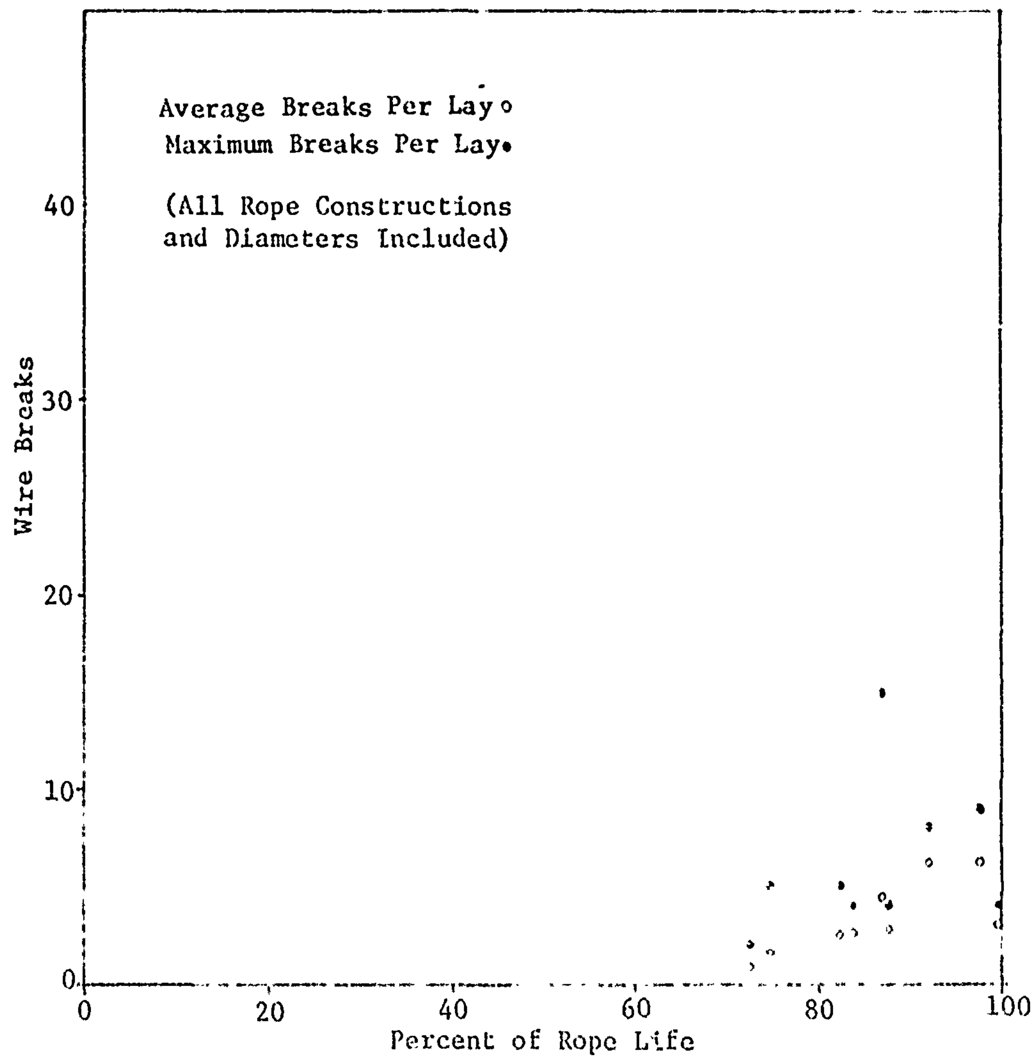

FIGURE 28. OBSERVED WIRE BREAKS
FOR D/d = 30, L = 60% RBS

FIGURE 29. ROPE CONDITION AT 83 PERCENT LIFE
d=1/2, C=1, D/d=20, T=20% RBS

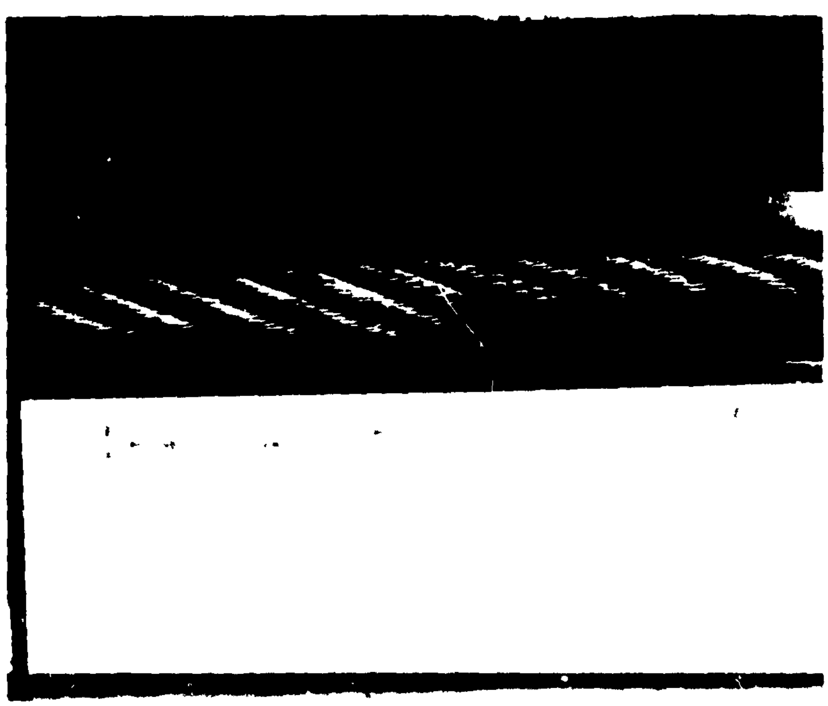

FIGURE 30. ROPE CONDITION AT 89 PERCENT LIFE
d=1/2, C=2, D/d=20, T=20% RBS

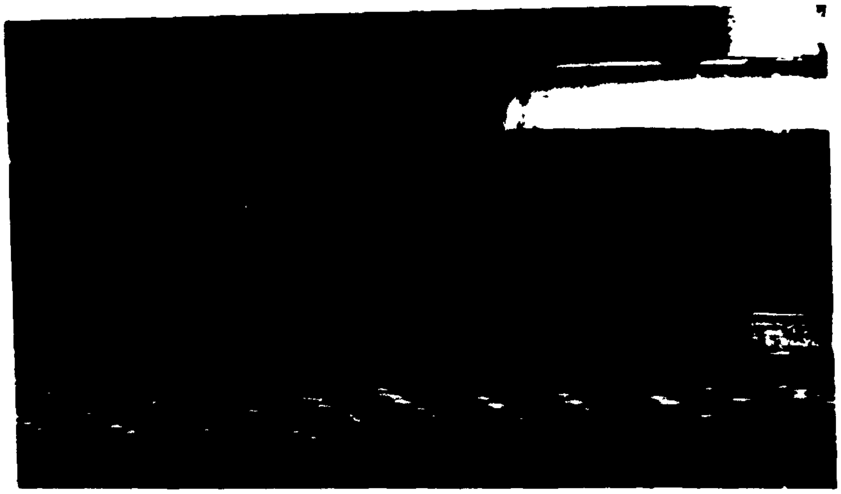

FIGURE 31. ROPE CONDITION AT 98 PERCENT LIFE
d=1/2, C=3, D/d=20, T=20% RBS

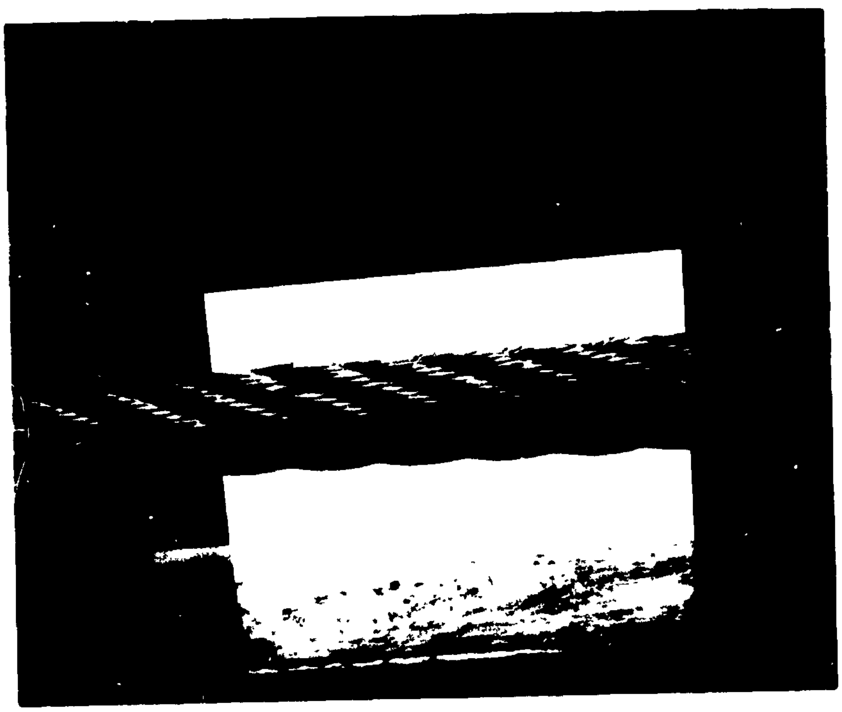

FIGURE 32. ROPE CONDITION AT 87 PERCENT LIFE
d=3/4, C=3, D/d=20, T=20% RBS

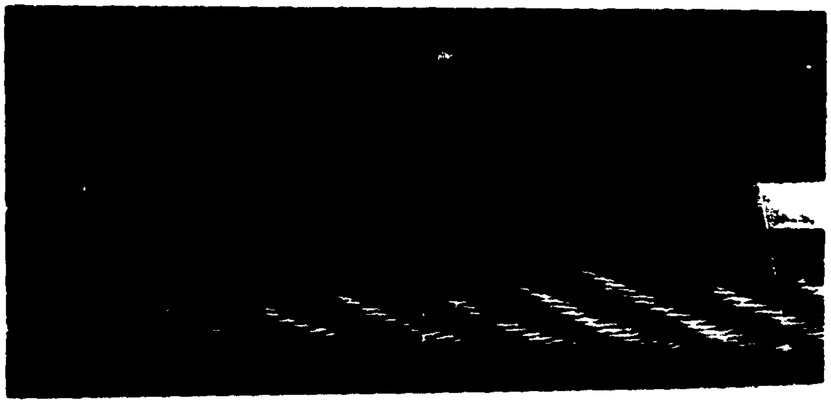

FIGURE 33. ROPE CONDITION AT 86 PERCENT LIFE
d=1/2, C=1, D/d=20, T=40% RBS

FIGURE 34. ROPE CONDITION AT 94 PERCENT LIFE
d=1/2, C=2, D/d=20, T=40% RBS

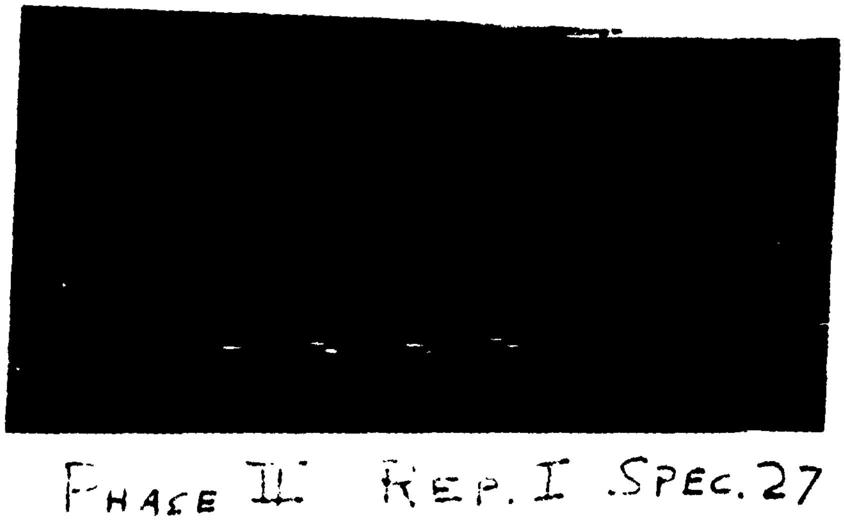

FIGURE 35. ROPE CONDITION AT 88 PERCENT LIFE
d=1/2, C=3, D/d=20, T=40% RBS

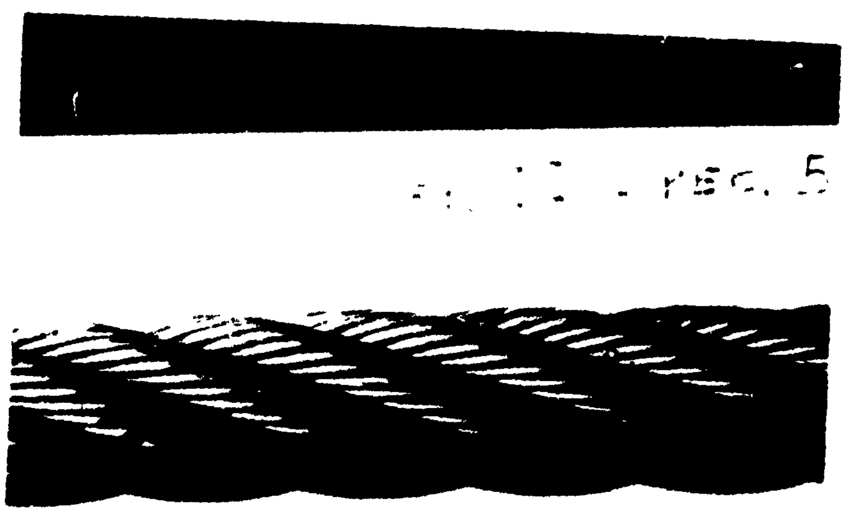

FIGURE 36. ROPE CONDITION AT 75 PERCENT LIFE
d=3/4, C=3, D/d=20, T=60% RBS

Wire-Rope Elongation

When a load is applied to a wire rope, it elongates due to "constructional" changes (e.g. strands seating down close to the core, wires seating down around the center of a strand, etc.). Further stretching occurs when the rope is cycled over a sheave. There is an initial rapid stretching, more "constructional stretch", followed by a period of slight, constant elongation. At the end of this midlife period, the rate of rope stretch again increases as wire breakage progresses.

For certain applications, rope elongation is used as a retirement criterion. Rope stretch is monitored and when the elongation curve begins to change in slope for the second time (corresponding to the final upswing in the curve), the rope is retired.

Figure 37 shows a typical elongation curve displayed by wire-rope specimens in the program. All rope specimens displayed initial constructional stretch, the magnitude of which varied with rope length, and load. A leveled-off midlife interval was evident in most cases. Some of the specimens, especially those tested under the more severe conditions, exhibited no final curve upswing, which makes predicting remaining life of these ropes on the basis of slope changes in the elongation curves a precarious gamble.

Elongation data for all ropes cycled to failure in the program may be found in Battelle Laboratory Record Books 23742, 27824, and 29700.

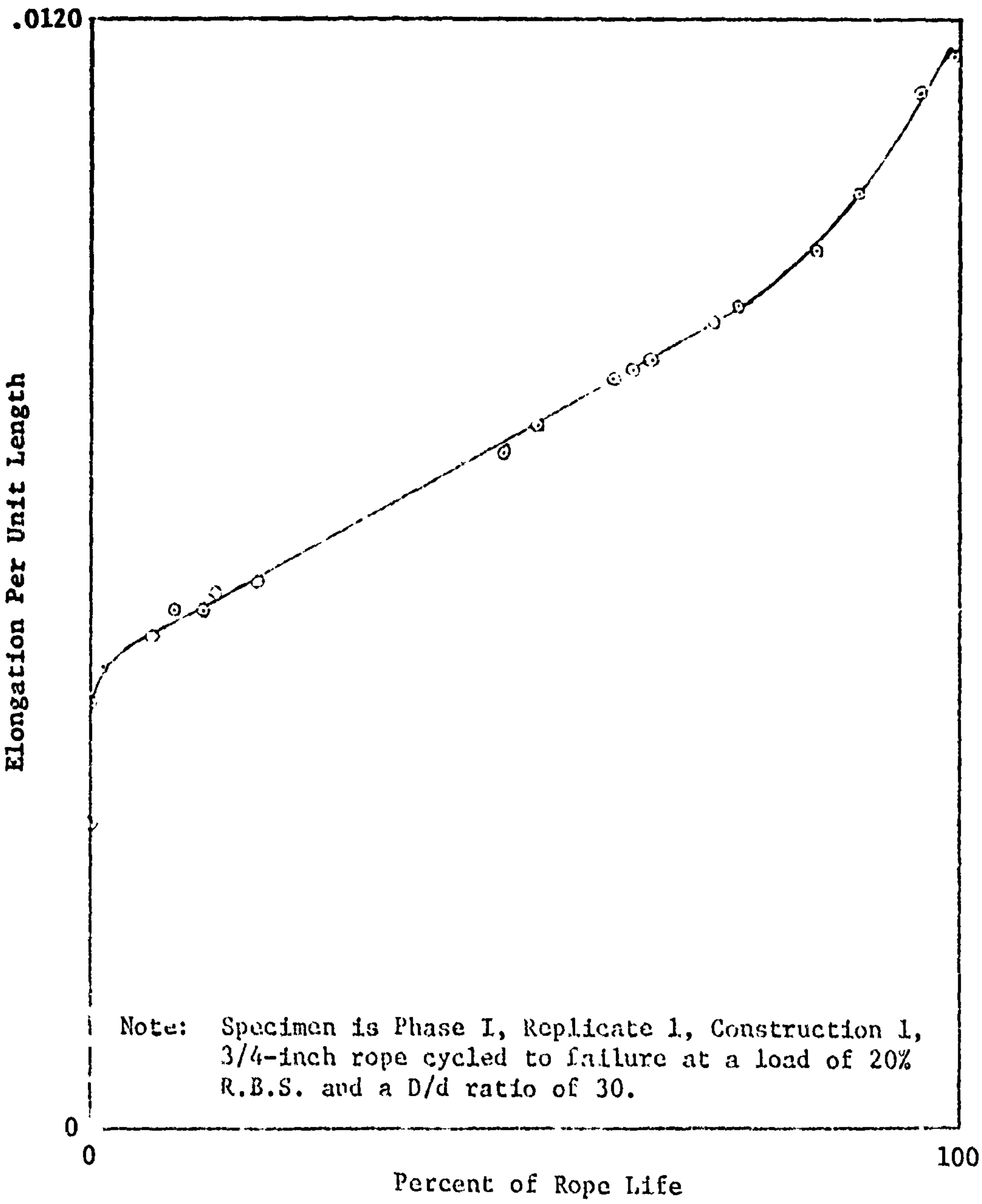

FIGURE 37. TYPICAL ROPE ELONGATION CURVE

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APPENDIX A

TABLE A-1. WIRE TENSION AND TORSION DATA

Rope Diameter, in.	Rope Construction	Wire Diameter, in.	Breaking Load, lbs	Ultimate Strength, psi	Torsions[a]
1/2	1	.032	218	271,000	56-61
		.028	180	292,000	50-52
		.028	180	292,000	52-56
		.024	124	274,000	52-53
		.023	47	113,000	50-67
1/2	2	.032	210	261,000	42-46
		.029	168	254,000	43-49
		.029	170	257,000	48-49
		.021	90	260,000	86-88
1/2	3	.036	281	276,000	44-49
		.036	280	275,000	50-52
		.025	134	273,000	46-49
		.022	104	274,000	54-59
		.020	90	286,000	64-68
3/4	1	.043	391	269,000	42-44
		.043	396	273,000	39-40
		.036	280	275,000	50-52
		.031	214	284,000	48-50
		.031	216	286,000	43-47

APPENDIX A

TABLE A-1. (Continued)

Rope Diameter, in.	Rope Construction	Wire Diameter, in.	Breaking Load, lbs	Ultimate Strength, psi	Torsions[a]
3/4	2	.048	432	239,000	37-46
		.048	440	243,000	41-42
		.044	402	264,000	40-41
		.044	401	264,000	37-43
		.032	212	264,000	39-41
		.032	216	269,000	39-44
		.032	206	256,000	40-40
		.021	90	260,000	80-88
3/4	3	.056	670	272,000	42-44[b]
		.056	665	270,000	47-49[b]
		.038	291	257,000	48-52
		.038	294	259,000	49-52
		.032	220	274,000	54-60
		.032	216	269,000	49-53
		.030	196	277,000	46-48
		.030	198	280,000	49-50

(a) Torsions in 4-inch gage length unless otherwise noted.
(b) Torsions in 8-inch gage length.

SOCKETING PROCEDURE

In general, wire rope failure due to bending over sheaves in field service is not influenced by the type of end fittings used. The end fittings are usually many rope lay lengths from the sheaves. However, in these experiments with short specimens and short fitting-to-sheave distances, special care was taken in the application of the terminations to avoid any such influence. Open spelter sockets were used and applied following standard procedures:

(1) Apply two hose clamps to the rope, one on either side of the location at which the rope is to be cut;
(2) Cut specimen to length;
(3) Seize the ends of the rope by wrapping with iron wire at a location corresponding to the final position of the socket nose;
(4) Broom rope strands and wires down to the seizing wires;
(5) Clean wires (trichloroethane was used);
(6) Apply flux;
(7) Slip socket over broomed wires;
(8) Heat socket to between 500 and 600°F;
(9) Pour zinc at about 950°F;
(10) Allow socket to air cool.

A holding fixture was used to align the cable with the sockets and to align the sockets with each other during the pouring operation, preventing rope bending or torque induced by the end fittings.

TABLE C-1. TEST NUMBERS, SPECIMEN NUMBERS, AND CUTTING ORDER FOR PHASE I, REPLICATE 1 EXPERIMENTS

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number		Cutting Order	
						Left Sheave	Right Sheave	Left Sheave	Right Sheave
1/2	1	20	10	2	1	4	3	3	6
1/2	1	20	20	47	1	94	93	20	7
1/2	1	20	30	40	1	80	79	12	5
1/2	1	40	10	24	1	48	47	1	15
1/2	1	40	20	23	1	46	45	13	9
1/2	1	40	30	33	1	66	65	10	19
1/2	1	60	10	10	1	20	19	14	11
1/2	1	60	20	20	1	40	39	4	17
1/2	1	60	30	4	1	8	7	8	2
1/2	2	20	10	45	2	90	89	31	40
1/2	2	20	20	30	2	60	59	26	37
1/2	2	20	30	25	2	50	49	36	38
1/2	2	40	10	41	2	82	81	33	29
1/2	2	40	20	14	2	28	27	24	32
1/2	2	40	30	46	2	92	91	28	25
1/2	2	60	10	3	2	6	5	30	27
1/2	2	60	20	7A	2	14*	13*	35	22
1/2	2	60	30	6	2	12	11	21	34

* Spares were substituted for these specimens.

TABLE C-1. (Continued)

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number		Cutting Order	
						Left Sheave	Right Sheave	Left Sheave	Right Sheave
1/2	3	20	10	37	3	74	73	41	49
1/2	3	20	20	44	3	88	87	57	51
1/2	3	20	30	31	3	62	61	53	58
1/2	3	40	10	36	3	72	71	47	52
1/2	3	40	20	50	3	100	99	59	44
1/2	3	40	30	5	3	10	9	42	48
1/2	3	60	10	9	3	18	17	55	54
1/2	3	60	20	43	3	86	85	56	43
1/2	3	60	30	34	3	68	67	45	50
3/4	1	20	10	17	4	34	33	63	61
3/4	1	20	20	8	4	16	15	79	77
3/4	1	20	30	29	4	58	57	67	68
3/4	1	40	10	18	4	36	35	75	76
3/4	1	40	20	15	4	30	29	72	64
3/4	1	40	30	32	4	64	63	62	65
3/4	1	60	10	53	4	106	105	73	71
3/4	1	60	20	1A	4	2*	1*	74	80
3/4	1	60	30	11	4	22	21	69	66

* Spares were substituted for these specimens.

TABLE C-1. (Continued)

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number Left Sheave	Specimen Number Right Sheave	Cutting Order Left Sheave	Cutting Order Right Sheave
3/4	2	20	10	27	5	54	53	88	83
3/4	2	20	20	13	5	26	25	97	86
3/4	2	20	30	28	5	56	55	95	92
3/4	2	40	10	49	5	98	97	81	84
3/4	2	40	20	42	5	84	83	82	96
3/4	2	40	30	19	5	38	37	89	99
3/4	2	60	10	26	5	52	51	87	91
3/4	2	60	20	48	5	96	95	93	90
3/4	2	60	30	21	5	42	41	85	94
3/4	3	20	10	35	6	70	69	102	101
3/4	3	20	20	12	6	24	23	108	107
3/4	3	20	30	16	6	32	31	119	110
3/4	3	40	10	51	6	102	101	120	114
3/4	3	40	20	54	6	108	107	113	118
3/4	3	40	30	39	6	78	77	106	109
3/4	3	60	10	22	6	44	43	115	112
3/4	3	60	20	38	6	76	75	105	116
3/4	3	60	30	52	6	104	103	117	103

TABLE C-2. TEST NUMBERS, SPECIMEN NUMBERS, AND CUTTING ORDER FOR PHASE I, REPLICATE 2 EXPERIMENTS

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number Left Sheave	Specimen Number Right Sheave	Cutting Order Left Sheave	Cutting Order Right Sheave
1/2	1	20	10	38	1	76	75	10	15
1/2	1	20	20	43	1	86	85	12	6
1/2	1	20	30	32	1	64	63	14	19
1/2	1	40	10	20	1	40	39	3	5
1/2	1	40	20	44	1	88	87	2	9
1/2	1	40	30	12	1	24	23	7	1
1/2	1	60	10	6	1	12	11	16	8
1/2	1	60	20	42	1	84	83	13	4
1/2	1	60	30	15	1	30	29	18	20
1/2	2	20	10	1	2	2	1	25	32
1/2	2	20	20	28	2	56	55	27	28
1/2	2	20	30	22	2	44	43	29	22
1/2	2	40	10	27	2	54	53	30	24
1/2	2	40	20	39	2	78	77	21	38
1/2	2	40	30	19	2	38	37	37	34
1/2	2	60	10	25	2	50	49	33	36
1/2	2	60	20	37	2	74	73	39	31
1/2	2	60	30	33	2	66	65	26	35

TABLE C-2. (Continued)

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number Left Sheave	Specimen Number Right Sheave	Cutting Order Left Sheave	Cutting Order Right Sheave
1/2	3	20	10	29	3	58	57	60	53
1/2	3	20	20	2	3	4	3	41	54
1/2	3	20	30	21	3	42	41	55	43
1/2	3	40	10	46	3	92	91	46	42
1/2	3	40	20	31	3	62	61	44	49
1/2	3	40	30	13	3	26	25	58	51
1/2	3	60	10	30	3	60	59	59	57
1/2	3	60	20	47	3	94	93	56	52
1/2	3	60	30	53	3	106	105	47	50
3/4	1	20	10	24	4	48	47	77	62
3/4	1	20	20	3	4	6	5	69	74
3/4	1	20	30	40	4	80	79	64	75
3/4	1	40	10	18	4	36	35	66	71
3/4	1	40	20	36	4	72	71	70	68
3/4	1	40	30	14	4	28	27	80	61
3/4	1	60	10	41	4	82	81	79	76
3/4	1	60	20	54	4	108	107	72	63
3/4	1	60	30	26	4	52	51	73	65

TABLE C-2. (Continued)

d, inch	C	L, % RBS	D/d	Test Number	Reel Number	Specimen Number		Cutting Order	
						Left Sheave	Right Sheave	Left Sheave	Right Sheave
3/4	2	20	10	35	5	70	69	93	87
3/4	2	20	20	45	5	90	89	89	85
3/4	2	20	30	10	5	20	19	94	88
3/4	2	40	10	16	5	32	31	86	81
3/4	2	40	20	23	5	46	45	84	90
3/4	2	40	30	8	5	16	15	91	83
3/4	2	60	10	51	5	102	101	96	98
3/4	2	60	20	7	5	14	13	92	97
3/4	2	60	30	49	5	98	97	95	82
3/4	3	20	10	9	6	18	17	16	112
3/4	3	20	20	34	6	68	67	106	114
3/4	3	20	30	52	6	104	103	109	113
3/4	3	40	10	5	6	10	9	118	117
3/4	3	40	20	17	6	34	33	115	120
3/4	3	40	30	11	6	22	21	101	103
3/4	3	60	10	48	6	96	95	111	104
3/4	3	60	20	4	6	8	7	102	107
3/4	3	60	30	50	6	100	99	119	108

TABLE C-3. TEST NUMBERS, SPECIMEN NUMBERS, AND CUTTING ORDER FOR PHASE II, REPLICATE 1 EXPERIMENTS

d, inch	C	L, % RBS	Test Number	Reel Number	Specimen Number		Cutting Order	
					Left Sheave	Right Sheave	Left Sheave	Right Sheave
1/2	1	20	15	1	30	29	5	3
1/2	1	40	9	1	18	17	1	4
1/2	1	60	3	1	6	5	6	2
1/2	2	20	11	2	22	21	14	12
1/2	2	40	12	2	24	23	8	10
1/2	2	60	8	2	16	15	9	11
1/2	3	20	4	3	8	7	16	18
1/2	3	40	14	3	28	27	19	21
1/2	3	60	7	3	14	13	20	17
3/4	1	20	10	4	20	19	28	27
3/4	1	40	17	4	34	33	23	26
3/4	1	60	18	4	36	35	22	25
3/4	2	20	13	5	26	25	35	32
3/4	2	40	1	5	2	1	34	30
3/4	2	60	6A	5	12*	11*	31	33
3/4	3	20	5	6	10	9	37	39
3/4	3	40	16	6	32	31	38	40
3/4	3	60	2	6	4	3	35	42

* Spares were substituted for these specimens.

TABLE C-4. TEST NUMBERS, SPECIMEN NUMBERS, AND CUTTING ORDER FOR PHASE II, REPLICATE 2 EXPERIMENTS

d, inch	C	L, % RBS	Test Number	Reel Number	Specimen Number		Cutting Order	
					Left Sheave	Right Sheave	Left Sheave	Right Sheave
1/2	1	20	8	1	16	15	1	4
1/2	1	40	9	1	18	17	3	2
1/2	1	60	18	1	36	35	5	7
1/2	2	20	5	2	10	9	13	8
1/2	2	40	4	2	8	7	14	11
1/2	2	60	16A	2	32*	31*	12	10
1/2	3	20	11	3	22	21	20	19
1/2	3	40	10	3	20	19	17	16
1/2	3	60	17	3	34	33	15	21
3/4	1	20	1	4	2	1	25	26
3/4	1	40	15	4	30	29	24	28
3/4	1	60	6	4	12	11	23	22
3/4	2	20	2	5	4	3	30	35
3/4	2	40	13	5	26	25	31	29
3/4	2	60	12	5	24	23	32	33
3/4	3	20	7	6	14	13	40	39
3/4	3	40	14	6	28	27	42	38
3/4	3	60	3	6	6	5	37	36

*Spares were substituted for these specimens.

TABLE D-1. RESULTS OF PHASE I REPLICATE 1 EXPERIMENTS
Simple single-sheave bending

Rope Diameter, Inches	Rope Construction (a)	Rope Tension, Percent RBS (b)	D/d (c)	Test Number	Bending Cycles to Failure (d) Left Sheave	Right Sheave
1/2	1	20	10	2	51,174	30,440
1/2	1	20	20	47	256,952	361,628
1/2	1	20	30	40	358,120	409,946
1/2	1	40	10	24	7,484	6,466
1/2	1	40	20	23	63,692	64,528
1/2	1	40	30	33	106,162	116,890
1/2	1	60	10	10	202	248
1/2	1	60	20	20	19,782	16,326
1/2	1	60	30	4	30,668	26,598
1/2	2	20	10	45	13,892	12,976
1/2	2	20	20	30	126,922	106,032
1/2	2	20	30	25	337,024	487,580
1/2	2	40	10	41	3,386	3,226
1/2	2	40	20	14	18,978	21,876
1/2	2	40	30	46	36,734	40,054
1/2	2	60	10	3	140	92
1/2	2	60	20	7A	7,064	5,996
1/2	2	60	30	6	13,668	13,322
1/2	3	20	10	37	20,956	19,048
1/2	3	20	20	44	167,190	188,214
1/2	3	20	30	31	237,412	209,348
1/2	3	40	10	36	4,922	4,028
1/2	3	40	20	50	40,382	31,620
1/2	3	40	30	5	50,954	60,958
1/2	3	60	10	9	50	48
1/2	3	60	20	43	15,150	11,800
1/2	3	60	30	34	23,130	25,330

TABLE D-1. (Continued)

Rope Diameter, Inches	Rope Construction (a)	Rope Tension, Percent RBS (b)	D/d (c)	Test Number	Bending Cycles to Failure (d) Left Sheave	Right Sheave
3/4	1	20	10	17	23,490	27,492
3/4	1	20	20	8	214,028	249,046
3/4	1	20	30	29	404,526	386,976
3/4	1	40	10	18	6,068	6,484
3/4	1	40	20	15	45,776	47,910
3/4	1	40	30	32	108,680	102,110
3/4	1	60	10	53	250	292
3/4	1	60	20	1A	17,574	17,880
3/4	1	60	30	11	33,622	34,480
3/4	2	20	10	27	15,496	16,596
3/4	2	20	20	13	156,604	165,484
3/4	2	20	30	28	270,234	355,268
3/4	2	40	10	49	2,800	2,260
3/4	2	40	20	42	25,928	25,542
3/4	2	40	30	19	84,584	69,208
3/4	2	60	10	26	52	60
3/4	2	60	20	48	9,306	9,816
3/4	2	60	30	21	27,150	30,280
3/4	3	20	10	35	18,742	23,398
3/4	3	20	20	12	169,052	193,812
3/4	3	20	30	16	484,184	484,366
3/4	3	40	10	51	6,048	5,206
3/4	3	40	20	54	32,534	35,816
3/4	3	40	30	39	100,538	88,980
3/4	3	60	10	22	112	124
3/4	3	60	20	38	13,480	12,050
3/4	3	60	30	52	30,508	30,340

TABLE D-2. RESULTS OF PHASE I REPLICATE 2 EXPERIMENTS
Simple single-sheave bending

Rope Diameter, Inches	Rope Construction (a)	Rope Tension, Percent RBS (b)	D/d (c)	Test Number	Bending Cycles to Failure (d)	
					Left Sheave	Right Sheave
1/2	1	20	10	38	33,066	34,382
1/2	1	20	20	43	221,178	228,308
1/2	1	20	30	32	235,284	292,740
1/2	1	40	10	20	6,944	7,244
1/2	1	40	20	44	71,216	71,072
1/2	1	40	30	12	101,564	93,432
1/2	1	60	10	6	364	302
1/2	1	60	20	42	22,282	20,752
1/2	1	60	30	15	42,308	38,908
1/2	2	20	10	1	15,320	14,052
1/2	2	20	20	28	91,018	100,746
1/2	2	20	30	22	288,634	321,214
1/2	2	40	10	27	2,938	3,122
1/2	2	40	20	39	23,692	23,354
1/2	2	40	30	19	32,180	43,580
1/2	2	60	10	25	118	82
1/2	2	60	20	37	7,816	7,338
1/2	2	60	30	33	13,542	13,030
1/2	3	20	10	29	19,926	18,324
1/2	3	20	20	2	157,256	185,498
1/2	3	20	30	21	191,552	230,384
1/2	3	40	10	46	5,062	4,280
1/2	3	40	20	31	39,112	44,038
1/2	3	40	30	13	51,634	59,230
1/2	3	60	10	30	54	44
1/2	3	60	20	47	13,130	14,272
1/2	3	60	30	53	24,038	24,354

TABLE D-2. (Continued)

Rope Diameter, Inches	Rope Construction (a)	Rope Tension, Percent RBS (b)	D/d (c)	Test Number	Bending Cycles to Failure (d)	
					Left Sheave	Right Sheave
3/4	1	20	10	24	26,020	28,340
3/4	1	20	20	3	249,028	288,528
3/4	1	20	30	40	360,708	376,294
3/4	1	40	10	18	6,518	6,424
3/4	1	40	20	36	50,898	54,616
3/4	1	40	30	14	118,030	118,242
3/4	1	60	10	41	234	180
3/4	1	60	20	54	19,766	19,910
3/4	1	60	30	26	45,068	51,380
3/4	2	20	10	35	17,518	16,600
3/4	2	20	20	45	162,786	199,368
3/4	2	20	30	10	403,004	352,000
3/4	2	40	10	16	2,496	2,460
3/4	2	40	20	23	26,008	26,468
3/4	2	40	30	8	87,938	82,998
3/4	2	60	10	51	56	72
3/4	2	60	20	7	9,344	11,224
3/4	2	60	30	49	27,922	23,344
3/4	3	20	10	9	19,536	21,836
3/4	3	20	20	34	217,644	197,930
3/4	3	20	30	52	417,882	406,646
3/4	3	40	10	5	4,828	7,676
3/4	3	40	20	17	37,046	32,642
3/4	3	40	30	11	107,514	90,152
3/4	3	60	10	48	140	120
3/4	3	60	20	4	12,464	12,978
3/4	3	60	30	50	36,262	34,092

TABLE D-3. RESULTS OF PHASE II REPLICATE 1 EXPERIMENTS

Two-sheave reverse bending
$D/d^{(c)} = 20$

Rope Diameter, Inches	Rope Construction (a)	Rope Tension, Percent RBS (b)	Test Number	Bending Cycles to Failure (d) Left Sheave	Right Sheave
1/2	1	20	15	137,864	174,392
1/2	1	40	9	38,288	43,460
1/2	1	60	3	12,108	13,584
1/2	2	20	11	49,904	66,584
1/2	2	40	12	13,884	16,572
1/2	2	60	8	2,916	6,612
1/2	3	20	4	84,388	90,324
1/2	3	40	14	17,760	20,252
1/2	3	60	7	7,960	9,620
3/4	1	20	10	84,156	103,338
3/4	1	40	17	18,764	23,560
3/4	1	60	18	8,700	10,648
3/4	2	20	13	52,144	71,800
3/4	2	40	1	13,728	18,484
3/4	2	60	6A	4,504	6,068
3/4	3	20	5	63,852	73,212
3/4	3	40	16	14,224	18,444
3/4	3	60	2	8,116	7,900

APPENDIX E

CELL MEANS FOR EXPERIMENTAL RESULTS

Legend for Tables E-1 through E-7

1. Cell means are average values of experimental results under the conditions specified. For example, the cell mean for Construction - 1 and D/d = 20 is the average of all experimental results in the factorial block taken under Construction - 1, D/d = 20 conditions. The average is taken over all diameters, all loads, etc.

2. All cell means are expressed as averages of logarithms of the bending cycles to failure.

3. Parameters and their levels are printed by the computer as follows:

D = Rope Diameter
Levels: 1 = 1/2 inch
2 = 3/4 inch

C = Rope Construction
Levels: 1 = Construction 1
2 = Construction 2
3 = Construction 3

L = Rope Load
Levels: 1 = 20% R.B.S.
2 = 40% R.B.S.
3 = 60% R.B.S.

Q = Sheave-to-Rope Diameter Ratio
Levels: 1 = 10
2 = 20
3 = 30

S = Side of Machine
Levels: 1 = Left Side
2 = Right Side

FOOTNOTES FOR TABLES D-1 THROUGH D-4.

(a) All ropes were manufactured from the same heat of steel and complied with the requirements of Federal Specification RR-W-410C as follows:

Construction 1 : Type I, Class 3 - 6 x 37 Warrington Seale, performed, right-regular lay, IWRC rope with each strand consisting of 36 wires of which 14 are outer-layer wires. This rope was manufactured from uncoated improved plow steel.

Construction 2 : Type III, Class 3 - 6 x 24 Warrington, preformed, right-regular lay rope with each strand consisting of 24 wires or which 16 are outer-layer wires. This rope was manufactured from galvanized improved plow steel and had a natural fiber core.

Construction 3 : Type I, Class 2 - 6 x 19 Warrington Seale, preformed, right-regular lay, IWRC rope with each strand consisting of 26 wires of which 10 are inner-layer and 10 are outer-layer wires. This rope was manufactured from uncoated improved plow steel.

(b) Rope tension is expressed as a percent of the minimum rated breaking strength per Federal Specification RR-W-410C.

(c) D/d = Ratio of sheave pitch diameter to rope nominal diameter.

(d) A rope bending cycle is defined as a straight-bend-straight flexure of the test section. During simple single-sheave bending experiments, each complete machine cycle provided two rope bending cycles; during two-sheave reverse-bending experiments, each machine cycle provided four rope bending cycles.

APPENDIX E

CELL MEANS FOR EXPERIMENTAL RESULTS

Legend for Tables E-1 through E-7

1. Cell means are average values of experimental results under the conditions specified. For example, the cell mean for Construction - 1 and D/d = 20 is the average of all experimental results in the factorial block taken under Construction - 1, D/d = 20 conditions. The average is taken over all diameters, all loads, etc.

2. All cell means are expressed as averages of logarithms of the bending cycles to failure.

3. Parameters and their levels are printed by the computer as follows:

D = Rope Diameter
Levels: 1 = 1/2 inch
2 = 3/4 inch

C = Rope Construction
Levels: 1 = Construction 1
2 = Construction 2
3 = Construction 3

L = Rope Load
Levels: 1 = 20% R.B.S.
2 = 40% R.B.S.
3 = 60% R.B.S.

Q = Sheave-to-Rope Diameter Ratio
Levels: 1 = 10
2 = 20
3 = 30

S = Side of Machine
Levels: 1 = Left Side
2 = Right Side

APPENDIX E

TABLE E-1. CELL MEANS FOR PHASE I, FIVE-WAY FACTORIAL

MEAN 4.31454

CELL MEANS

D =	1	2
	4.2625	4.3466

C =	1	2	3
	4.4796	4.1687	4.2953

L =	1	2	3
	5.0389	4.3699	3.5349

Q =	1	2	3
	3.3539	4.6469	4.9458

S =	1	2
	4.3137	4.3154

	C =	1	2	3
D =	1	4.4929	4.1258	4.2288
	2	4.4664	4.2117	4.3617

	L =	1	2	3
D =	1	5.0071	4.3446	3.4958
	2	5.0706	4.3951	3.5740

	L =	1	2	3
C =	1	5.1464	4.5403	3.7522
	2	4.9498	4.1896	3.3066
	3	5.0204	4.3795	3.4659

	Q =	1	2	3
D =	1	3.3564	4.6342	4.8628
	2	3.3515	4.6595	5.0228

	Q =	1	2	3
C =	1	3.5732	4.8177	5.0479
	2	3.1770	4.4751	4.6541
	3	3.3025	4.6478	4.9355

	Q =	1	2	3
L =	1	4.3260	5.2660	5.5246
	2	3.6522	4.5673	4.5801
	3	2.0645	4.1074	4.4328

	S =	1	2
D =	1	4.2862	4.2787
	2	4.3412	4.3520

	S =	1	2
C =	1	4.4771	4.4821
	2	4.1676	4.1699
	3	4.2954	4.2942

	S =	1	2
L =	1	5.0271	5.0506
	2	4.3760	4.3691
	3	3.5434	3.5264

	S =	1	2
Q =	1	3.3569	3.3429
	2	4.6420	4.6518
	3	4.9462	4.9514

D = 1

	L =	1	2	3
C =	1	5.1604	4.5646	3.7536
	2	4.9653	4.1397	3.3323
	3	4.9556	4.3294	3.4014

D = 2

	L =	1	2	3
C =	1	5.1324	4.5100	3.7507
	2	4.9944	4.2399	3.4008
	3	5.0052	4.4295	3.5705

APPENDIX E

TABLE E-1. (Continued)

D = 1	Q =	1	2	3
C =	1	3.6145	4.6470	5.0170
	2	3.2238	4.4632	4.7584
	3	3.2127	4.6525	4.8212

D = 2	Q =	1	2	3
C =	1	3.5319	4.7884	5.0788
	2	3.1362	4.5471	4.9578
	3	3.3922	4.6432	5.0498

D = 1	Q =	1	2	3
L =	1	4.3334	5.2271	5.4667
	2	3.6663	4.5851	4.7803
	3	2.0494	4.6904	4.3475

D = 2	Q =	1	2	3
L =	1	4.3186	5.3048	5.5885
	2	3.6561	4.5494	4.9799
	3	2.0796	4.1244	4.5180

C = 1	Q =	1	2	3
L =	1	4.4967	5.4666	5.5415
	2	3.8254	4.7629	5.0326
	3	2.4036	4.2833	4.5096

C = 2	Q =	1	2	3
L =	1	4.1628	5.1270	5.5396
	2	3.4463	4.3715	4.7032
	3	1.6994	3.9269	4.2795

C = 3	Q =	1	2	3
L =	1	4.3645	5.2641	5.4927
	2	3.7125	4.5614	4.6545
	3	1.8965	4.1181	4.4492

D = 1	S =	1	2
C =	1	4.4465	4.4692
	2	4.1294	4.1221
	3	4.2327	4.2249

D = 2	S =	1	2
C =	1	4.4577	4.4751
	2	4.2058	4.2175
	3	4.3660	4.3534

D = 1	S =	1	2
L =	1	4.9992	5.0156
	2	4.3413	4.3479
	3	3.5181	3.4734

D = 2	S =	1	2
L =	1	5.0550	5.0863
	2	4.3999	4.3904
	3	3.5087	3.5794

C = 1	S =	1	2
L =	1	5.1321	5.1666
	2	4.5398	4.5468
	3	3.7594	3.7450

C = 2	S =	1	2
L =	1	4.9380	4.9617
	2	4.1690	4.1906
	3	3.3759	3.3573

C = 3	S =	1	2
L =	1	5.0112	5.0297
	2	4.3629	4.3766
	3	3.4950	3.4709

APPENDIX E

TABLE E-1. (Continued)

U = 1			
	S =	1	2
Q =	1	3.3779	3.3228
	2	4.6550	4.6334
	3	4.8437	4.8690
U = 2			
	S =	1	2
Q =	1	3.3398	3.3631
	2	4.6490	4.6701
	3	5.0347	5.0249
C = 1			
	S =	1	2
Q =	1	3.5881	3.5564
	2	4.8075	4.8278
	3	5.0437	5.0321
C = 2			
	S =	1	2
Q =	1	3.1965	3.1635
	2	4.4693	4.4209
	3	4.8430	4.8052

C = 3			
	S =	1	2
Q =	1	3.3061	3.2959
	2	4.6491	4.6466
	3	4.9339	4.9370
L = 1			
	S =	1	2
Q =	1	4.3301	4.3220
	2	5.2447	5.2373
	3	5.5066	5.5427
L = 2			
	S =	1	2
Q =	1	3.6881	3.6564
	2	4.5654	4.5691
	3	4.8782	4.8819
L = 3			
	S =	1	2
Q =	1	2.0785	2.0505
	2	4.1159	4.0990
	3	4.4358	4.4297

APPENDIX E

TABLE E-2. CELL MEANS FOR PHASE I, FOUR-WAY FACTORIAL

MEAN 4.31454

CELL MEANS

D =	1	2
	4.2825	4.3466

C =	1	2	3
	4.4706	4.1697	4.2953

L =	1	2	3
	5.1389	4.3009	3.5349

O =	1	2	3
	3.3579	4.6469	4.9458

C =	1	2	3
D = 1	4.4099	4.1258	4.2238
2	4.4664	4.2017	4.3617

L =	1	2	3
D = 1	5.0071	4.3446	3.4956
2	5.0706	4.3951	3.5749

L =	1	2	3
C = 1	5.1444	4.5473	3.7522
2	4.9498	4.1898	3.3665
3	5.0274	4.3795	3.4859

O =	1	2	3
D = 1	3.3574	4.6342	4.8628
2	3.3575	4.6595	5.0288

O =	1	2	3
C = 1	3.5732	4.8177	5.3479
2	3.1770	4.4751	4.8541
3	3.3025	4.6478	4.9355

O =	1	2	3
L = 1	4.3243	5.2060	5.5246
2	3.6622	4.5073	4.8951
3	2.9645	4.1074	4.4328

D = 1

L =	1	2	3
C = 1	5.1674	4.5946	3.7536
2	4.9653	4.1397	3.3323
3	4.9556	4.3294	3.4014

D = 2

L =	1	2	3
C = 1	5.1374	4.5160	3.7537
2	4.9944	4.2399	3.4058
3	5.0852	4.4295	3.5705

D = 1

O =	1	2	3
C = 1	3.6146	4.8470	5.1179
2	3.2238	4.4032	4.7554
3	3.2127	4.5525	4.8212

D = 2

O =	1	2	3
C = 1	3.5319	4.7884	5.5798
2	3.1302	4.5471	4.9578
3	3.3922	4.6432	5.0498

D = 1

O =	1	2	3
L = 1	4.3334	5.2271	5.4637
2	3.6633	4.5351	4.7833
3	2.9494	4.0984	4.3475

APPENDIX E

TABLE E-2. (Continued)

		O = 1	2	3
D = 2				
L =	1	4.3186	5.3[illegible]49	5.59[illegible]5
	2	3.6[illegible]61	4.5494	4.0799
	3	2.[illegible]796	4.1244	4.51[illegible]1
C = 1				
L =	1	4.49[illegible]7	5.4[illegible]68	5.5415
	2	3.8254	4.[illegible]029	5.[illegible]326
	3	2.4[illegible]06	4.2333	4.5696
C = 2				
L =	1	4.18[illegible]8	5.1270	5.53[illegible]6
	2	3.44[illegible]8	4.3775	4.7432
	3	1.8904	3.92[illegible]9	4.2795
C = 3				
L =	1	4.3[illegible]45	5.2[illegible]41	5.4927
	2	3.7125	4.5574	4.3645
	3	1.84[illegible]5	4.1181	4.4492

APPENDIX E

TABLE E-3. CELL MEANS FOR PHASE I, FOUR-WAY FACTORIAL

Experimental results for first-breaking specimens only.

MEAN 4.28716

CELL MEANS

D =	1	2
	4.2516	4.3029

C =	1	2	3
	4.4553	4.1394	4.2669

L =	1	2	3
	5.3389	4.3657	3.5872

O =	1	2	3
	3.7137	4.6077	4.9212

C =	1	2	3
D = 1	4.4521	4.0972	4.1996
2	4.4494	4.1914	4.3352

L =	1	2	3
D = 1	4.9712	4.3196	3.4633
2	5.2464	4.3722	3.5507

L =	1	2	3
C = 1	5.1117	4.5786	3.7254
2	4.9120	4.2746	3.3765
3	4.9957	4.3423	3.4650

O =	1	2	3
D = 1	3.3144	4.5767	4.8336
2	3.3137	4.6426	5.3098

O =	1	2	3
C = 1	3.5592	4.7673	5.0296
2	3.1645	4.4735	4.8222
3	3.2654	4.6191	4.3151

O =	1	2	3
L = 1	4.2372	5.2747	5.4045
2	3.6335	4.7520	4.8528
3	2.0125	[illegible]	4.4166

D = 1

L =	1	2	3
C = 1	5.1138	4.3847	3.7217
2	4.9722	4.1162	3.2034
3	4.9276	4.2916	3.3767

D = 2

L =	1	2	3
C = 1	5.1096	4.5063	3.7291
2	4.9559	4.2211	3.3676
3	5.2637	4.3884	3.5573

D = 1

O =	1	2	3
C = 1	3.5734	4.4274	4.9907
2	3.1350	4.7791	4.7167
3	3.1843	4.6172	4.7047

D = 2

O =	1	2	3
C = 1	3.5083	4.7725	5.1677
2	3.1133	4.5281	4.9272
3	3.3437	4.6212	5.0355

D = 1

O =	1	2	3
L = 1	4.3011	5.1932	5.4198
2	3.6442	4.5653	4.7482
3	1.3279	4.7616	4.3332

APPENDIX E

TABLE E-3. (Continued)

C = 2

Q =	1	2	3
L = 1	[illegible]	[illegible]	5.[illegible]
2	3.[illegible]	4.[illegible]	4.[illegible]74
3	2.[illegible]	4.[illegible]	4.4997

C = 1

Q =	1	2	3
L = 1	4.4[illegible]7[illegible]	5.[illegible]	5.[illegible]176
2	3.[illegible]	4.7[illegible]	5.[illegible]134
3	2.3[illegible]36	4.2[illegible]77	4.[illegible]

C = 2

Q =	1	2	3
L = 1	4.1[illegible]7[illegible]	5.[illegible]7[illegible]	5.4016
2	3.4[illegible]	4.[illegible]	4.[illegible]
3	1.8[illegible]	3.4[illegible]	4.2[illegible]

C = 3

Q =	1	2	3
L = 1	4.2[illegible]	5.[illegible]	5.4[illegible]
2	3.[illegible]2	4.[illegible]	4.8[illegible]
3	2.[illegible]	4.[illegible]	4.4[illegible]

N = 1 C = 1

Q =	1	2	3
L = 1	4.[illegible]14	5.[illegible]7[illegible]	5.4[illegible]
2	3.8[illegible]	4.[illegible]7[illegible]	4.[illegible]
3	2.3[illegible]27	4.2[illegible]	4.5[illegible]7[illegible]

N = 1 C = 2

Q =	1	2	3
L = 1	4.[illegible]	4.[illegible]	5.[illegible]
2	3.[illegible]984	4.[illegible]273	4.5[illegible]
3	1.0[illegible]	3.[illegible]217	4.1[illegible]

N = 1 C = 3

Q =	1	2	3
L = 1	4.[illegible]71[illegible]	[illegible]	[illegible]
2	3.6[illegible]	4.[illegible]	4.7[illegible]
3	1.[illegible]23	4.[illegible]	4.[illegible]

N = 2 C = 1

Q =	1	2	3
L = 1	4.[illegible]	5.[illegible]	5.57[illegible]
2	3.7[illegible]	4.[illegible]	5.[illegible]
3	2.3[illegible]	4.27[illegible]	4.5[illegible]

N = 2 C = 2

Q =	1	2	3
L = 1	4.2[illegible]	5.2[illegible]	5.[illegible]
2	3.3[illegible]	4.[illegible]	4.[illegible]
3	1.7[illegible]21	3.[illegible]	4.[illegible]

N = 2 C = 3

Q =	1	2	3
L = 1	4.[illegible]	5.26[illegible]	5.[illegible]471
2	3.[illegible]	4.[illegible]131	4.[illegible]
3	2.[illegible]	4.[illegible]	4.[illegible]

APPENDIX E

TABLE E-4. CELL MEANS FOR PHASE I, FOUR-WAY FACTORIAL
Experimental results for second-breaking specimens only.

MEAN [illegible]

CELL MEANS

D =	1	2
	4.3134	[illegible]

C =	1	2	3
	[illegible]	[illegible]	4.3237

L =	1	2	3
	[illegible]	[illegible]	3.5528

O =	1	2	3
	[illegible]	[illegible]	4.0724

D = \ C =	1	2	3
1	[illegible]	4.1576	[illegible]
2	[illegible]	[illegible]	[illegible]

D = \ L =	1	2	3
1	[illegible]	[illegible]	3.5776
2	[illegible]	[illegible]	3.5984

C = \ L =	1	2	3
1	[illegible]	[illegible]	3.7784
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]

D = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]

C = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	4.0558

L = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	4.1298	[illegible]

D = 1

C = \ L =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	3.4261

D = 2

C = \ L =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	4.2787	[illegible]
3	[illegible]	[illegible]	[illegible]

D = 1

C = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]

D = 2

C = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]

D = 1

L = \ O =	1	2	3
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]

APPENDIX E

TABLE E-4. (Continued)

D = 2

	C =	1	2	3
L =	1	4.3433	[illegible]	5.6774
	2	3.6897	4.7623	5.9124
	3	2.1133	4.1794	4.5366

C = 1

	D =	1	2	3
L =	1	4.3742	[illegible]	5.5654
	2	3.9433	4.7712	5.0459
	3	2.4475	[illegible]	4.5904

C = 2

	C =	1	2	3
L =	1	4.1379	5.1553	5.5977
	2	3.4571	4.3973	4.7784
	3	1.9474	[illegible]	4.2095

C = 3

	C =	1	2	3
L =	1	4.3325	[illegible]	5.5110
	2	3.7159	[illegible]	4.5273
	3	1.9177	[illegible]	[illegible]

D = 1 C = 1

	C =	1	2	3
L =	1	4.6227	[illegible]	5.5795
	2	3.9671	4.8712	5.2373
	3	2.4774	4.3271	4.5566

D = 1 C = 2

	C =	1	2	3
L =	1	[illegible]	[illegible]	5.5074
	2	3.7121	4.3573	4.6212
	3	2.1701	3.9717	4.1337

D = 1 C = 3

	D =	1	2	3
L =	1	4.3136	5.2715	[illegible]
	2	3.5537	4.6753	4.7709
	3	1.7137	4.1674	4.3951

D = 2 C = 1

	D =	1	2	3
L =	1	4.4459	5.4292	5.5912
	2	3.9173	4.7183	5.0565
	3	2.4170	4.2757	4.5242

D = 2 C = 2

	C =	1	2	3
L =	1	4.2317	5.2592	5.5770
	2	3.4222	4.4192	4.0757
	3	1.9177	4.3711	4.4676

D = 2 C = 3

	D =	1	2	3
L =	1	4.3542	5.3126	5.5531
	2	3.9334	4.5614	5.1160
	3	2.1133	4.1215	4.5219

APPENDIX E

TABLE E-5. CELL MEANS FOR PHASE II, FOUR-WAY FACTORIAL

MEAN 4.36[illegible]

CELL MEANS

D =	1	2
	4.4064	4.3244

C =	1	2	3
	4.5346	4.1982	4.3634

L =	1	2	3
	4.9151	4.3001	3.8913

S =	1	2
	4.3706	4.4[illegible]2

	C =	1	2	3
D =	1	4.5415	4.1074	4.3352
	2	4.4278	4.2379	4.3416

	L =	1	2	3
D =	1	4.9585	4.3559	3.9043
	2	4.8713	4.2444	3.8777

	L =	1	2	3
C =	1	5.0736	4.4797	4.0513
	2	4.7635	4.1739	3.6723
	3	4.9030	4.2475	3.9396

	S =	1	2
D =	1	4.3624	4.4503
	2	4.2938	4.3500

	S =	1	2
C =	1	4.4921	4.5772
	2	4.1632	4.2331
	3	4.3335	4.3933

	S =	1	2
L =	1	4.8813	4.9488
	2	4.2618	4.3385
	3	3.8437	3.9133

D = 1

	L =	1	2	3
C =	1	5.1963	4.5246	4.1133
	2	4.7453	4.1616	3.6703
	3	4.9453	4.2814	3.9292

D = 2

	L =	1	2	3
C =	1	4.9609	4.3321	3.9393
	2	4.7917	4.1963	3.6337
	3	4.8611	4.2137	3.9500

D = 1

	S =	1	2
C =	1	4.5057	4.5772
	2	4.1273	4.2573
	3	4.3845	4.4159

D = 2

	S =	1	2
C =	1	4.3784	4.4771
	2	4.1995	4.2283
	3	4.3145	4.3646

D = 1

	S =	1	2
L =	1	4.9251	4.9916
	2	4.3043	4.3876
	3	3.8368	3.9718

APPENDIX E

TABLE E-5. (Continued)

D = 2		
S =	1	2
L = 1	4.4366	4.9159
2	4.1997	4.7134
3	3.8626	3.8543

C = 1		
S =	1	2
L = 1	5.0210	5.1261
2	4.4432	4.5147
3	4.0119	4.0907

C = 2		
S =	1	2
L = 1	4.7042	4.8120
2	4.1354	4.2125
3	3.5701	3.6709

C = 3		
S =	1	2
L = 1	[illegible]	4.9172
2	[illegible]	4.2443
3	3.9041	3.4133

D = 1 C = 1		
S =	1	2
L = 1	5.1411	5.0414
2	4.5953	4.5743
3	4.0835	4.1459

D = 1 C = 2		
S =	1	2
L = 1	4.7614	4.7892
2	4.1357	4.1375
3	3.5438	3.7959

D = 1 C = 3		
S =	1	2
L = 1	4.9357	4.9542
2	4.2419	4.3209
3	3.8955	3.9727

D = 2 C = 1		
S =	1	2
L = 1	4.9519	5.0229
2	4.2912	4.3751
3	3.9431	4.0355

D = 2 C = 2		
S =	1	2
L = 1	4.7459	4.8355
2	4.1351	4.2374
3	3.7165	3.5511

D = 2 C = 3		
S =	1	2
L = 1	4.8619	4.3573
2	4.1717	4.2557
3	3.9222	3.3779

APPENDIX E

TABLE E-7. CELL MEANS FOR PHASE II, THREE-WAY FACTORIAL
Experimental results for second-breaking specimens only.

MEAN		4.31576		
CELL MEANS				
	D =	1	2	
		4.3624	4.2691	
	C =	1	2	3
		4.4921	4.1249	4.33[illegible]3
	L =	1	2	3
		4.9761	4.2018	3.8093
	C =	1	2	3
D =	1	4.6[illegible]67	4.1276	4.3545
	2	4.3784	4.1228	4.3062
	L =	1	2	3
D =	1	4.9261	4.3243	3.8368
	2	4.8262	4.1993	3.7819
	L =	1	2	3
C =	1	5.0210	4.4432	4.0119
	2	4.7242	4.1354	3.515[illegible]
	3	4.8831	4.2068	3.9011
	D = 1			
	L =	1	2	3
C =	1	5.1411	4.5953	4.08[illegible]8
	2	4.7614	4.1357	3.5438
	3	4.9357	4.2419	3.8858
	D = 2			
	L =	1	2	3
C =	1	4.9010	4.2912	3.9431
	2	4.7469	4.1351	3.4862
	3	4.83[illegible]6	4.1717	3.9164