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BEHAVIOR OF STATIONARY WIREropes
IN TENSION AND BENDING

BY

DOUGLAS M. STEWART, Jun. Am. Soc. C. E.

WITH DISCUSSION BY

MESSRS. C. D. MEALS, G. P. BOOMSLITER, INGVALD E. MADSEN, AND
DOUGLAS M. STEWART.

BEHAVIOR OF STATIONARY WIRE ROPES IN TENSION AND BENDING

By DOUGLAS M. STEWART, JUN. AM. SOC. C. E.

Synopsis

This experimental investigation of the behavior of wire ropes in tension and bending was undertaken in order to determine their strengths and the stresses produced under load, and to compare these values with those given by the several formulas in common use. Altogether, nine tension and thirty-six bending specimens were tested over sheaves of four diameters. The ropes selected were 1 in. in diameter, with hemp centers, and the tests included studies of regular and Lang lay ropes, of 6 X 7 and 6 X 19 construction preformed and non-preformed types, and of two different grades of steel. Important results are contained in the curves for loss of strength in bending and for the variation in modulus of elasticity of the rope under pre-stressing, and a comparative summary is given of stresses and strengths as observed and as computed by several formulas.

Introduction

Since wire ropes were first produced in the early part of the Nineteenth Century, with a view to obtaining high strength combined with flexibility over sheaves, the question of the stresses set up by bending them has been a subject of sharp controversy. Literally dozens of formulas have been developed to evaluate this bending stress, most of them of an empirical nature, and each wire rope user, in the past, has given preference to one or another in
the light of his practical experience with ropes in service. In some cases, the formula was merely an expression of the results of a series of tests on specimens to determine the loss of strength over various sizes of sheaves, from which the bending stress could be evaluated in some measure. This has led recently to the expression of formulas for loss of strength in bending, which, in the end, is a more practical concept than that of the stresses to which this loss is due.

It was for the purpose of investigating the merits of these numerous bending formulas that this test program was originally conceived. Undoubtedly, there is a marked difference between the stress conditions in a stationary wire rope bent over a sheave and in one which is in rapid motion over the same sheave and possibly subjected to reverse bending as well. The scope of this investigation has been limited to a study of stationary ropes only, and while they hold admittedly a relatively minor place in wire-rope usage, the results may point the way to a clearer understanding of stress conditions in moving ropes as well as in stationary ones.

A program of tests of ropes over sheaves was planned accordingly, and a means devised for measuring the stress in any of the outer wires. For purposes of comparison a tension specimen of each type of rope was needed, and further stress observations were taken on these specimens. Because of the need in certain stress formulas for a value of the modulus of elasticity of the rope as a whole, numerous observations of this property were made, and this determination soon became one of the major branches of the investigation. Considerable data have been collected also on the untwisting effect in wire ropes under tension, on their shrinkage in diameter as their hemp centers are consolidated, and on the coefficient of friction between rope and sheave.

Notation.—The symbols used in this paper are summarized for reference in Appendix I.

THE PROBLEM

Review.—Probably the first and simplest formula that has been derived for the purpose of expressing the stress in a wire rope bent over a sheave was that of Reuleaux,

\[ s = E \frac{d}{D} \]  

(1)

which was derived from the expression for bending stress in a slightly curved beam, by substituting instead of the diameter of the rod acting as a beam, the diameter of one wire (presumably in the outer layer) used in the rope. D is the diameter of the sheave and E, the modulus of elasticity of the wire, generally assumed to be about 28,500,000 lb per sq in. This formula is given by the late Robert Charles Strachan, M. Am. Soc. C. E. (4), F. C. Carstarphen, M. Am. Soc. C. E. (1), and by numerous other writers.


\* For reference to figures in parentheses, see "Bibliography", Appendix II.
It was soon found that Equation (1) gave values of the stress which were far too high to be practicable, in many cases even exceeding the ultimate strength of the wire for small sheave sizes. Accordingly, attempts were made to modify the formula by empirical and semi-empirical means. Shortridge Hardesty, M. Am. Soc. C. E. (2), has derived the formula (4):

\[ s = E \frac{d}{D} \cos a \cos b \]  

in which \( a \) is the angle between a helical wire and the axis of the strand and \( b \) is the angle between a strand and the axis of the rope.

Mr. R. W. Chapman (5) modified Equation (2) by expressing the formula as:

\[ s = E \frac{d}{D} \cos^2 a \cos^2 b \]  

which gives values for the stress lower than those given by Equations (1) and (2).

B. R. Leffler, M. Am. Soc. C. E. (3) gives an empirical modification of this formula as adopted by the New York Central Railroad Company in 1928,

\[ s = \frac{2 Ed}{3 D} \cos^2 a \cos^2 b \]  

Mr. Carstarphen (1) makes mention of an empirical formula of even simpler form,

\[ s = 0.44 E \frac{d}{D} \]  

although it is not mentioned on what test results this formula is based.

All the preceding formulas have involved the use of the modulus of elasticity of the wire, and the tendency has been to reduce the abnormally high stress values by some coefficient. In 1918, Mr. James F. Howe (2) suggested that the proper value of \( E \) to use in a formula of the general type of Equations (1) to (5) was the modulus of elasticity of the rope as a whole, \( E_r \); thus,

\[ s = E_r \frac{d}{D} \]  

or, as it is often used,

\[ s = \frac{E_r d_r}{D + d_r} \]  

This formula gave values considerably lower than those of Equation (2) or Equation (3), when using a value of 12,000,000 lb per sq in. as the modulus of elasticity of the rope.

In 1933, Mr. Carstarphen (1) approached the problem from an analytical standpoint, and on the basis of a wire rope consisting of a double set of open-coiled helical springs, in turn bent around a constant radius, arrived at an expression for the loss of strength of a wire due to such bending:

\[ P = \frac{\pi (d)^4 E G}{16 R r_s [2 G (1 + \sin^2 a) + E \cos^2 a]} \]
in which \( P \) = loss of strength in a given wire; \( d \) = the diameter of a given wire; \( E \) = modulus of elasticity of a given wire; \( G \) = modulus of rigidity of a given wire, \( \left[ G = \frac{E}{2 (1 + \mu)} \right] \); \( \mu \) = Poisson's ratio; \( R \) = radius of a sheave, \( \left[ R = \frac{1}{2} (D + d_r) \right] \); \( r_r \) = radius from the center of the strand to the center of the wire in question; and, \( \alpha \) = the angle between the perpendicular to the axis of a rope and the tangent to the center line of the wire.

In Equation (8), when \( r_r = 0 \), substitute \( r_r \) which is defined as the radius from the center of a wire rope to the center wire of a strand.

The total loss of strength in a rope is equal to the value of \( P \) multiplied by the number of wires, or if the strand consists of a number of layers of different sized wires, a value of \( P \) must be computed for each layer and multiplied by the number of wires of that size in the layer. If a value of the bending stress were desired, this could presumably be obtained by dividing \( \Sigma P \) by the net area of steel in the rope. According to Mr. Carstarphen, Equation (8) "takes into account the diameter of the wires, the rope, the radius of curvature, the angle of lay, the modulus of elasticity in tension, and the modulus of rigidity." The test results reported in the same paper seemed to support this method of computing loss of strength.

Any of the preceding formulas, for bending stress, \( f \), may be adopted to give loss of strength, or ultimate strength in bending, \( S \), by inserting them in the general form of the equation:

\[
S = A (t - s) \varepsilon \text{ ........................................ (9)}
\]

in which \( A \) is the net area of steel in a wire rope; \( t \) is the ultimate unit tensile strength of a wire; and \( \varepsilon \) is the efficiency of the rope in plain tension. Equation (8) is given by C. D. Meals, Assoc. M. Am. Soc. C. E. (1), and others, using Equation (7) to determine a value for \( \varepsilon \). Mr. Meals further developed an equation for the strength of a wire rope in tension, from which the efficiency, \( \varepsilon \), might be computed:

\[
S_i = n_s \cos \beta \left( \sum_{i=1}^{n_w} S_i \cos \alpha_i \right) \text{ ........................................ (10)}
\]

in which \( n_s \) is the number of strands in a rope; \( n_w \) is the number of wires of a given diameter in the \( i \)th layer; \( S_i \) is the tensile strength of a wire in the \( i \)th layer; \( \alpha_i \) is the angle of pitch of the wires in the \( i \)th layer; and \( n_i \) is the number of layers of wires in a strand.

J. H. Griffith, M. Am. Soc. C. E., and Mr. J. E. Bragg (6) gave both Equation (9) and an empirical formula for tensile load based on the minimum results of tests, as:

\[
T = C \times 75000 \alpha_p \text{ ........................................ (11)}
\]
in which, $D$ is the diameter of the cable, in inches; and $C$ is a constant for various constructions (see Table 1).

**TABLE 1.—VALUES OF C FOR MEAN IN EQUATION (11)**

<table>
<thead>
<tr>
<th>Rope</th>
<th>Range</th>
<th>Mean*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From:</td>
<td></td>
</tr>
<tr>
<td>6×19 plow steel</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>8×19 plow steel</td>
<td>0.8</td>
<td>1.00</td>
</tr>
<tr>
<td>8×19 cast steel</td>
<td>0.8</td>
<td>1.00</td>
</tr>
<tr>
<td>6×42 tiller rope</td>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>6×7 guy rope</td>
<td>0.3</td>
<td>0.45</td>
</tr>
</tbody>
</table>

* Approximate.

On the assumption that slipping does not occur between the straight and curved wires, Mr. Carstarphen gave the following formula (1) for the tensile strength of a rope,

$$ S = \cos (a + b) A S_w $$

in which $S_w$ is the ultimate strength of the wire.

The foregoing equations for stresses and strengths in bending and in tension are only a few of the many that can be found in engineering literature. They were chosen as representative of current usage, and the range in values given by them demonstrates clearly the uncertainty that still exists as to the ultimate effect of bending stresses on the strength of a wire rope. Each of these formulas has been applied to the wire ropes used in this investigation, and a table of the results is included herein, under the heading, "Summary".

**The Present Investigation.**—The most logical manner in which to determine the bending stresses and loss of strength in wire ropes, seemed to be a series of tests on ropes on which the stresses could be measured by some standard extensometer. Fortunately, such equipment was available in the form of four tensometers that could be mounted on individual outer wires at different points around the sheave. From these readings unit strains were recorded directly, by multiplying by the predetermined constant for each instrument. To convert these values to unit stresses, it was necessary to draw, from auxiliary samples of the wires used, stress-strain curves for each size of outer wires encountered. From these curves the observed strains could then be transformed readily to their corresponding stress values, thus giving values of the stress in the outer wires at any point along a sheave or on a straight tension specimen.

This same principle is made use of time and time again in laboratory work on mild steel specimens, where extensometer readings of strain below the elastic limit are multiplied by 29,000,000 lb per sq in. in order to give the stress at these points. The difference lies in the fact that steel, such as is used in wire-rope manufacture, does not have a sharp, well-defined elastic limit since it is heat-treated, with the result that the stress-strain curve shows a proportional limit of about 40% of the ultimate strength. Furthermore, in
the tests to destruction, strains were recorded on the ropes in most cases to about 90% of the ultimate load, the uniformity of the stress-strain curves of the wire even at these high loads permitting such readings to be made with considerable accuracy.

On the tension tests, a means was sought to determine the modulus of elasticity of the rope as a whole, in addition to the stresses in individual outer wires. One of the most satisfactory methods in use in the past has been described by G. P. Boomsliter, M. Am. Soc. C. E. (8). He utilized an 8-in. strain-gauge set in holes on brass rings soldered to the rope. Considerable difficulty was encountered due to the untwisting effect of the rope under load, which caused errors in his readings. In order to adapt this method to the present tests, and to minimize such errors, it was decided to use a 10-in. strain-gauge, with holes located on $\frac{1}{4}$-in. square brass lugs, curved to fit the rope and soldered to it. In this manner, the tendency of the rig to tear away as the rope shrinks under load was eliminated. To compensate for twist, two scales reading to hundredths of an inch were placed 10 in. apart on the rope, and read with the vertical hair of a surveyor's transit; the proper corrections to the measured gauge lengths were then computed after the completion of the test. The stress-strain curve of the rope could then be drawn readily and the modulus of elasticity obtained in the usual manner.

The tests reported by Professor Boomsliter showed quite definitely that the modulus of elasticity of a wire rope, especially one with a hemp center, is a decidedly variable quantity, and tends to increase as the number of loadings increases and as the stress to which the rope is loaded each time is raised. In view of these results, it was decided to investigate more fully this property of wire ropes with hemp centers and to load each tension specimen seven times to approximately 50% of its ultimate load, taking readings on the first, third, fifth, and seventh loadings. As the tests proceeded, it was found advisable to observe also the second loading. All bending specimens were similarly loaded seven times before finally fracturing them, both to insure conditions similar to those in their companion tension specimens and to work the individual wires so as to equalize the stress in them, as indicated by the tensometer readings.

Program of Tests

Because of the large number of variables involved in an investigation of this nature, it was decided to restrict as many of them as possible, and to confine the study to a determination of basic relationships. For this reason, the size of the rope to be tested was set at 1 in., since this was the minimum on which the outer wires extended along the surface far enough to admit attaching a tensometer on a $\frac{1}{4}$-in. gauge length. Similarly, a rope with a hemp center was selected as being more typical than one with an independent wire rope center, and less likely to be confusing in any analysis.

The variables to be investigated were: (1) Sheave diameter; (2) construction; (3) lay; (4) preforming; and (5) grade of steel.
(1) **Sheave Diameter**.—Four values of $D$ were selected: 18 in., 14 in., 10 in., and 7 in., each measured at the root of the groove.

(2) **Construction**.—Ropes of both $6 \times 7$ and $6 \times 19$ construction were tested (see Fig. 1). The $6 \times 19$ ropes contained six filler wires of the same grade of steel as the main wires, added to give a smoother surface to the strand.

(3) **Lay**.—Both regular lay and Lang lay ropes were included (see Fig. 2). In regular lay ropes the angle of lay of the wire in the strand is equal and opposite to that of the strand in the rope, with the result that the outer wires lie parallel to the axis of the rope. In Lang lay construction, both wires and strands are twisted in the same direction. As the angle of lay was in all cases very close to $18\frac{1}{2}^\circ$, the outer wires in a Lang lay rope were inclined at $37^\circ$ to the axis of the rope.

(4) **Preforming**.—The process of manufacture by which both wires and strands are given an initial helical curvature as they are formed, is known as preforming. This process will be described in detail in succeeding paragraphs. Both preformed and non-preformed types were tested.

(5) **Grade of Steel**.—Most of the specimens tested were of cast steel, of the grade produced by almost all wire rope manufacturers, with a specified ultimate strength of 205,000 to 220,000 lb per sq in. A few tests were made for correlation on specimens of plow steel, with an ultimate strength of 235,000 to 250,000 lb per sq in.

**Specimens**.—Five specimens constituted a set. Of these, one was a tension specimen, 4 ft 6 in. long, and four were bending specimens, 7 ft long; for
the four sheave sizes. All the ropes were socketed by means of molten zinc in forged steel open sockets, and all the foregoing dimensions were taken from inside to inside of sockets. These sets were numbered as shown in Table 2.

TABLE 2.—Properties of Test Specimens (Hemp Center; $d_r = 1$ Inch).

<table>
<thead>
<tr>
<th>No. of set</th>
<th>Type</th>
<th>Lay</th>
<th>Forming</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cast steel</td>
<td>Regular</td>
<td>Non-preformed</td>
</tr>
<tr>
<td>2</td>
<td>Cast steel</td>
<td>Regular</td>
<td>Preformed</td>
</tr>
<tr>
<td>3</td>
<td>Cast steel</td>
<td>Lang</td>
<td>Non-preformed</td>
</tr>
<tr>
<td>4</td>
<td>Cast steel</td>
<td>Lang</td>
<td>Preformed</td>
</tr>
<tr>
<td>9</td>
<td>Cast steel</td>
<td>Regular</td>
<td>Non-preformed</td>
</tr>
<tr>
<td>10</td>
<td>Cast steel</td>
<td>Regular</td>
<td>Preformed</td>
</tr>
<tr>
<td>11</td>
<td>Cast steel</td>
<td>Lang</td>
<td>Non-preformed</td>
</tr>
<tr>
<td>12</td>
<td>Cast steel</td>
<td>Lang</td>
<td>Preformed</td>
</tr>
<tr>
<td>13</td>
<td>Plow steel</td>
<td>Regular</td>
<td>Non-preformed</td>
</tr>
</tbody>
</table>

For determining the physical properties of the wires which made up these ropes, tensile tests were made on ten samples of each size of wire entering each construction, both of cast and plow steel. These sizes were as shown in Table 3.

TABLE 3.—Sizes of Wires

<table>
<thead>
<tr>
<th>Construction</th>
<th>Number of wires in one round</th>
<th>Diameter, $d$, in inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6 \times 7$</td>
<td>One core wire</td>
<td>0.115</td>
</tr>
<tr>
<td></td>
<td>Six outer wires</td>
<td>0.105</td>
</tr>
<tr>
<td>$6 \times 19$</td>
<td>One core wire</td>
<td>0.073</td>
</tr>
<tr>
<td></td>
<td>Six intermediate wires</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>Six filler wires</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>Twelve outer wires</td>
<td>0.065</td>
</tr>
</tbody>
</table>

Observations were taken on these single wire specimens, of proportional limit, ultimate strength, modulus of elasticity, and location of fracture, and an average stress-strain curve was plotted for each size up to about 85% of the ultimate strength. Average values of these observations were used for determining the physical constants of the wire, and the probable error from this mean was noted.

MANUFACTURING PROCESSES

The various manufacturing processes and machines used in the production of wire and wire rope have been rather fully described elsewhere, notably by Messrs. Carstarphen (1) and Meals (1). The process is reduced essentially to three steps: First, the drawing and treating of the wire; second, the spinning of these wires into a strand of the desired size and construction; and, third, the closing of several strands around a hemp or wire rope center to form a wire rope. It is during this last step that the ropes are preformed, if so desired, so that the wires and strands are permanently deformed and lie in the finished rope with no tendency to unravel or kink.
Fig. 3 shows a large vertical closing machine at the point where six strands are drawn through a die over a lubricated hemp center to form a non-preformed, regular lay rope. The frame and die are held stationary, and the slotted cone and spools from which the strands are drawn rotate. In addition, the spools are given a planetary motion so that the strands are laid into the rope without any twist, and their lay is controlled by the speed with which the finished rope is withdrawn. For forming Lang lay rope, the frame is rotated in the reverse direction, and the spools given a back turn to minimize the untwisting effect.

The contrast between this method and that used in making preformed ropes is illustrated in Fig. 4. The frame and die are the same, but, in this case, the smooth cone is replaced by one on which are mounted three small sheaves for each strand. These sheaves are placed as shown in Fig. 4 and the strands threaded around them so that a helical permanent set is imparted to them. This set is noticeable in the section of the strands just as they enter the closing die. The proper position of the small sheaves must be determined very exactly in order that the helix will be of the exact size required for forming the desired rope. In preforming Lang lay ropes, these small sheaves are replaced by spiral holes through which the strands are drawn, in order to minimize the twisting action to which this type is subject.

TESTING APPARATUS

All specimens both in tension and in bending were tested in a 300,000-lb testing machine, which was calibrated to 200,000 lb and found to be correct within 0.25 per cent. For the tension tests, the sockets were passed through the holes in the two heads of the machine and secured by steel plates, in which 1\(\frac{3}{4}\) -in. holes had been drilled to receive the socket pins. Brass gauge points for the gauge were cut from a section of 1-in. brass pipe, and when properly cleaned with emery paper were soldered to the rope. In all cases except the first test, where six gauge lengths were provided, two gauge lengths were used, directly opposite each other at about the center of the specimen. By exercising proper care in soldering, only one of all the brass gauge points broke away in the course of testing, and the fracture of the rope was never traceable to the heat treatment of wires in the vicinity of the soldering operations. For measuring the twist, two paper scales graduated to 0.02 in., were affixed to one side of the cable, just under each gauge point, by rubber bands, and these scales were read to 0.01 in: on the vertical hair of a surveyor's transit set up on a near-by table. The gauge holes in the brass plugs were also aligned vertically with this transit when drilled.

The operation of attaching the tensometers proved to be the most difficult part of the tension set-up, as the ropes contracted appreciably under load, causing the gauges to become loose. However, after some experimentation, it was found that for regular lay ropes a pair of tensometers could be mounted opposite each other on a standard gauge-holder, and could be held in place
FIG. 3.—WIRE ROPE MACHINE FABRICATING A REGULAR LAY, NON-PREFORMED ROPE.

FIG. 4.—WIRE ROPE MACHINE MODIFIED FOR FABRICATING A REGULAR LAY, PREFORMED ROPE.
by connecting the far ends of the holder by a short strong spring. This arrangement gave consistently good readings even at very high loads. For Lang lay ropes this device could not be used, however, due to the fact that the outer wires lay at an angle of 37° to the axis of the cable. For this reason the two tensometers were mounted separately, on fittings especially built to hold the gauges at the required angle and allow some play as this angle changed under load. On many of the tension specimens measurements were taken of the diameter before loading and at nearly full load, with a pair of slide calipers, to determine the decrease in diameter under load.

The bending tests required the construction of a special testing rig shown in Fig. 5. The upper head of the testing machine was removed from its supporting columns, and across two of them was placed diagonally a framework consisting of two 15-in. channels, held vertically in place by \( \frac{1}{2} \) in. plates welded to their ends and separated by a slot 2\( \frac{1}{4} \) in. wide. At the middle of the top face of these channels were welded two semi-circular bearing blocks, cut to fit the 4-in. steel pin which served as an axle for the sheaves. This allowed the sheaves to pass through the slot between the channels, leaving the top half, over which the cable passed, free for the mounting of gauges. The lower ends of the rope passed downward through the slot and the sockets were held by pins in plates welded to a short section of reinforced H-beam. To the lower face of this beam was welded a vertical steel piece which, in turn, was gripped by the jaws of the testing machine. The sheave at all times was free to rotate on its pin and the pin in its bearing-blocks; and from the gauge readings it is believed that very nearly the same stress was developed in the rope on each side of the sheave at all times.

The four sheaves were machined from solid steel plates, 2 in. in thickness, and in accordance with modern practice, as noted by Mr. Meals (7), the grooves were made 1\( \frac{1}{16} \) in. in diameter, and semi-circular to facilitate measurements on the ropes. A 4-in. hole was cut in the center of each sheave, and carefully machined so that the steel axle could be inserted easily by hand which insured a snug fit.

It was decided to place the four tensometers available, one at the top of the sheave, one at the 45° point, and one at each tangent point, since a good average reading was required at the latter point because of the high stresses present. Several ideas were tried for holding the gauges in place and, at the same time, meeting the problems of shrinkage and sliding along the sheave due to tension. As finally arranged (see Fig. 6), the apparatus consisted of two slotted steel rings which were slipped over the axle on either side of the sheave. To these were attached short, stiff springs, and these, in turn, carried small turnbuckles and wire loops of varying length. Small rods were passed through the holes in the gauges, in the case of regular lay ropes, and slipped through these wire loops (Fig. 6). The gauges were held firmly in place by tightening the turnbuckles until there was an appreciable tension in the springs on either side, and the gauge was free to move slightly along the sheave as the rope stretched. Various combinations of length of springs and wire loops enabled this apparatus to be used on all four sheave sizes.
For the Lang lay ropes the rig used was identical except that special holders of welded construction had to be devised for keeping the gauges fixed at an angle of 37 degrees. Although it was a rather delicate matter to set up the gauges for a test, this apparatus gave consistently good results. In some cases, the gauge could not be set directly at the tangent points, as no strand came to the surface there, and in this case they were set on the next strand above the tangent point, the stretch causing them to pull down slightly during the test.

On all the regular lay ropes, an attempt was made to evaluate the bending stress by a plain bending test without tension. For this purpose an auxiliary rig was devised, consisting of a steel plate bolted fast in a horizontal position to a heavy table. In this plate were drilled holes into which steel pins could be inserted to simulate sheave diameters of 50, 25, 18, 14, 12, 10, 81/2, and 7 in. A space was left clear in the center to allow placing a pair of tensometers on the rope, one on the compression side and one on the tension side, and the rope was bent over these diameters in succession by hand, while readings were taken of the strains that occurred. This apparatus was inherently awkward, and only by averaging a great number of results could any definite trends be established. The rig was not adapted for Lang lay ropes, as the attachments necessary for holding the gauges in place would not fit in the space allowed.

Single wire tests for determining the stress-strain curve were made on a 2000-lb, hand-power testing machine, with specimens about 15 in. long.
DISCUSSION OF TEST DATA

The great mass of data taken during these tests does not permit the inclusion of all the test results. Accordingly, an attempt has been made to follow through the procedure in one particular typical instance, giving all the results and curves obtained; and to summarize the results in the form of curves for the remaining sets of ropes. Particular exceptions or variations from the typical results are noted and in some cases illustrated.

Tension Tests.—A typical set of curves was obtained in these tests on Set No. 2, a 1-in. 6 × 7 cast, regular lay, preformed rope. The strain readings on the rope as a whole, corrected for twist, have been plotted in Fig. 7 for the seventh loading. Similar curves were plotted for each of the preceding loadings in which the load was carried to only 35,000 lb, and the modulus of elasticity noted in each case. The first rope tested (Set No. 13) was arranged with three gauge lengths on each side. The center set showed values of the modulus about 3% greater than those at either end, and in the belief that this center value was more truly representative, only one pair of gauge lines, located at the center of the specimen, was used in all future tests.

![Figure 7: Load Strain Curve of 1-Inch, 6 × 7, Cast-Steel Regular Lay, Preformed Wire Rope; Seventh Loading; Net Area = 0.374 Inch².](image_url)

The reasons for the initial curvature of the load-strain curve, shown plainly in Fig. 7, are discussed by Messrs. Griffith and Bragg (6). Their conclusion is that at low loads the elongation under stress is not wholly elastic,
due to the presence of initial curvature in the strands and wires from the laying and a certain "slack" or curvature in the rope itself.

Fig. 8 presents curves showing the rise in modulus of elasticity with repeated loadings for all sets of ropes tested (see Table 2). The sharp initial rise in all these curves after the first loading is due to the large initial consolidation of the hemp center, and the compacting of the wires and strands. It will be noted that, in general, the $6 \times 7$ ropes (Sets Nos. 1 to 4) show values greater than the $6 \times 19$ construction. Furthermore, the Lang lay ropes (Sets Nos. 3, 4, 11, and 12) show a slightly higher modulus than the regular lay ropes, and the preformed ropes (Sets Nos. 2, 4, 10, and 12) seem to run higher than the non-preformed types. The one plow-steel specimen (Set No. 13) had a slightly higher modulus than its companion cast-steel rope.

![Figure 8: Variation in Modulus of Elasticity of Wire Ropes with Repeated Loadings](image)

The 1-in., $6 \times 19$ cast, Lang lay, non-preformed rope (Set No. 11) was tested for seven loadings to 10,000 lb (14% of the ultimate load), with a view to determining whether the same increase in modulus occurred at working loads as at relatively high loads. The seventh loading was then continued to 35,000 lb, or 49% of the ultimate, which was repeated until the eleventh loading, when the test was carried to destruction. Fig. 8 shows that at working loads a rise in modulus of elasticity does occur, but that the values are...
much lower than when the load is increased to about the proportional limit. This is explained by the fact that at these low loads the stress-strain curve was still concave upward. The value selected as the modulus in such cases was the slope of the tangent to the curve at the maximum load. In every case, the slope was less than that found when the load was further increased, indicating quite definitely that the rope had not yet, at the low loads, reached a period of elastic behavior.

For the tension test of Set No. 2, Fig. 9 shows the load-strain curves for the average of two individual wires, as shown by the tensometers, for each loading. On the first loading, both gauges ran off the scale early in the test, but succeeding loadings show the wires to be taking stress in a very uniform manner. It is evident that the first loading tends to redistribute and equalize the stress in the several wires and further loadings bring the rope to an almost perfectly elastic state as regards these stresses. The fact that the curve for the seventh loading breaks away at exactly 35,000 lb is indicative that the proportional limit of some of the wires had been passed on preceding loadings, and that these had become slightly strain-hardened and the proportional limit raised accordingly.

The strains for the seventh loading (Fig. 9) were transformed into stresses as explained previously by use of a stress-strain curve for the single wire. Fig. 10 shows the stress-strain relations for this particular size of wire, 0.105 in. in diameter, cast steel.
The results of this transformation are expressed in the form of a load-stress curve, as shown in Fig. 11(a). It will be noted that up to the proportional limit the curve follows very closely the dotted line representing the load divided by the net area of steel, which is the curve for a homogeneous bar of the same area of cross-section. Beyond this point there is a reverse curve (although this is not present in every case). When extrapolated to a value of the load equal to the observed ultimate load on the rope, this reverse curve shows a stress value of 219,500 lb per sq in., which checks very closely the average single-wire strength for this grade, namely, 219,000 lb per sq in. As always, in extrapolating curves, there is a chance for error, but as every curve showed this ultimate stress to be close to 219,000 lb per sq in., these load-stress curves seem to be well established.

The curve in Fig. 11(a) is typical of all those obtained on regular lay ropes. On Lang lay ropes, a different kind of curve was obtained, as is illustrated by Fig. 11(b), for 1-in., 6 x 19 cast-steel, Lang lay, preformed rope. In this case the stress in the outer wires is considerably lessened, and falls well below the dotted line for load divided by net area for the greater part of the test, but picks up rapidly at the end. In the case of Fig. 11(b), the stress below the proportional limit is 0.803 times that given by the dotted line, which may be assumed to be that for the regular lay rope. Theoretically, this factor should be \( \cos 37^\circ \), or 0.799, since the outer wires are inclined at 37\(^\circ\) to the axis of the rope. The average value of this ratio for all the Lang lay ropes tested was 0.783, and this agreement is within the limits of experimental error.

The difference in load-stress curves for the tension tests of preformed and non-preformed ropes is obscured by the incidental variations of each test. There seems to be no appreciable difference in the stress conditions for the two cases when loaded up to seven times, although some tendency for a quicker equalization of stress in the individual wires has been noted for the preformed type. The 6 x 7 ropes show a less steep load-stress curve than those of the 6 x 19 construction, indicating the presence of higher stresses, but this increase is in inverse proportion to the net area of section, and the foregoing facts are modified only in this proportion.
A summary of the untwisting effect observed for every rope is presented in Table 4. The values given are in inches of circumferential twist in a 10-in. gauge length, and the load to which each loading was taken is also recorded.

These values show the decrease in twist with repeated loadings and are useful for purposes of comparison. The preformed ropes (Sets Nos. 2, 4, and 10) in general show less twist than the non-preformed ropes, with the exception of Set No. 10, which is about the same as Set No. 9. The Lang lay ropes

![Graph](image-url)

**Fig. 11.—Load Stress for Tension Test; 1-Inch, Cast-Steel Wire Rope, Preformed.**

**Table 4.—Inches of Circumferential Twist in 10-Inch Gauge Length**

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Load, in thousands of pounds</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
<th>Seventh</th>
<th>Eighth</th>
<th>Ninth</th>
<th>Tenth</th>
<th>Eleventh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>0.11</td>
<td>0.09</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>60</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>37.5</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>0.09</td>
<td>0.07</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>60</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>0.03</td>
<td>0.01</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
<td>37.5</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>35</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>60</td>
<td>0.08</td>
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<td>6</td>
<td>35</td>
<td>0.09</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>37.5</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>40</td>
<td>0.15</td>
<td>0.07</td>
<td>0.05</td>
<td>0.08</td>
<td>0.08</td>
<td>60</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8</td>
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<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>37.5</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>40</td>
<td>0.06</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>60</td>
<td>0.09</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>0.09</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>65</td>
<td>0.07</td>
<td></td>
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<td>65</td>
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<tr>
<td>11</td>
<td>50</td>
<td>0.14</td>
<td>0.05</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>64</td>
<td>0.10</td>
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<td>10</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>0.06</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>65</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>13</td>
<td>50</td>
<td>0.14</td>
<td>0.08</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>64</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
BEHAVIOR OF STATIONARY WIRE ROPEs

(Sets Nos. 3, 4, 11, and 12) do not show any greater untwisting than regular lay ropes; in fact, Set No. 12 shows much less twist than its companion specimen, Set No. 10. It must be remembered, however, that the ends of these specimens were totally fixed against rotation under load, by the frictional forces acting on the heads of the testing machine. Ropes of 6 X 7 construction (Sets Nos. 1, 2, 3, and 4) seem to untwist about as much as those of the 6 X 19 construction.

Data on the shrinkage of wire ropes due to consolidation of the hemp center are available for most of the specimens tested. These data are assembled in Table 5, the diameters being recorded to the nearest 0.01 in., and show that a rope will acquire a permanent decrease in diameter of 1% to 2% when loaded to 50% of its ultimate load, and that the total decrease at fracture is about 5 to 6% of the original diameter.

**TABLE 5.—DECREASE IN DIAMETER (INCHES) OF ROPES UNDER LOAD**

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Average original</th>
<th>At beginning of final loading</th>
<th>During final loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.01</td>
<td>0.98</td>
<td>60 000</td>
</tr>
<tr>
<td>2</td>
<td>1.02</td>
<td>0.98</td>
<td>67 500</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.98</td>
<td>62 500</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>0.98</td>
<td>60 000</td>
</tr>
<tr>
<td>5</td>
<td>1.02</td>
<td>0.98</td>
<td>68 000</td>
</tr>
<tr>
<td>11</td>
<td>1.02</td>
<td>1.01</td>
<td>65 000</td>
</tr>
<tr>
<td>12</td>
<td>1.04</td>
<td>1.02</td>
<td>65 000</td>
</tr>
</tbody>
</table>

The efficiency of a wire rope in tension is its ultimate load divided by the product of the net area by the ultimate strength of the wire, the denominator being the theoretical maximum load that a homogeneous rod could attain. Values of the efficiencies obtained in these tests are tabulated in the “Summary”.

**Bending Tests.**—Set No. 1 (Table 2), has been selected as typical of the bending test results obtained. Observations were made of the strains at the top of the sheave for the first, third, and fifth loadings, and of the strains at the top, 45° point, and the two tangent points for the seventh loading to destruction. The load-strain curves for these loadings of the specimen bent over the 18-in. sheave, are shown in Fig. 12(a); very similar curves were obtained over the other three sheave sizes. The friction effect on stress at the top of the sheave is well illustrated by the curves for the first, third, and fifth loadings. As all the stresses are below the proportional limit, these are also load-stress curves to another scale. Upon release of the load, the stress at the top point remained constant until the friction load caused by stretching the cable decreased to zero, and built up until slipping occurred along the sheave in the reverse direction. Thus, this drop is a measure of twice the frictional force present. According to the foregoing reasoning, the values of strain at the tangent points should follow back the original curve as the load is removed, with no hysteresis, and this has been found to be the case. On practically every one of the Lang lay ropes, an initial compression was observed on the first loading, which is evidently due to poor initial stress distribution inherent in this type of construction.
The transfer of strain values to stresses as described for the tension test was made for the seventh loading of Fig. 12(a), giving the set of load-stress curves shown in Fig. 12(b). These curves show very definitely that the maximum stress lies at the tangent point, where the rope meets the sheave; and that the stress decreases progressively up and around the sheave, due to the increasing frictional forces present, to a minimum value at the top. The coefficient of friction of rope on the sheave was determined in each instance by the formula:

$$\frac{S_0}{S_p} = \tan^2 \phi$$  

(13)

Two values of the stress ratio for each sheave size were taken from the load-stress curves, one at the proportional limit and one near the ultimate load; in most cases these values were in reasonable agreement. The values of $f$ for all four sheave sizes of each set were then averaged, with the results shown in Table 6. The average values for regular lay ropes is about 0.14, and for Lang lay ropes the value is raised to 0.28, due to the fact that the inclined wires on the surface offer much greater resistance to slippage than the wires of regular lay construction, which are parallel to the direction of motion.

In eleven cases out of the thirty-six bending tests, the load-stress curve for the 45° point at the lower loads fell to the left of the curve for the top point, indicating a lower stress to be present. It seems likely that the stresses at the top and at the 45° point for low loads are not very different, and that differences in the individual wires on which the gauges were set account

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for this seeming inconsistency. It might be noted that in every case where this occurred, the curves crossed and showed higher stress at the 45° point before the gauges were removed from the rope prior to failure.

**TABLE 6.—COEFFICIENT OF FRICTION**

<table>
<thead>
<tr>
<th>Set No. (see Table 2):</th>
<th>Coefficient, ( f )</th>
<th>Average Coefficient, ( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.146</td>
<td>0.432</td>
</tr>
<tr>
<td>2</td>
<td>0.156</td>
<td>0.344</td>
</tr>
<tr>
<td>9</td>
<td>0.101</td>
<td>0.392</td>
</tr>
<tr>
<td>10</td>
<td>0.149</td>
<td>0.348</td>
</tr>
<tr>
<td>13</td>
<td>0.133</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.137</td>
<td>0.379</td>
</tr>
</tbody>
</table>

The Lang lay ropes showed load-strain and load-stress curves similar in form to the specimens of regular lay ropes. These curves, as in the tension test, lie to the left of the corresponding curves for regular lay rope, and show
on an average 80% of the stress values. Again, the difference between stress conditions in preformed and non-preformed ropes was not marked after seven loadings, and the $6 \times 7$ ropes showed stresses higher than the $6 \times 19$ ropes in inverse proportion to their net areas. The plow-steel specimens showed exactly similar effects, with loads and stresses raised in proportion to the ultimate strengths of the single wires.

The manner in which the bending specimens failed supports the observations drawn from the preceding curves that the greatest stress occurs at the tangent points. With a very few exceptions, all bending specimens failed at one of the tangent points. The only exceptions were those that failed at the socket, which failure occurred for only two specimens of Set No. 12. This fact is demonstrated clearly in Fig. 13, which also illustrates the difference in the type of failure of preformed and non-preformed ropes. Fig. 13(a) shows Set No. 9, non-preformed, while Fig. 13(b) shows Set No. 2, preformed, after fracture of each rope. The scattering of the wires in the non-preformed rope and the relatively little disintegration of the preformed type, are distinctly shown. This effect was noticeable in both the $6 \times 7$ and the $6 \times 19$ constructions, although to a greater extent in the latter. The decrease in strength as the sheave size decreases, is demonstrated by the ultimate loads in Fig. 13.

All the ropes of $6 \times 19$ construction failed gradually, snapping wires being heard in the interior of the specimen at loads considerably below the ultimate, in some cases as much as 10 per cent. The $6 \times 7$ ropes, however, contained only one core wire to a strand, of quite large diameter, and these ropes failed suddenly with little or no warning. In general, two to four strands were broken, and in only one instance were all six strands of the rope broken simultaneously.

The striking similarity between the curves for stress at the tangent point over all four sheave sizes and the corresponding
curve for the tension test, led to the plotting of these values for Set No. 1 on the same co-ordinates, as shown in Fig. 14. All the curves are seen to coincide within the range of experimental errors, and this was found to be the case for all the ropes tested, although the agreement was not so perfect for the Lang lay ropes. This demonstrates that the bending stress is not increased after the rope is initially bent over the sheave, but that thereafter the rope behaves exactly as in a tension test. Bending over a given sheave, therefore, is equivalent to shifting the curve of Fig. 14 to the right by a constant amount, thus causing the curves to intersect the vertical line representing their ultimate strength at successively lower values of the load as the bending stress increases. This fact served as a basis for a graphical determination of the bending stress, by extrapolating the load-stress curve to the breaking load and subtracting the stress there observed from the known ultimate strength of 219,000 lb per sq in. Although this method is admittedly crude, its accuracy in determining bending stress may be judged from the values recorded in the table on correlation of bending stress formulas, given in the "Summary".

The shape of the load-stress curve in all cases is essentially the same. One would normally expect this to be a straight line for a homogeneous material, but in a composite body, such as a wire rope, opportunity is given for some wires to yield more than others and thus to redistribute the stresses in a strand. An explanation of the observed fact that beyond the proportional limit the outer wires take more than their proportional share of the stress, as shown by the breaking away of the curves to the right of a straight line, is found in a theoretical analysis of stress distribution in a strand, presented by Messrs. Griffith and Bragg (6). They showed that the stress in a wire of a given ring is directly proportional to \( \cos^4 a_n \), in which \( a_n \) is the angle of lay of the wires in the strand. The ratio of stress in the outer wire to stress in the core wire, therefore, should be 0.899, below the proportional limit. When the inner wire or wires reach this point, they begin to yield first, and this ratio will rise, approaching unity as a maximum, until theoretically at fracture the stress in all wires should be equal. Actually, certain weaker inner wires will fail before this condition is realized. This theory is supported by the experimental observations that on 6 × 19 ropes snapping, wires were invariably heard in the interior of the specimen at loads well below the ultimate.

For illustration an exaggerated condition was chosen, in which the strain in the outer wire was assumed as 0.74 times the strain in the core wire. Proper values of the stress were then selected from a typical wire stress-strain diagram, and these were plotted against percentage of total load, as shown in Fig. 15, together with the average stress curve, which is a straight line, as would be expected. The similarity of the curve marked "Outer Wire" to the observed load-stress curves is notable, and for comparison there has been included on this plot the results of the tension test of the 1-in., 6 × 19 cast-steel, regular lay, preformed specimen. It is evident that the assumption that the outer wire takes 74% of the stress in the core wire, below the proportional limit, was none too extreme.
The results of the plain bending test without tension, in which the regular lay ropes were bent by hand over steel pins, are represented typically by Fig. 16, for 1-in., cast-steel, non-preformed ropes of $6 \times 7$ and $6 \times 19$ construction. Each point is the average of two readings on each of four ropes, a total of eight readings. These curves are interesting in that they show that the stress on both the tension and the compression sides of the rope increases nearly linearly with the ratio of rope diameter to sheave diameter at the root. Although in every case the compressive stress exceeds the tensile stress, this is of little importance, as the addition of direct stress in the form of a pull will decrease this stress and soon bring these wires into tension as well. When these strains are transformed into stresses, another value is obtained for the bending stress, and these results have also been listed in tabular form in the “Summary”. The values for the $6 \times 7$ ropes were much higher than those for the $6 \times 19$ construction, and the method broke down completely for these values. However, the trend is notable, and as will be shown subsequently, the loss of strength of a rope varies in exactly this manner with the ratio of rope diameter to sheave diameter.

A summary is presented in Fig. 17 of the loss in strength in bending plotted against the ratio of rope diameter to sheave diameter for every set of ropes tested. A curve presented by Mr. A. S. Raideren (1) for tests on 5-in., $6 \times 19$ plow-steel, regular lay, non-preformed ropes, is also included with the reciprocal of his ordinate scale used in this case. It is believed that by inverting this ratio (thus converting a hyperbolic curve into a straight line), the curve may be fitted much more easily to a number of fairly erratic points, as the origin is fixed and only one degree of freedom is allowed in locating the curve. The curved relationship shown for some of the sets may very well
be due to an inaccurate value for the tension test, which affects all the points, and is equivalent to shifting the curve up or down. Such a shift has been made in the case of Set No. 11, where the tension specimen failed at the socket at a load of 71,650 lb, without developing its full strength. This load was so low as to indicate an actual increase in strength over the 18-in. and 14-in. sheaves, and in view of the relationships amply demonstrated in the other ropes, the value has been raised to 75,000 lb by shifting the straight line to pass through the origin, and the loss in strength computed on this basis. The short arrows on this plot serve merely to identify each point with its proper curve, and do not indicate that the point itself has been moved.

It may readily be seen that the non-preformed ropes show a greater loss in strength in every case than the preformed types. Similarly, in all but one instance, the Lang lay ropes show less loss in strength than their corresponding specimens of regular lay, due to the lower bending stresses present. There seems to be very little difference between the results for the 6 × 7 and 6 × 19 constructions and for the cast and plow grades of steel, when the loss is considered on a percentage basis. Considerably more data are needed, however, before any definite conclusions can be reached on these points.

A third method used in determining the bending stress in the rope is to divide the loss in strength by the product of net area and efficiency in tension, the denominator being the effective net area resisting bending. The results are shown in the "Summary".

**Single-Wire Test Data.**—A summary of test data on the various specimens of single wire tested is given in Table 7. On the basis of these results, an average ultimate strength of cast steel used in these ropes was selected as 219,000 lb per sq in., and for plow steel as 246,500 lb per sq in. A modulus of elasticity of 26,500,000 lb per sq in. was selected as characteristic of both the cast-steel and plow-steel specimens. Fig. 10 is an example of the average stress-strain relation for the ten samples of cast-steel wire 0.105 in. in
As an example of the consistency of these data, for the plow-steel specimens all had ultimate strengths within 3.2% of the average value, whereas 95% had values of modulus of elasticity within 7% of the average.

The cast steel showed similar consistency with minor exceptions, notably the modulus values for the specimens 0.115 in. in diameter. Although the diameters of all test specimens were measured to 0.0001 in., the nominal diameters were used in computing net areas in all further calculations, on the basis that they represented an average condition of manufacture.

### Significance of Results

The most significant results of the tension tests on the various wire ropes studied are contained in the plots for increase in the modulus of elasticity of the rope as a whole with repeated loadings. In the past a value of 12 000 000 lb per sq in. has often been considered the maximum modulus that a wire rope would attain, and this value has frequently been termed conservative when used in bending stress formulas. From the data presented herein it may be noted that one excessive loading up to about 50% of the ultimate load will raise the modulus frequently greater than 14 000 000 lb per sq in., and even with working loads as low as 14% of the ultimate, a definite increase in modulus occurs, although it is probable that the value would never reach as high a figure as when overloaded once. For running ropes, it is considered

### TABLE 7—Single-Wire Test Data

<table>
<thead>
<tr>
<th>Set No</th>
<th>Nominal diameter, in inches</th>
<th>No. of specimens</th>
<th>Average diameter, in inches</th>
<th>Average area, in square inches</th>
<th>Average modulus of elasticity, in pounds per square inch</th>
<th>Average proportional limit, in pounds per square inch</th>
<th>Average ultimate strength, in pounds per square inch</th>
<th>Proportional limit + ultimate strength (percentages)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Wires Used in 6x7 Cast-Steel Wire Ropes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.105</td>
<td>10</td>
<td>0.1043</td>
<td>0.005844</td>
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<td>0.010243</td>
<td>25 910 000</td>
<td>53 900</td>
<td>220 200</td>
<td>24.5</td>
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<td>Average</td>
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<td></td>
<td></td>
<td></td>
<td>217 800</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>(b) Wires Used in 6x19 Cast-Steel Wire Ropes</td>
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<tr>
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desirable to have a fairly low modulus, so that the rope can "give" and absorb some of the shocks of sudden starting, whereas for stationary installations the reverse is true. In the case of suspender cables and guy-work for which accurate lengths are needed, the value of several pre-stressings to a fairly high load may be seen very plainly. This procedure has been followed in the past, and values for the modulus greater than 19,000,000 lb per sq in. have been obtained on large suspender cables for suspension bridges.

Of equal significance are the load-stress curves for both tension and bending over sheaves. It has been shown that the bending stress is not increased after the rope is once bent over a sheave, and that thereafter the rope at the tangent point behaves as if it were in pure tension. The point of maximum stress has been shown to be at the tangent point, falling off to a minimum at the top of the sheave due to the frictional forces acting. Probably the true point of maximum stress is just slightly above the tangent point, since it takes a short distance for the bending stresses to come into action and the frictional losses are low at this point. The stress distribution in the strand itself has been pointed out, and indications are that the inner wires take considerably higher stresses than the outer wires at ordinary working loads. The beneficial effect of Lang lay rope in reducing stresses in the wires both in tension and in bending is notable, the reduction being proportional to the cosine of the angle which the surface wires make with the axis of the rope, in this case, 37 degrees. A disadvantage of this type of cable, however, lies in its greater tendency to kink and untwist, and the ends should always be rigidly fixed against rotation.

None of the formulas dealing with wire ropes takes preforming into account. It is significant that for the ropes tested the summary of ultimate loads which follows shows that the preformed ropes are about 4% to 5% weaker in straight tension due to the process of manufacture. However, they are shown to develop less loss of strength due to bending, in some instances by quite appreciable amounts. The initial stress distribution among the individual wires of a preformed rope does not seem to be greatly improved over a non-preformed rope, but there is some tendency for re-adjustment and equalization of stress to occur more quickly in a preformed specimen. The modulus of elasticity of the preformed ropes seems to run slightly higher than that of the non-preformed types. The chief advantages to the use of preformed ropes seems to be the ease in handling, cutting, and splicing them, the elimination of kinking to a large extent, and the manner in which they tend to remain closed when several wires are broken rather than bristling with jagged ends.

The curves for loss of strength over sheaves are of primary importance, and a new and simpler method of plotting these curves has been shown. The various features of these curves have been discussed previously, but it is worth noting here that Mr. Rairden's (1) curve based on tests of 1/8-in. wire ropes does not agree with the results herein obtained, although a ratio of the diameters has been used. This leads to the speculation that possibly the ratio of rope to sheave diameter may not be the proper one to use in such a
plot, and indicates the need of further experimentation on ropes of different diameters to discover whether results on one diameter can be transformed to another diameter by a simple ratio.

**Summary**

Three tables are presented to summarize the wire-rope test results and the formulas with which they were compared. The first, Table 8, presents seven bending-stress formulas, and observed values obtained in most cases by three

**TABLE 8.—SUMMARY OF BENDING-STRESS FORMULAS (ALL STRESSES IN THOUSANDS OF POUNDS PER SQUARE INCH)**

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Equation (1)</th>
<th>Equation (2)</th>
<th>Equation (3)</th>
<th>Equation (4)</th>
<th>Equation (5)</th>
<th>Equation (6)</th>
<th>Equation (7)</th>
<th>Equation (8)</th>
<th>Loss of strength divided by ( A_k )</th>
<th>From load-stress curve at breaking point (tensile values)</th>
<th>From plain bending test (tensile values)</th>
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</table>

*On basis of ultimate load in tension of 75 000 lb. †Fractured at socket.
different methods, as explained previously. Values that are underlined exceed the ultimate strength of the wire, even with no tensile load applied. The second, Table 9, summarizes the observed values of ultimate load and efficiency in tension as well as those predicted by the three formulas. The third, Table 10, presents similar predicted values of the ultimate load in bending over each of the four sheave sizes by two formulas, and the observed values for comparison.

**TABLE 9.—SUMMARY OF PREDICTED AND OBSERVED VALUES OF ULTIMATE LOAD IN TENSION**

<table>
<thead>
<tr>
<th>Set No. (see Table 2):</th>
<th>Equation (10)</th>
<th>Equation (11)</th>
<th>Equation (12)</th>
<th>Observed load, in pounds</th>
<th>Values, efficient (percentage)</th>
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<td>Load, in pounds</td>
<td>Efficient (percentage)</td>
<td>Load, in pounds</td>
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<td>75 000</td>
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</tr>
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</table>

* Using $C = 0.86$ for 6x19 east-steel ropes.

† Values should be 75 000 lb and 82.1% efficient as explained in test.

Which of the three observed values of bending stress is the most nearly correct is a doubtful question. From the foregoing discussion, the limitations of the plain bending test without tension and the method of extrapolating the load-stress curve to the breaking point are apparent, and the most logical method seems to be the first one presented in Table 8 Column (9)—that of dividing the loss of strength by the product of net area and efficiency in tension. Either on this basis or by striking an average of all three methods, one must exclude all the formulas except Equation (8) as giving values too conservative for use on stationary ropes. Although Equation (8) frequently does not come very close to the observed values, in view of the doubt as to
the accuracy of these latter values, the discrepancy is not nearly as large as for any of the other formulas, and Equation (8), although unwieldy, gives results most comparable with the test data.

For the tension test predictions (Table 9), Equation (11) is admittedly based on minimum values, which are low. Equation (10) gives values that are in most cases slightly too high, whereas Equation (12) fits the test data very well on the average. According to this latter formula, all the ropes tested should show efficiencies of 79.9%, whereas the average for the seven ropes was 80.6 per cent. One factor, however, which the equation does not take into account is the slight loss of strength due to preforming.

Ultimate loads in bending could be predicted for any of the formulas listed in Table 8, but the last two only have been selected as giving possibly reasonable values. Mr. Meals states (1) that for his formula (a modification of Mr. Leffler's formula), the error is a maximum for the lower ratios of \( \frac{D}{d} \). This statement is fully confirmed and values of ultimate load over the 7-in. sheave are far too low, in two cases even being a minus quantity. For large-sized sheaves as recommended in modern practice, Equation (10) tends to approach the observed values, but is consistently conservative. Equation (12), from which the expression for bending stress was derived, might be expected to give equally good predictions for strength, and observation will disclose that predictions based on this formula vary from the observed values in no case by more than 14%, in this case on the safe side. The average error on the unsafe side in only 2.5% and on the safe side, 4.5 per cent.

It should be remarked that all the formulas that have been found herein to vary from the observed data, have varied on the safe side, and that those which best fit the data vary sometimes on the safe side, but almost as often on the unsafe side, although the percentage error is very small in comparison with all the other formulas. Undoubtedly, velocity and reverse bending affect the ultimate load and the bending stress adversely, and until more tests are made of wire rope in motion under load, it is preferable on such installations to err on the safe side in stress computations.

**Conclusions**

From a study of the data obtained in this investigation, the following conclusions have been drawn, applying to stationary wire ropes with hemp centers in tension and in bending over sheaves:

1. The modulus of elasticity of a rope as a whole was increased about 50% by one loading to 50% of the ultimate load, and continued to rise slowly upon further repetitions of the load. Even for ordinary working loads such a rise took place, but the values for modulus were only from 60 to 70% of the values when overloaded by pre-stressing.

2. For tension tests of regular lay ropes below the proportional limit of the wires, the stress in the outer wires coincided very closely with that obtained by dividing the load by the net area of cross-section.

3. The variation in stress with load for ropes bent over sheaves was exactly the same as for the same ropes in tension, except that a definite
bending stress, the magnitude of which depended on the sheave size, was added at the time of bending, and this did not vary as the load increased.

(4) The maximum stress in a wire rope bent over a sheave occurred at or immediately above the point of tangency to the sheave, and the rope might be expected to fracture at this point. The minimum stress in the rope occurred at the top of the sheave.

(5) Initial fracture in ropes of $6 \times 19$ construction, and probably also in the case of those of $6 \times 7$ construction occurred in the interior wires of the strands, the stress in the core wire being always greater than that in the outer wires up to the point of initial fracture.

(6) The percentage loss of strength of a rope bent over a sheave varied linearly with the ratio of rope diameter to sheave diameter at the root.

(7) The coefficient of friction of a regular lay rope on a steel sheave was roughly 0.14, and of a Lang lay rope, roughly, 0.38.

(8) The stresses in the outer wires of a Lang lay rope were reduced in proportion to the cosine of the angle of inclination with the axis of the rope, a reduction of very nearly 20% for ordinary construction.

(9) A preformed rope showed less loss of strength in bending over sheaves, but also about 5% lower tensile strength and efficiency than a non-preformed rope.

(10) The most satisfactory formulas found for the prediction of bending stress, tensile strength, and loss of strength due to bending, were those presented by Mr. Carstarphen (1).

Acknowledgments

The testing program was conducted as a co-operative investigation with the Wickwire Spencer Steel Company, which Company furnished all the wire ropes tested and fitted the sockets. The tests were made in the Fritz Engineering Laboratory of Lehigh University, at Bethlehem, Pa., between November 1934, and May, 1935. The writer is indebted to Messrs. A. S. Rairden and Carl King, of the Wickwire Spencer Steel Company, for their valuable aid and suggestions, and to Inge Lyse, M. Am. Soc. C. E., Research Associate Professor of Engineering Materials, for his aid in supervising the tests and interpreting the results. Acknowledgment is also made to the members of the Laboratory Research Staff who have assisted materially in the conducting of these tests. A number of the illustrations used have been loaned by Mr. Rairden.

APPENDIX I

Notation

The symbols used in this paper are defined as follows:

$$a = \text{angle that a helical wire makes with the axis of the strand; }$$
$$a_4 = \text{Angle } a \text{ of the wires in the } i\text{th layer; } a_n = \text{angle of lay of Wire No. } n;$$
BEHAVIOR OF STATIONARY WIRE ROPES

\( b \) = angle that a strand makes with the axis of the rope;
\( d \) = diameter of a wire in a rope; \( d_r \) = diameter of a wire rope;
\( e \) = base of Naperian logarithms;
\( f \) = coefficient of friction;
\( g \) = a subscript denoting "at the point of tangency";
\( i \) = a subscript denoting the ith layer of strands in a rope;
\( l \) = a subscript denoting "layers";
\( n \) = number; \( n_s \) = number of strands in a rope; \( n_w \) = number of wires in a given diameter in the ith layer; \( n_l \) = number of layers of wires in a strand; as a subscript, \( n \) denotes "number";
\( p \) = a subscript denoting "at the top";
\( r \) = radius of a wire in a rope; \( r_s \) = radius from the center of the strand to the center of the wire in question; \( r_r \) = radius from the center of a wire rope to the center wire of a strand; as a subscript, \( r \) denotes "rope";
\( s \) = unit bending stress; as a subscript, \( s \) denotes "strand";
\( t \) = ultimate unit tensile strength of a wire; as a subscript, \( t \) denotes "tension";
\( w \) = a subscript denoting "wire";
\( A \) = area of a wire rope;
\( C \) = a constant representing a relation between the total tension on a wire rope, and its diameter, for various constructions;
\( D \) = diameter of sheave;
\( E \) = modulus of elasticity of a wire in a rope; \( E_r \) = modulus of elasticity of a wire rope;
\( G \) = modulus of rigidity in a rope = \( \frac{E}{2} (1 + \mu) \);
\( P \) = loss of strength in a wire due to bending;
\( R \) = radius of a sheave = \( \frac{1}{2} (D + d_r) \);
\( S \) = ultimate strength of a wire rope in bending; \( S_i \) = strength of a wire in the ith layer; \( S_t \) = strength of a wire rope in tension; \( S_w \) = ultimate strength of a wire;
\( \alpha \) = angle between the perpendicular to the axis of a rope and the tangent to the center line of a wire;
\( \epsilon \) = efficiency of a rope in plain tension;
\( \mu \) = Poisson's ratio.

APPENDIX II

BIBLIOGRAPHY


C. D. Meals,* Assoc. M. Am. Soc. C. E. (by letter).—Another “link in the chain” has been wrought by Mr. Stewart in his splendid paper pertaining to the strength of stationary wire ropes looped over sheaves. Of the bending stress formulas, Equations (1) to (7) inclusive, it may be noted that Chapman’s (5)* formula antedated Hardesty’s (2)* formula; the former was published in 1908 and the latter in 1918; consequently, it should not be implied that Chapman modified Equation (3).

Equation (5) was developed by Josef Hrabak† and published in 1902. Hrabak’s writings on the subject are frequently ignored, and yet he presented the first logical theory on the subject as compared to the Reuleaux formula in vogue in 1902. Howe’s formula, Equation (6), was first published in 1907, although credit is generally given to his 1918 paper (2)++. The years 1902 to 1918 saw the publication of many formulas for the calculation of bending stresses in operating wire ropes, and there may have been some justification for the consideration given the subject, as ropes did break before being worn appreciably, which was considered as indicative of abnormal bending stresses.

With the present knowledge of designing wire ropes, it is appreciated that improper proportioning of the wires lead to their premature breaking. If less time had been spent on bending stress theories and more time devoted to the engineering design of the rope, the troubles experienced would have been greatly eliminated.

In discussing bending stresses in wire rope, the author of an article‡ published in 1930, noted that “the intensity of stress due to bending varies inversely as the radius of curvature; consideration of this fundamental fact leads to the conclusion that the wires in contact with the sheave or drum, i.e., those bent to the least radius of curvature, are subjected to the greatest bending stress.” An extensive experience in testing moving wire ropes, under load, over one sheave and under another sheave, subjecting the rope to a reverse bending, has verified the foregoing statement.

In a discussion of Leffler’s paper (3)§, the writer noted that “the maximum bending stress [in an operating wire rope] is not necessarily in the outer wires of the strand farthest from the axis of the rope.” With some types of wire ropes and under certain conditions of loading and operation, however, the outer wires of the strand break next to the manila center of the rope where they are not susceptible to inspection.

For the determination of the strength of a wire rope bent over a sheave and subject to a static load, in a recent paper¶, the writer modified Equa-

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*Wire Rope Engr., The B. Greening Wire Co., Ltd., Hamilton, Ont., Canada.
†“Die Drahtselle”, by Josef Hrabak.
tion (9) as follows,

\[ S = k_1 A e \left( t - \frac{E_r D}{D + d_r} \right) \]  

in which \( k_1 \) is a correction factor with the following values:

<table>
<thead>
<tr>
<th>( \frac{D}{d_r} )</th>
<th>( k_1 )</th>
<th>( \frac{D}{d_r} )</th>
<th>( k_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.150</td>
<td>8</td>
<td>1.080</td>
</tr>
<tr>
<td>4</td>
<td>1.135</td>
<td>10</td>
<td>1.055</td>
</tr>
<tr>
<td>5</td>
<td>1.120</td>
<td>12</td>
<td>1.03</td>
</tr>
<tr>
<td>6</td>
<td>1.105</td>
<td>14</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>1.095</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

and \( E_r \) is the modulus of elasticity of the rope as manufactured and as determined by the first-run loading on it, the load not to exceed 30% of the strength of the rope.

The use of Equation (14) will increase the values given in Table 10, under the heading, "Equation (9)" and using the first-run modulus values given in Fig. 8. The changes in tabular values are given separately in Table 11. These values show an appreciable advance compared with the data given in Table 10 for Equation (9); if the loadings on the ropes had not been so abnormally high, lower first-run moduli would have resulted, with a corresponding increase in the values of Table 11.

It should be appreciated that Equation (14) is only an approximation, and yet it gives values quite closely in accord with the results of Skillman's (9)\textsuperscript{a} and Rairden's (1)\textsuperscript{a} series of tests and also with the test results of many 6 × 19 and 6 × 37, steel-center, suspender ropes as used on recent suspension bridges; although, as indicated previously, it is not in as close agreement with Mr. Stewart's test results.

For 6 × 19 ropes with manila centers, the efficiencies of the ropes reported by Mr. Stewart are higher than those of Skillman's (9)\textsuperscript{a} tests for 6 × 19 Warrington plow-steel ropes and of Rairden's (1)\textsuperscript{a} tests of 6 × 19 filler-wire improved plow-steel ropes, and it appears from a comparison of these three, series of tests that the efficiencies may vary for the different types and grades of 6 × 19 ropes and even for ropes of the same type as made by the different
manufacturers; consequently, too much reliance must not be placed on any particular formula until more tests are conducted to verify their accuracy, although no brief is being held for Equation (14) as the writer appreciates its limitations.

Equation (10) has been used for a number of years to determine the strengths of special wire ropes and has found to be more accurate than is indicated in Table 9. To verify this statement, tests were made of \( \frac{3}{4} \)-in. and 1-in. ropes with manila centers, the data pertaining to the ropes being noted in Table 12, and the results of these tests in Table 13.

**TABLE 12.—DESCRIPTION OF \( \frac{3}{4} \)-INCH AND 1-INCH WIRE ROPES**

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Description of ropes</th>
<th>Metallic area, in square inches</th>
<th>Metal angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1-in., 6 \times 7 Lang lay plow-steel, non-preformed</td>
<td>0.31975</td>
<td>14° 15' 12° 13' 15° 13'</td>
</tr>
<tr>
<td>15</td>
<td>1-in., 6 \times 9 filler-wire regular lay east-steel, non-preformed</td>
<td>0.41268</td>
<td>17° 28' 14° 4' 18° 50'</td>
</tr>
<tr>
<td>16</td>
<td>1-in., 6 \times 10 filler-wire regular lay plow-steel, non-preformed</td>
<td>0.41268</td>
<td>17° 28' 14° 4' 18° 50'</td>
</tr>
<tr>
<td>17</td>
<td>1-in., 6 \times 19 filler-wire regular lay plow-steel, preformed</td>
<td>0.41268</td>
<td>16° 44' 13° 28' 19° 10'</td>
</tr>
</tbody>
</table>

The ropes were tested by the Ontario Department of Mines, in Toronto, Ont., Canada, and the individual wires of the ropes were checked-tested by the Steel Company of Canada, Limited, at Hamilton, Ont. It will be seen from Table 13 that Equation (10) does agree quite closely with test values, and it is difficult to reconcile these efficiencies with those noted by Mr. Stewart in Table 9.

**TABLE 13.—ACTUAL AND CALCULATED BREAKING STRENGTHS AND EFFICIENCIES OF WIRE ROPES**

<table>
<thead>
<tr>
<th>Set No.</th>
<th>ACTUAL TESTS</th>
<th>EQUATION (10)</th>
<th>EQUATION (12)</th>
<th>EQUATION (16)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load, in pounds</td>
<td>Efficiency (per centage)</td>
<td>Load, in pounds</td>
<td>Efficiency (per centage)</td>
</tr>
<tr>
<td>14</td>
<td>66 050</td>
<td>90.2</td>
<td>65 300</td>
<td>89.1</td>
</tr>
<tr>
<td>15</td>
<td>67 285</td>
<td>85.6</td>
<td>67 500</td>
<td>86.0</td>
</tr>
<tr>
<td>16</td>
<td>83 425</td>
<td>85.4</td>
<td>83 700</td>
<td>85.7</td>
</tr>
<tr>
<td>17</td>
<td>81 225</td>
<td>85.9</td>
<td>81 900</td>
<td>85.6</td>
</tr>
</tbody>
</table>

One criticism of Equation (12) is that it does not take into consideration the difference in the angles of lay of the various wires in a strand. For example, it will give the same efficiency for a 6 \times 19 two-operation strand, a strand having 12 wires laid over 7, as for a 6 \times 19 one-operation strand rope as a filler-wire construction; and yet it must be obvious that the efficiency of the latter is greater than that of the former construction. Equation (10) makes this differentiation, whereas Equation (12) does not; also, the latter part of Equation (10) will give the breaking strength of the individual strands of the rope quite accurately.
Equation (12) may be modified to take into consideration the varying lays of wires in the strand by taking $a$ as the average angle of lay of all the wires in the strand, or

$$a = \frac{\sum \frac{n_g}{n}}{n},$$

which, for a 19-filler wire strand, becomes,

$$a = \frac{6a_1 + 6a_2 + 12a_3}{25} \quad (15)$$

and, accordingly, Equation (12) may be written:

$$S = A S_0 \cos (a + b) \quad (16)$$

Values in accordance with Equation (16) are noted in Table 13.

It is regrettable that certain pitfalls were not avoided in Mr. Stewart's tests inasmuch as they detract somewhat from the value of the paper. Among others, four may be noted, as follows:

(a) Loadings at 49% of the rope strength for the determination of the modulus of elasticity values; (b) a decidedly short gauge length of 10 in. for the measurement of the stretch of the rope under load; (c) the use of fixed clamps on the rope; and (d) the adoption of ropes with manila centers.

(a).—Loadings at 49% of the Rope Strength for the Determination of the Modulus of Elasticity Values.—Most certainly this is an abnormally high loading and not representative of any engineering or commercial practice pertaining to wire rope; lower loadings are more in keeping with actual practice and would result in lower modulus values. Such abnormally high loads result in a permanent breaking down of the structure of the manila center, nicking of strand against strand, and a high modulus value that is unreal in so far as standard practice is concerned.

(b).—A Decidedly Short Gauge Length of 10 Inches for the Measurement of the Stretch of the Rope Under Load.—It has been general practice in modulus tests of wire ropes, to use a gauge length as long as possible; Skillman (9) used a gauge length of 50 in., and for most of the suspender ropes as used on the large suspension bridges built in recent years, the gauge length has been 80 in. The merit of the longer gauge length is that any irregularities or errors in measurements or in the behavior of the rope are not proportionately of much consequence as they must be in the shorter gauge lengths; those experienced in such testing will appreciate this point.

(c).—The Use of Fixed Clamps on the Rope.—Special swivel clamps have been used that are free to swivel or rotate, and, consequently, to eliminate any twisting of the measuring apparatus due to the untwisting of the rope.

(d).—The Adoption of Ropes with Manila Centers.—That such ropes are used to avoid confusion in the mathematical analyses is appreciated, but they are not as typical as those with an independent wire-rope center (IWRC); particularly for the consideration of the loss in strength due to bending, as this applies to suspender ropes for suspension bridges and such ropes are always made with an independent wire rope center.

It is a fact fairly well known to wire-rope engineers, that the tensile strengths of preformed wire ropes are from 3 to 5% lower than the strengths
of non-preformed ropes, but sales policies have, conveniently "glossed over" this fact. For the preforming of Lang lay wire ropes, the use of quills as described by Mr. Stewart is not necessary, as the roller head shown in Fig. 4 may be used; in fact, roller heads only are used in the making of all types and diameters of preformed Lang lay wire ropes by the writer's Company.

Relative to the coefficients of friction given in Table 6, it is presumed that these are for ropes that were dry—that is, devoid of any heavy lubricant. Mr. William Hewitt published data pertaining to this subject in 1905, and it may be interesting to compare his values with those of the author.

That the bending stress in a Lang lay rope is approximately 20% less than that in a regular lay rope verifies a statement that the writer made in 1928 regarding such ropes.

Mr. Stewart shows the same confusion as did Carstarphen and Rairden in the paper cited (1) in considering that the loss of strength of a stationary wire rope looped over a sheave is the same as the bending stress in a moving wire rope operating over a sheave; the former is more susceptible of mathematical analyses than the latter. Reasons and examples were cited by the writer in his discussion of Carstarphen's paper (1) to indicate that the latter was not susceptible to such an analysis and surely not to the extent that a "prediction of the bending stress" could be satisfactorily assured, as noted in Conclusion (10) of the paper. It would be a boon to the wire-rope users as well as to the manufacturers if such a prediction was possible.

G. P. BOOMSLITER, M. AM. Soc. C. E. (by letter).—In calling attention to the increase in the modulus of elasticity of a wire rope under successive applications of load, Mr. Stewart has rendered a valuable service. A value of $E$ of 18,000,000 lb per sq in. is not too great. As the author has shown, this value is perhaps high for repetitions of load under the proportional limit but, at some time or other during their period of use, most hoisting ropes are stressed beyond the calculated load. The writer is reminded of two such cases in his brief experience with wire ropes.

In one case a mine cage was customarily left all night at the bottom of a 250-ft shaft down which came the fresh air draft to a mine. One cold night the cage froze fast to the floor. It was finally pulled loose by stressing the hoisting rope, but the rope was 8 ft longer after pulling it loose than it was before. In another case, the 'circuit, breaker on a hoist went out as a load of coal was being lifted in a shaft. A telemeter attached to the hoisting rope immediately above the cage showed that the action of the safety devices in stopping the cage caused stresses which were 2.29 times the dead load stresses. Many other conditions result in occasional applications of high stress to a rope so that after a short period of service its modulus of elasticity has been increased beyond that of a new rope. Indeed, calculations made in the telemeter test referred to, indicated a modulus of elasticity for the rope there tested of between 19,000,000 and 20,000,000 lb per sq in.

10 Prof. of Mechanics, West Virginia Univ., Morgantown, W. Va.
Mr. Stewart deserves congratulations for his clever method of attaching the tensometers to his wire rope when it was bent about a sheave. He has pointed the way for further investigations of bending stress in wire rope. However, the results of bending tests such as those of this paper are likely to be misleading. Undoubtedly, they determine the stresses due to bending a wire rope about a thimble, or in a stationary rope bent over a sheave while in an unstressed condition, since there is no constraint as the wires adjust themselves to the curved position about the sheave, but a heavily loaded rope running over a sheave will have other stresses which the author has not considered. These stresses are due to the frictional resistance to sliding of the wires upon each other when the loaded straight rope bends about the sheave. To illustrate, consider an axial load of 30,000 lb on one of Mr. Stewart's 1-in. ropes of regular lay as it passes over a sheave. Each strand of 19 wires will be assumed to take one-sixth of the load, or 5,000 lb.

The lay length of the strand will be taken as \(93 \frac{d}{15}\) and \(d\) as \(\frac{d_r}{15}\), in which \(d_r\) = the diameter of the rope; and \(d\) the diameter of the individual wires. The lay length will then be \(\frac{93}{15}\), or 6.2 in. and the length of half a lay will be 3.1 in. The lay angle is 18° 39'. The component of stress in a strand normal to the axis is 5,000 tan 18° 39' = 1,688 lb.

Let Fig. 18(b) represent a half lay length of the strand. Fig. 18(a) shows the components of the stresses at the two ends of the length which are normal to the strand length. These components are held in equilibrium by pressures of the other strands, assumed normal to the strand in question. By analogy with the pressures and tensions in a cylindrical vessel, the total lateral pressure in a length of a half lay will be \(2 \times 1,688 = 3,375\) lb. Now, assume that the lower end of this length is in contact with the sheave. The upper end will be at the outside of the rope. The part in contact with the sheave will shorten and the part at the outside of the rope will lengthen. This is done by the slipping of the strand on its neighbors, but this slipping will be done against a friction. Assuming a coefficient of friction of 0.15, the frictional force set up to oppose this motion in a half lay length will be 506 lb. This force will be a measure of the difference between the stress in this
strand at contact with the sheave and at the outside of the rope. Note that this is 10.3% of the axial stress in the strand.

If the normal length of the rope is maintained at its line of contact with the sheave, all this frictional restraint (506 lb), will measure the increase in strand tension at the outside of the rope. If there is slip on the sheave the normal length of the rope is maintained along a line somewhere between the sheave and the outside of the rope. Assuming that this line coincides with the rope center, the stress at the inside is decreased and that at the outside increased, each by one-half the frictional restraint, or 253 lb. The area of the wire in one strand, as taken from Table 3 of the paper, would be 0.0694 sq in. The unit stress due to direct load would be 72,000 lb per sq in., and the frictional bending stress according to the first assumption would be 7,490 lb per sq in., and 3,745 lb per sq in., according to the second. These stresses, of course, are in addition to the stresses due to flexural bending. They would be independent of the ratio of the sheave diameter to the rope diameter. The formula expressing this stress would be:

$$ s_f = 2 s_a \tan \alpha f $$

(17)

in which $s_a$ is the axial unit stress in the rope; $\alpha$ is the angle of lay; and $f$ is the coefficient of friction between strands. Since the same condition exists between the wires in a strand, Equation (17) is decidedly approximate and is given simply to indicate the effect of frictional resistance on sliding. The coefficient of friction is also assumed. Only further tests will indicate what it actually is, but the writer is firmly of the opinion that tests such as those presented by Mr. Stewart are likely to be misleading if assumed for a heavily stressed rope passing over a sheave. If a rope were rusted so that it could not slip, it would bend as a unit, of course, and Equation (7) would be a proper formula for bending stress. If it were so well lubricated that the friction was that of an oil layer on oil, this stress could be neglected. It is very doubtful whether this last condition would exist in a rope under heavy service. It is more likely that neglect would make $f$ more than 0.15.

INGVALD E. MADSSEN,^22 JUN. AM. SOC. C. E. (by letter).—The assumption is made in this paper that the loss of strength of wire ropes over sheaves is practically all due to bending stresses, and thus may be evaluated by some bending stress formula. The writer believes that this assumption is not entirely justified, because all bending stress formulas are based on elastic conditions, and, consequently, cannot apply with any accuracy above the elastic limit, and certainly not at the breaking loads. Most of the usual stress theories, apparently, give absurd stresses for the breaking loads, and, consequently, have been disparaged as not picturing true conditions. However, these theories actually may not be so far wrong within the elastic limit. This would seem to be borne out by the breaking of ropes in service under comparatively low loads, because the bending of the rope over sheaves causes stresses far above the fatigue limit, and it takes a relatively small number of repetitions of load to cause some of the wires to break.

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^22 Apprentice Engr., M. of W., P. R. R., Pittsburgh, Pa.
The same conditions are present in the usual structural research problems. In order to determine the stresses in a structure, experimentally, the strains are measured and multiplied by the modulus of elasticity of the material (usually 30,000,000 lb per sq in. for steel). However, if the material has exceeded its yield point, large strains are present, and if the method is then applied, calculated stresses result which are far greater than the breaking stress for the material. Analogously, the same thing occurs when the stress theories for bending in wire rope, are extrapolated to the breaking loads.

Actually, when a wire is bent over a sheave, large bending stresses occur at first; but as soon as the yield point of the wire is reached the wire yields, resulting in a re-adjustment of stress. Since practically all the wires used in cables have no definite yield point, this is a gradual process.

There are several other causes that will weaken a rope when tested over a sheave. One of the most important is the nicking effect which occurs between the outside wires of the strands. As the strands are wrapped around the center core, the outside wires of the strands bear on each other, and since these individual wires cross each other at a fairly sharp angle on the inside of the strand, they nick each other as the rope compresses under load. These nicks reduce the cross-sectional area of the individual wires, and, consequently, weaken the wire. When a rope is bent over a sheave, the nicking effect is more pronounced, since the bottom of the rope bears on the sheave, and the normal force between the wires will be augmented by the radial force of the rope on the sheave and its reaction. This radial force is equal to the tension in the rope divided by the radius, or, in other words, is inversely proportional to the diameter of the rope. No nicks of any magnitude occur between the wires of the same strand, since these wires cross each other at a small angle, and have a long bearing surface on each other.

Thus, the wires which will break first are not the inside wires as has been usually assumed, but the outside wires of the strands which break at the nicks formed by the crossing wires. These breaks are not visible to the eye, and were determined only by unraveling several cables which had broken over a sheave at one of the tangent points. When this was done, it was

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discovered that a large number of the outside wires of the strands, and only these, were already broken at the other tangent point, showing that these wires were the first to break.

The writer continued Mr. Stewart's work, and tested 1-in., 6 X 21, 1-in. 6 X 19 Seale, and 1-in. 6 X 19 Warrington, regular lay, non-preformed cables, with just about the same results obtained by the author. However, it was felt that if the wires were nicked by testing them over sheaves, these wires, of course, would be weakened permanently, which would be revealed in a simple tension test. After the several cables had been tested in tension, and over the 18, 14, 10, and 7-in. sheaves, they were unraveled, and ten individual wires of each size in the rope were taken from the part of the rope which lay over the sheave. These wires were carefully straightened by hand. Nick was noticeable in all the outside wires, and a view of a typical nick is shown in Fig. 19. The reduction in cross-section is clearly shown. On the inside wires, there were no appreciable nicks and only a very small decrease in strength was revealed in the tension tests.

The nicks in the outer wires were larger in the specimens broken over the smaller sheaves, as would be expected, and, consequently, these wires were weaker than those taken from the cables which had been tested over the larger sheaves. This loss in strength of individual wires (diameter, 0.0795 in.) is shown by Curve A, Fig. 20. A graph of the loss in strength of the cables (cast-steel, regular lay, non-preformed) over the various sheaves is shown by Curve B, Fig. 20, and it is seen that the loss of strength of the cable over the various sheaves, and the loss of strength due to nicking are quite similar. The results shown, for the 1-in. 6 X 19 Seale, and the results for the other cables were essentially the same. These results show that a large proportion of the loss of strength in cables is due to the nicking effect.

The occurrence of these nicks is an added explanation of the failure of cables running over sheaves at fairly low loads. Under the repetition of loads, the wires chafe on each other, enlarging the nicks and reducing the strength until the wire breaks, and this effect is much more pronounced when reverse bends are present.

Stress-strain curves were also drawn of the wires from the broken cables. For some reason, which is most likely the change in cross-section of the individual wires due to abrasion and squeezing in the cable, the stress-strain relationship of the wire seems to change during the testing of the rope. In
Fig. 21 are shown the stress-strain curves for a single wire in the rope. The dotted line is obtained from the wires which went into the rope. The full line is obtained from individual wires taken from a broken rope, and this is the curve that should be used in transposing strain data to stress data. If this is done, the load stress curves in the author's Fig. 11, will approach the load-divided-by-net-area line. Similar curves demonstrating this fact for the 1-in., 6 × 19 Seale are shown in Fig. 22. Curve E is obtained by using the dotted line in Fig. 21. This curve is seen to be similar to the 1-in. 6 × 7 regular lay, shown in Fig. 11. Curve C in Fig. 22, is obtained by using the solid line in Fig. 21, and, at the breaking load, the stress in the wires is about equal to the average stress. This is what one would expect, since the plastic flow of the wires above the yield point, re-adjusts the stress throughout the various wires so that they are nearly equally stressed, and at the breaking load they have the same stress.

This condition is contrary to the author's theoretical stress distribution shown in Fig. 15. The writer believes that this distribution is in error for several reasons: First, the wrong stress-strain diagram for the single wires was used; second, the instruments used to measure strain, measured it along the chord of the curved wire, and not the actual strain; and, third, the stress
in the outer wire is balanced against the assumed stress in the core wire, whereas actually there are enough more outside wires than core wires so that the average stress in the cable is not far from the stress in the outer wires. If these factors were taken into account, the stress in all the wires would be seen to be equal to the average stress as shown in Fig. 22.

A few more remarks on the general behavior of wire ropes may be appropriate. A wire rope may be considered as a single solid bar, or an assembly of individual wires, each acting separately. If thought of as a bar, the usual theories for curved beams would apply. Actually, the behavior of a wire rope is somewhere between these two conditions, the exact degree depending on the relative friction between the wires, the lubrication of the rope, the resistance of the individual wires to abrasion, and similar factors. The indeterminacy and the variation in these factors would tend to remove wire ropes from the fields of mathematical analysis. All bending stress theories are based on the assumption that the stress of a rope over a sheave varies from a maximum at the outside of the rope to a lesser stress on the sheave; and yet these theories assume that if an individual wire is taken out as a free body for analysis, the stress at the two ends of the wire is the same, and that there are no forces acting along the wire. If a section of any individual wire is taken, it will go from the outside of the rope to the inside. The difference between the two ends of the wire must be due to forces introduced by friction and the bearing of one wire on another, which forces are practically always neglected in analysis, but they cannot be neglected and still give a true picture of what actually occurs in the rope.

DOUGLAS M. STEWART, Jr., AM. Soc. C. E. (by letter).—Various discussers of this paper have stated certain of the limitations in the testing and analysis of stationary wire ropes in bending over sheaves. For these contributions the writer is especially grateful.

Mr. Meals has assisted in clearing up the chronology of the various formulas for bending stress listed. His previous conclusion that the maximum bending stress does not necessarily lie in the outer wires of the strand was supported in the paper. Equations (14) and (16) give values much more consistent with the test results obtained than those considered in the paper, and indicate that for sheaves of a diameter, such as that normally used in practice, Equation (14) can be used safely and will give fairly accurate predictions of strength.

Loadings of the tensile specimens too close to 50% of the ultimate strength, in determining the modulus of elasticity, were admittedly abnormally high when considered in the light of conventional factors of safety; and yet, as pointed out by Professor Boomsliter, overloads of this amount are frequently experienced in ordinary hoisting ropes, and when pre-stressing suspender cables for bridges to raise the modulus, such loads are commonly used. As shown by Set No. 11, in the ordinary range of working loads, a value of

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Douglas M. Stewart, Jr., Engr., Ingersoll-Rand Co., New York, N. Y.
\[ E_r = 10,000,000 \text{ lb per sq in.} \]  may be expected after a few loadings, and it is a matter for further investigation to determine whether such a rope in normal service will attain modulus values comparable with those tested.

The general consistency of test results for each specimen, and the agreement between measurements made on opposite sides of the specimen, indicate that a 10-in. gage length was adequate, although a greater length is undoubtedly to be preferred when physical limitations permit. On the specimens on which six 10-in gage lengths were used, a difference of only 2% in modulus between those nearest the sockets and those at the center shows this consistency, and the writer believed that accuracy of this order was within the experimental limits of such testing. Special swivel clamps would no doubt have been of assistance in eliminating twisting of the measuring apparatus, but corrections for twist using the transit and scale were of very small magnitude except for loads near the breaking point. The use of ropes with hemp centers for these tests was dictated by practical considerations, and the question of whether this type, or that with an independent wire-rope center, is the more typical seems debatable. An extended research into the properties of such ropes would clarify many questionable points in the analysis.

Professor Boomsliter has stated clearly one of the chief causes of variation in any mathematical analysis of stresses in a wire rope. There can be no question that forces of the nature described actually exist in a rope, but since so many assumptions must be made in considering them, such frictional stresses are usually neglected. That these forces may have an appreciable effect on the strength of a rope, in certain cases, is shown in the numerical example considered. Variation in the quantity of lubricant used in the ropes was not attempted; all tests were made on new commercial ropes and represent current practice in this respect. Mr. Madsen makes mention of such stresses in the last paragraph of his discussion, but the very fact that strengths in both bending and tension may be predicted with fair accuracy by the formulas given, whether empirical or otherwise, indicates that too careful consideration is not justified.

Mr. Madsen has had the opportunity of carrying on the writer’s work on various other types of wire rope specimens, and his conclusions merit careful consideration. It is to be regretted that complete results of his tests were not available for his discussion.

Specifically referring to Mr. Madsen’s discussion, it is stated that the usual stress theories, as represented by Equations (1) to (7), inclusive, may not be far from wrong below the elastic limit. These formulas actually indicate that the elastic limit (if a wire rope may be said to possess such a property) is reached long before the point shown by actual tests. Furthermore, breaking of stationary ropes in service under low loads almost never occurs, although no one will deny that fatigue will cause breakage in moving ropes at values of load far less than that given by any of these formulas. Since the bending stress is constant regardless of the load on the rope, it is
obvious that if exceptionally large stresses are indicated by such formulas at the breaking load, the error will be even greater proportionally at lower values of the direct stress.

The nicking effect of one wire on another has been emphasized clearly, and the reduction in area (and, hence, in ultimate load) is appreciable. Although care must be taken in interpreting tests on specimens of this nature after being stressed almost to failure, it is apparent that the loss in the strength of the rope must be affected by this nicking of certain of the outer wires. In any cross-section, however, the number of such wires is not large, being limited to those in the outer layer of a strand where it touches another strand. The use of a stress-strain curve for a wire that has been loaded practically to failure, over the entire range of a tensile test, does not seem to be justified. From Fig. 20, the percentage loss in strength of the wire in a tensile test is very close to zero, which means that, at failure, the wire should show an ultimate strength of about 219 000 lb per sq in. This strength is very close to that obtained in Curve E of Fig. 22, whereas Curve C shows a stress of only about 185 000 lb per sq in. at failure, or about 15% lower strength. Fig. 21 cannot be based on wires taken from a tension specimen and still be consistent with Fig. 20, and values taken from such a curve based on nicked wires from a bending specimen (which themselves are not typical of conditions prevailing over the cross-section) are of little help in correcting Fig. 22.

The correct stress-strain curve of the wire to use would be one based on a gradual nicking, such as takes place in the rope, but lacking this, the original stress-strain curve seems to give the best results. The difference in length between the chord length measured in a ¼-in. gage length on the wire and the actual center-line length is so small that it may safely be neglected. That the stress in the inner wires is greater than the average over the cross-section, is appreciated by wire-rope manufacturers, who make the inner wires slightly larger to withstand this effect.

The need for more extensive research in this field, to explain the apparent inconsistencies of various experiments has been mentioned previously, and is emphasized by the discussions of this paper.