PROCEEDINGS PAPER

A Study of Stress Relaxation in Prestressing Reinforcement

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INTRODUCTION

Relaxation is defined as the loss of stress in a stressed material held at constant length. Another manifestation of the same basic phenomenon, creep, is defined as the change in length of a material under stress. Since no generally satisfactory quantitative relationship between creep and relaxation has been developed, relaxation tests must be carried out whenever relaxation data are required, although creep tests are simpler to perform.

Relaxation characteristics of prestressing reinforcement are of interest in prestressed concrete construction, even though pure relaxation does not exist under practical conditions. Creep and shrinkage of the concrete and fluctuations in superimposed load change the length of the tendon. Nevertheless, the tendon does not deform freely and the stress in it can change. Thus, the conditions are comparable more to a relaxation test than to a creep test.

The attitude toward the effect of relaxation has changed considerably over the last two decades. At first, relaxation losses were considered to be quite critical because they affected the working stresses which governed the design. At the same time, it was thought that the reinforcement reached a stable stress in a matter of a few weeks if not hours and that the relaxation losses were limited to a very small fraction of the initial stress. By the time it was established that relaxation losses could amount to as much as 20 percent of the initial stress over a long period of time, it was recognized that partial loss of prestress is not necessarilly accompanied by a loss in flexural strength.

At present, a knowledge of the losses resulting from relaxation is required primarily in relation to the serviceability of a prestressed member. In this respect, it should be mentioned that the critical quantity is the remaining stress and not the loss. The recognition of this fact makes a considerable difference in the interpretation of the available test data.

Object and Scope

The object of this paper is to present and evaluate the results of available relaxation tests with a view to the development of expressions for estimating the effects of stress relaxation.

Appendix A presents a detailed description of 57 tests carried out at the University of Illinois.

Appendix B summarizes the results of 444 tests carried out in the course of 17 investigations at different laboratories.

The data from all 501 tests are

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discussed in the paper which includes a bibliography on stress relaxation.

Definitions

Yield Stress: 0.1 percent offset stress

Initial Stress Ratio: Initial stress/yield stress

Final Stress Ratio: Final stress/initial stress

METHODS OF STRESS MEASUREMENT

A relaxation test requires equipment which will determine the stress in the specimen while keeping the strain constant. The neccssity for long durations of tests under controlled environment puts practical limits on the size of the specimen and related equipment. These criteria have been satisfied or nearly satisfied by various investigators using different methods which can be categorized in four groups and are described briefly in the following sections.

The Vibration Method

The vibration method involves the determination of the stress in the wire by measuring its frequency of lateral vibration. It was used first by Dawance [1948].

The measured frequency of vibration is converted to stress with the use of a calibration for a given mode of vibration obtained prior to the relaxation test. This method makes it possible to use rather short lengths of specimens since the stress is measured without any appreciable movement of the anchorages. Wires with a length to diameter ratio of approximately 200 have been used in tests.

One application of the vibration method is described in detail in Appendix A.

The Lever Method

Some investigators stressed the wires through a lever system which made it possible to use relatively small weights to develop the necessary stress in the wire. The length of the specimen was maintained constant by removing the weights as it became necessary.

Variations of this system were used by Bannister [1953], the C.U.R. [1958], Kajfasz [1958] and others.

The Balance Method

The characteristic of this method is the determination of the stress in the wire by balancing, temporarily, the tension in the wire by a known force. One end of the wire is gripped and pulled until the reaction of the near anchorage is zero. The measured force corresponding to this condition is the tension in the wire.

Magnel [1948] and Spare [1952] used this method with different mechanical arrangements.

Closely allied to this method is the one involving direct measurement of the force (Bate [1958] and Kingham [1961]) with the use of a dynamometer in series with the wire. To give an indication of the change in stress, the dynamometer has to deform. However, this deformation can be arranged to be small in relation to the length of the specimen so that the change in strain in the specimen is very small.

The Deflection Method

The deflection method, used by Gifford [1953], involved the determination of the stress in the wire by measuring its lateral deflection at mid-length under a known load. The relation between the force in the wire and the lateral deflection

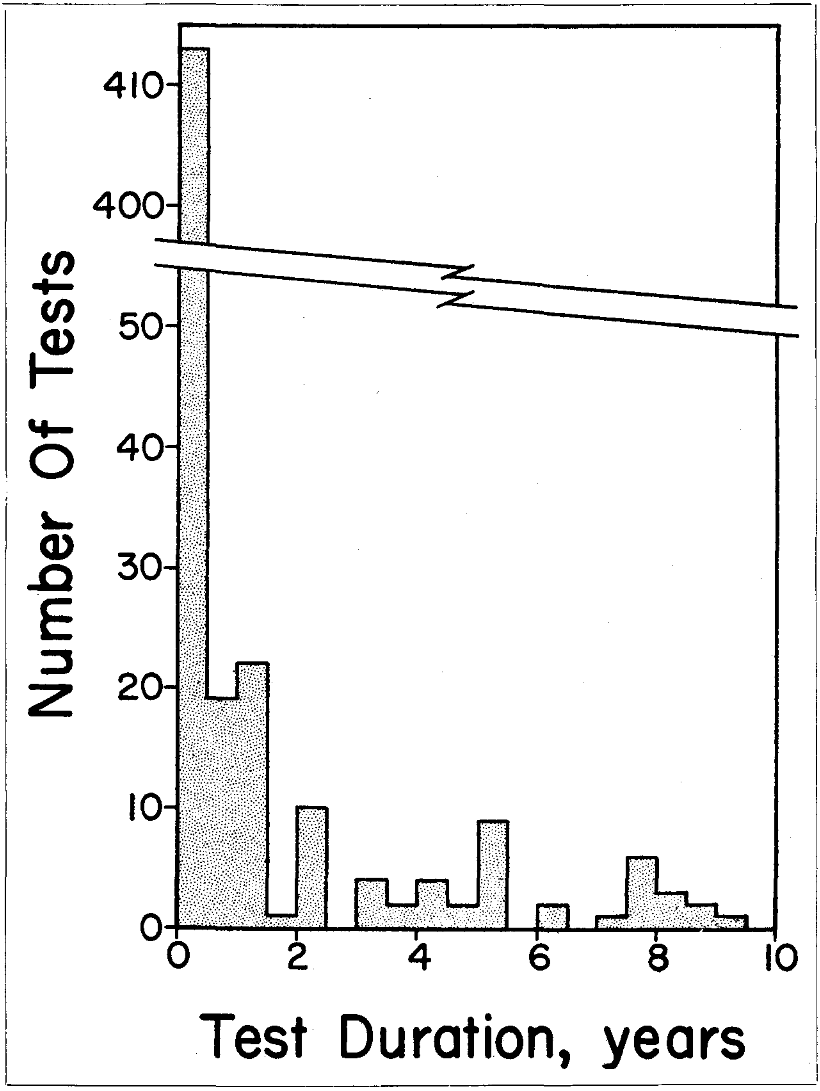

Fig. 1—Frequency Distribution of Test Durations.

was derived assuming that the wire segments were straight and the angle they made with the horizontal was small. (The lateral deflection was about 0.25 in. for specimens 210 in. long.)

SCOPE OF DATA

The variables in the relaxation tests were: test duration, type of steel, initial stress, stress history (prestretching), and temperature. All but a few of the tests were carried out on single wire. The data on strand are limited to those reported by Schwier [1955], Kajfasz [1958], and Kingham [1961]. Temperature was a controlled variable only in the tests reported by Papsdorf and Schwier [1958].

Test Duration

Despite early impressions to the contrary, one conclusion that many investigators have come to is that the phenomenon of relaxation is not shortlived. It appears from the available evidence that relaxation may continue indefinitely although at a diminishing rate. Consequently, the significance of a given test depends on its duration.

As indicated earlier, this report draws information from 501 individual tests, an impressive number. However, the impact of this number is reduced when the durations of these tests are considered. Figure 1 shows the number of tests for different test durations grouped in half-year intervals. Only 18 percent of the 501 tests exceeded a duration of one-half year. A total of 36 tests exceeded a duration of 3 years and only 15 tests exceeded 6 years. Of these 15 tests, 8 were reported by Levi [1958] and 7 are described in Appendix A of this report.

It is hoped that a breakthrough will be made in the technique of relaxation tests by the achievement of a reliable understanding of the time-temperature interaction. Long-time losses at working stress and temperature levels can then be estimated closely by short-time tests under high temperatures and/or stresses. However, the final confirmation of any such procedure may have to await the development of long-time data under ordinary conditions.

Type of Steel

All tests discussed in this report have been carried out on cold-drawn wire which is produced from billets of high-carbon steel usually in three steps: hot-rolling, lead patenting, and cold-drawing. Billets are first hot-rolled into rods. To give them the ductility and strength required in the cold-drawing process, they are heated to a temperature sufficient to transform the grain structure of the steel and then cooled in a lead bath to arrest the grain structure in the sorbitic stage. Following this process, the rods are drawn through dies of successively smaller size to the desired diameter. The drawing operation tends to decrease the ductility and increase the strength of the wire.

Frequently, the wire is subjected to further treatment to produce additional changes of the physical properties. The most common treatments employed are: stress-relieving, oil tempering, and straightening.

Stress-relieving is a controlled time-temperature heat-treatment process. It consists of heating the wire for a short period of time to temperatures in the range of 500°F to 1000°F; the time and temperature being varied to remove the residual stresses without destroying the fibrous grain structure. The process produces a wire with increased elastic limit and ductility over the as-drawn wire.

Oil tempering is a heat-treatment process in which the fibrous structure is destroyed by heating the wire to about 1700°F, quenching it in an oil bath and immersing it in lead at about 800°F. The elastic limit is increased by this process, but ductility remains low.

Drawn wire retains a high degree of curvature when wound on a reel directly from the wire drawing block. The radius of curvature is small making the wire difficult to handle. Therefore, it is mechanically straightened to increase the free radius. Wire which has been heat-treated generally has a free radius greater than as-drawn wire since the heat-treating equipment uses larger diameter reels. Because the free radius is sufficiently large, heat-treated wire is not usually straightened.

The tests described were made on wires subjected to various types of treatment subsequent to drawing. The pertinent information, wherever available, is given in detail in Appendices A and B. About three-fourths of the total number of tests were conducted on wire in the as-drawn condition.

Initial Stress

The absolute value of the initial stress is not significant in studying data from wires having different stress-strain characteristics. The ratio of the initial stress to the 0.1-percent offset stress was chosen as a comparison index in this study.

Figure 2 shows the frequency distribution of the ratio of the initial stress to the 0.1-percent offset stress for 228 tests for which the 0.1-percent offset stress was available. The range extends from 0.29 to 1.44. However, 86 percent of the data lie between 0.5 and 1.0. Although the 0.1-percent offset stress is not given for a substantial portion of the data reported, it appears from the other strength information provided that the picture presented in Fig. 2 is representative of the whole group of data.

Prestretching

Prestretching involves the application to the wire of a sustained stress equal to or greater than the initial stress for a short period of time prior to anchoring the wire. It is intended to reduce relaxation losses.

A number of investigations included prestretched specimens to determine the effect of this variable on relaxation losses. Since the operation has not been standardized, tests were conducted on specimens prestretched for various lengths of time and at various amounts of stress as shown in the table at the bottom of this page.

Tests were conducted on prestretched wires with non-prestretched companion specimens to allow evaluation of the effect of prestretching on relaxation losses.

DISCUSSION OF DATA ON STRESS RELAXATION

Effect of Initial Stress

To illustrate the effect of initial stress on relaxation losses, the data from Series SR100 reported in Appendix A are plotted in Fig. 3. The loss is shown as a function of the initial stress. All data refer to the same type of wire.

The curve in Fig. 3, drawn merely to show the trend, indicates that as the initial stress increases, the loss increases at an increasing rate. This trend was representative of all available test results.

As mentioned earlier, it is not possible to compare data from different types or even shipments of

Source	Stress	Time	No. of Prestretched Specimens
Dumas	0 to 50% above initial stress	2 minutes	20
Kajfasz	10% above initial stress	10 minutes	11
Gifford	12 ksi above initial stress	2 minutes	5
Appendix A	10% above initial stress	10 or 15 minutes	16
			52

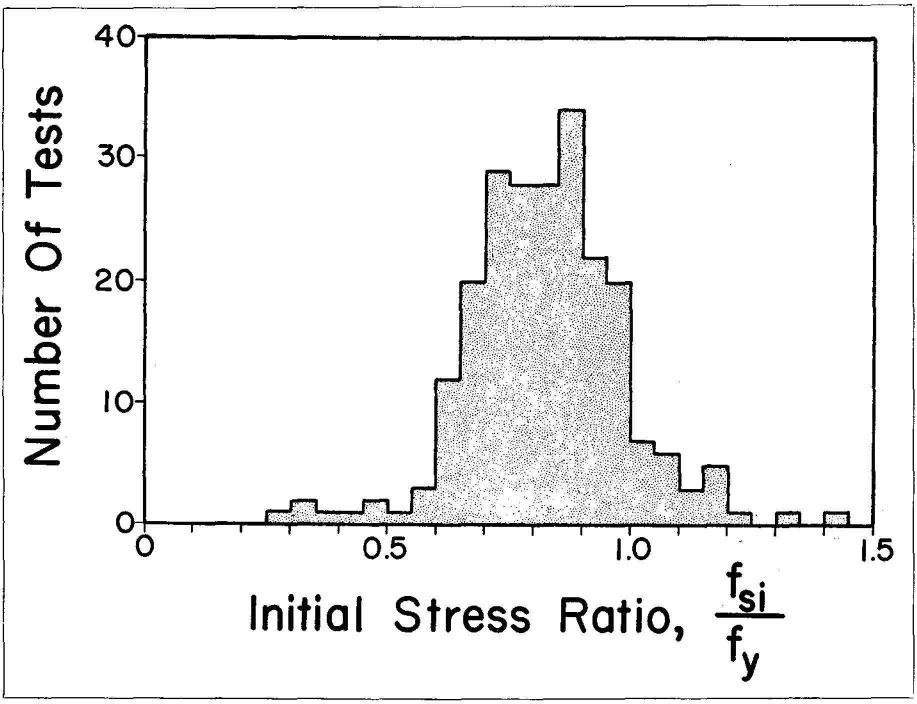

Fig. 2—Frequency Distribution of Initial Stress Ratios.

wire on the basis of the parameters used in Fig. 3. In work related to creep of metals, the ratio of the initial stress to the yield stress is often used as an index value for comparing data from metals having different yield stresses and subjected to different stresses. Since creep and relaxation must result from the same basic mechanism, it was assumed in this study that the ratio of the initial stress to the yield stress is a critical parameter affecting relaxation.

For steels used in the tests, there was no definite yield point. Hence, this had to be defined arbitrarily and was chosen as the stress corresponding to the 0.1-percent offset. The choice was influenced by the facts that (a) much of the available data had been reported in terms of this definition, (b) it gave an early indication of inelastic action as compared with the 0.2-percent offset stress or the stress at one-percent strain, and (c) for heat-treated wire used in the U.S. the difference between the 0.1-percent offset stress and the stress at one-percent strain is usually less than 10 percent (See Table A.1, Appendix A).

Figure 4 shows the data from tests on three different types of wire reported in Appendix A. The loss is plotted as a ratio of the initial stress (the loss ratio). The abscissas represent ratios of the initial stress to the 0.1-percent offset stress, (the initial stress ratio). Three significant and general trends are indicated: For initial stress ratios less than about one half, relaxation losses are insignificant. The loss ratio increases at an increasing rate with the initial stress ratio although it can be represented closely by a straight line. Loss ratios are different for different types of wire.

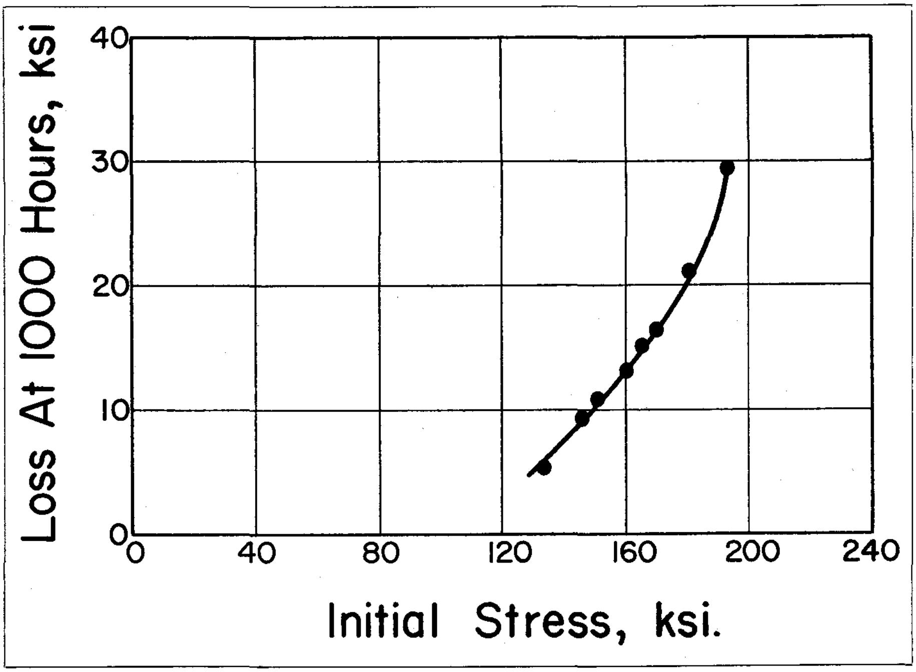

Fig. 3—Effect of Initial Stress Level on Relaxation Loss; Data from Series SR100, Appendix A.

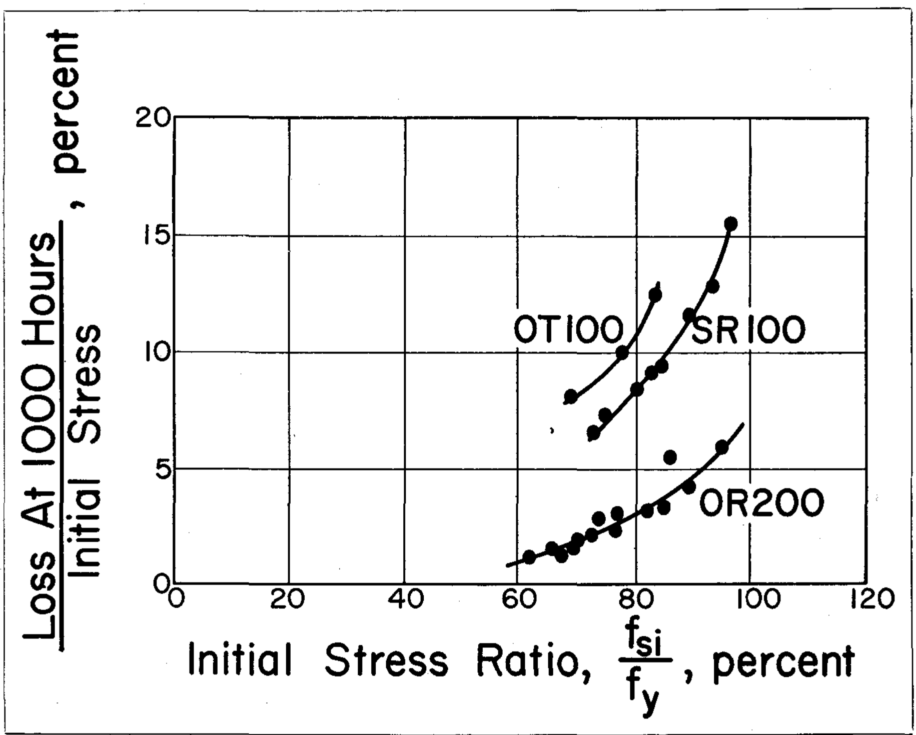

Fig. 4—Effect of Initial Stress Level on Relaxation Loss; Data from Series OT100, SR100, and OR200, Appendix A.

The effect of initial stress on the rate of relaxation loss can be studied with the help of Fig. A.3, A.4 and A.5 in Appendix A. The relaxation rate increases with the initial stress ratio approximately in direct proportion to the total loss expected. Figure 5 is a plot of the ratio of the relaxation loss at a given time to the total measured loss versus time for seven specimens (OR210, 307-P, 308, 309-P, 310, 403-P, and 405) for which measurements up to 50,000 hours were available. These specimens developed about three-quarters of the total loss in one year. There was no apparent effect of the initial stress ratio on this proportion.

Effect of Prestretching

The term prestretching is used in this report to denote the operation in which the stress in the wire is increased to a level equal to or higher than the intended initial stress, held at that level for a short period of time, and then anchored at the intended initial stress. This operation has been claimed to reduce relaxation losses considerably.

On the basis of what is known about time-dependent phenomena in materials under stress, it can be reasoned that prestretching will reduce relaxation losses. Consider the time-dependent deformations for a material put under a constant stress at time t_o. If this material is put in

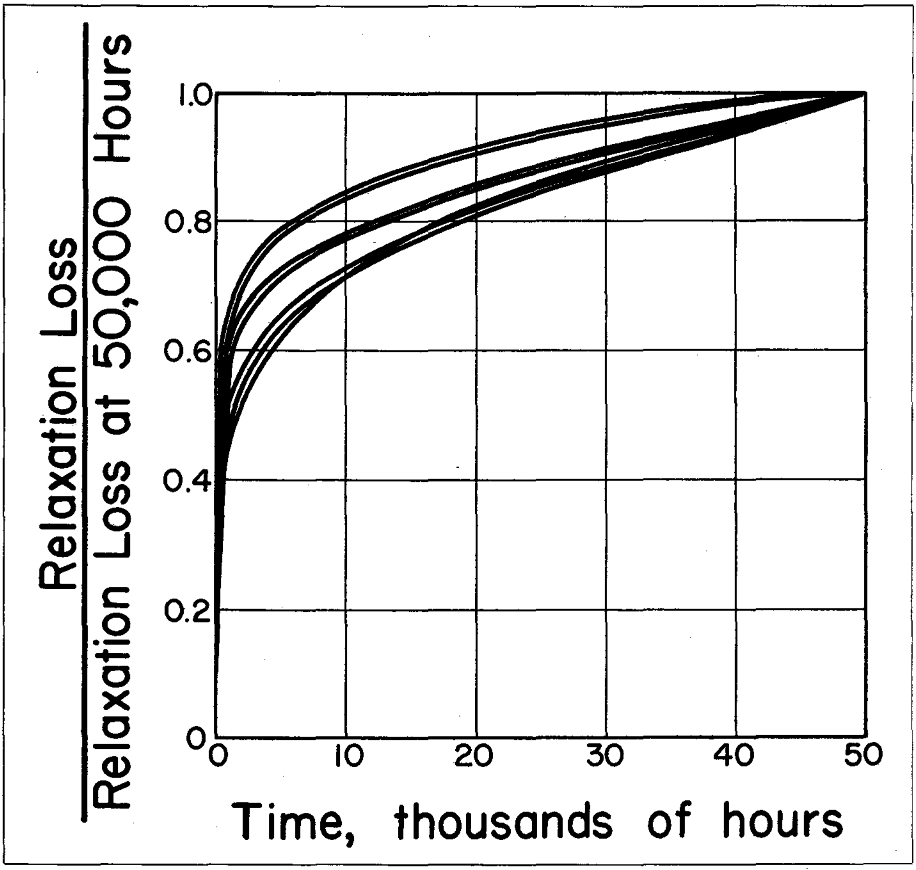

Fig. 5—Rate of Relaxation Loss.

service at a later time t_l, the effective time-dependent deformation can be considered to be that occurring after time t_l. This is effectively the manner in which prestretching reduces relaxation loss: the loss that occurs during the period of prestretching is subtracted from the total loss.

The fact that the stress is increased to a higher level could be quite significant if the desired initial stress itself had not been quite high. With the practical levels of initial stress on the order of 75 percent of the strength of the steel, it is not feasible to prestretch it by more than about 15 percent above the desired initial stress. Hence, the overstress should have little effect on the results of the operation. Almost the same effect could be achieved by holding the stress at the desired level for a length of time. However, under practical conditions it may be easier to overstress the wire to a certain level and avoid the necessity to maintain the stress at a constant level during the prestretching period.

Thus, the reduction in relaxation loss resulting from prestretching should be approximately equal to the loss occurring over the period of prestretching. The rate of relaxation loss with time is quite high immediately after stressing. However, it is not so high as to make this an appreciable effect in the long run if the prestretching period is limited to a matter of minutes.

The average ratio of the loss occuring over the first 15 minutes to that occurring at six years for four specimens tested at the University of Illinois (Appendix A) is 5 percent. Had these specimens been prestretched for 15 minutes, it is conceivable that the measured loss would be less by that amount which would not be sufficient to yield conclusive evidence in relation to the experimental scatter.

A direct comparison of the effect of prestretching on the relaxation losses of specimens under test for a reasonably long duration of time can be made with the use of data provided by Gifford [1953] and in Appendix A.

Gifford reports test results on five pairs of specimens, each pair consisting of one prestretched and one non-prestretched specimen at the same level of initial stress. The test duration was 10,080 hours and the ratio of the initial stress to the 0.1-percent offset stress of the wire ranged from 0.50 to 0.98. Data on these specimens are provided in Table B.7, Appendix B.

A measure of the efficiency of the prestretching operation is the ratio shown at the bottom of this page. The average value of this ratio for the five pairs reported by Gifford was 100.2 percent with a range of 99 to 102 percent. In terms of the remaining stress in the wire, prestretching for a short period of time (2 min.) did not appear to be worthwhile.

The efficiency ratio described above is plotted against the logarithm of time in Fig. 6 and against the initial stress ratio in Fig. 7 for comparable pairs of specimens in Series OR200, OR300, and OR400 reported in Appendix A. The periods (10 or 15 min.) and overstresses involved in the prestretching operation are given in Table A.1. The

$$\frac{\text{Final stress, prestretched specimen}}{\text{Initial stress, prestretched specimen}} \Big/ \frac{\text{Final stress, non-prestretched specimen}}{\text{Initial stress, non-prestretched specimen}}$$

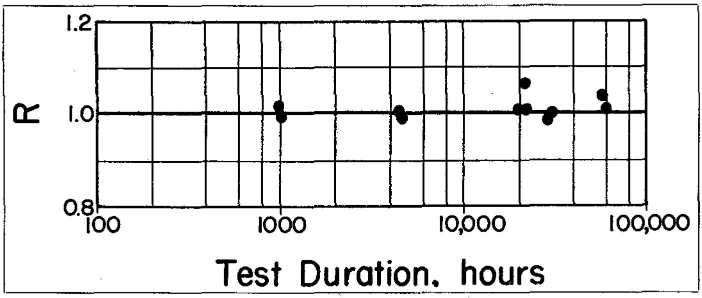

Fig. 6—Effect of Prestretching in Tests of Different Durations.

$$R = \frac{\text{Final stress, prestretched specimen}}{\text{Initial stress, prestretched specimen}} \Big/ \frac{\text{Final stress, non-prestressed specimen}}{\text{Initial stress, non-prestretched specimen}}$$

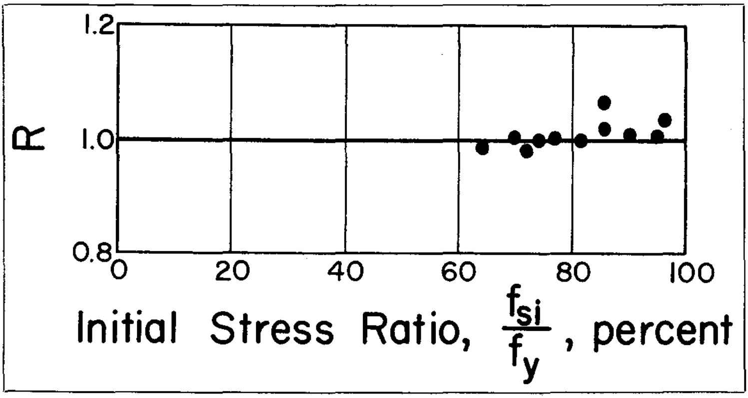

Fig. 7—Effect of Prestretching in Tests with Different Initial Stress Ratios.

$$R = \frac{\text{Final stress, prestretched specimen}}{\text{Initial stress, prestretched specimen}} \Big/ \frac{\text{Final stress, non-prestressed specimen}}{\text{Initial stress, non-prestretched specimen}}$$

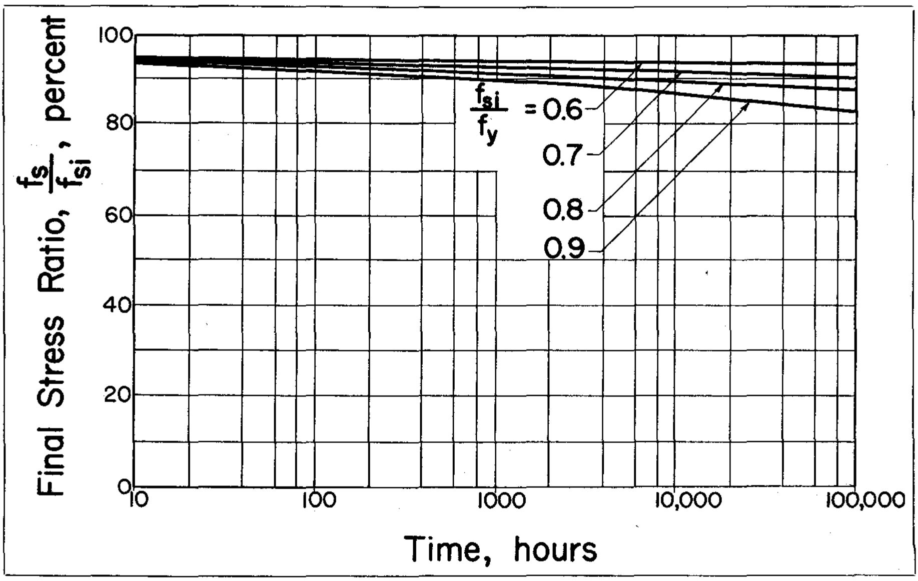

Fig. 8—Variation of Stress with Time According to Equation 1.

data in Fig. 6 and 7 indicate that the effect of prestretching was insignificant.

The effect of prestretching was also investigated by Kajfasz [1958] who concluded that it was unimportant. On the other hand, Dumas [1958] considered its effect on relaxation losses to be quite beneficial. However, as it can be seen in Table B.12 of Appendix B, the difference in final stress for a group of wires tensioned to the same initial stress but with different overstresses was rather small.

On the basis of available evidence, it appears that prestretching is of little consequence if the prestretching period is limited to a matter of minutes.

There is a practical aspect of prestretching that should be mentioned here. This is the prestretching involved in a pretensioning operation. The tendon is stressed between abutments for a period of, say, two days. Then, the stress is transferred to the concrete with a drop in stress of about 30,000 psi. In this case both the time period and change in stress level are significant in relation to relaxation losses since 30 to 40 percent of the loss may be expected to occur in the first two days.

Expressions for Estimating the Amount of Stress Relaxation

The available experimental data reveal that the major factors affecting stress relaxation are: (a) the initial stress ratio, (b) the type of steel, (c) the program of stressing, and (d) the temperature.

The influence of the initial stress ratio (the ratio of the initial stress to the "yield" stress) is significant and this variable must be considered in any expression developed to predict the effect of stress relaxation.

The relaxation losses measured in tests on steels of different types have been observed to be different even when all other variables were ostensibly the same. Since it is beyond the scope of this study to relate relaxation losses to the microscopic structure of the material, two courses of action may be followed: to derive different expressions for particular types of steel or to use a general expression on the basis of all data considered. The first alternative is undesirable not only because it eliminates the general objective of obtaining a useable method for estimating the effects of stress relaxation but also because limiting a certain expression to a certain type of steel would not fulfill the desired end; test results on specimens from different heats of the same type of steel have indicated different relaxation losses. Consequently, it was decided to ignore this variable in the expressions to predict the effect of relaxation losses, with the understanding that the definition of the initial stress ratio would take into account part of the effect of the type of steel.

Most of the effect of the program of stressing can be anticipated using a simple relation between relaxation loss and time. Therefore, a special parameter was not included for this effect in the expression for relaxation losses.

Temperature variations can have a critical effect on relaxation if the range is abnormally high. Schwier [1958] found that an increase in temperature from 72°F to 212°F magnified relaxation losses eight times. However, under ordinary working conditions this variable may be ignored.

In accordance with the preceding discussion, it was decided to express the remaining stress in the wire as a function of time modified only by the initial stress ratio. It should be emphasized at this stage of the discussion that the quantity sought is the remaining stress in the wire and not the relaxation loss. This is quite critical in the interpretation of the data. The relative scatter in the relaxation loss data is considerable. However, the corresponding relative scatter in the value of the remaining stress is much smaller. A relative error of 100 percent in relaxation loss may represent a relative error of only two percent in the remaining stress.

Papsdorf and Schwier [1958] suggest that the curve describing the variation of the remaining stress with the logarithm of time is S-shaped: the slope of the curve increases at first and then starts decreasing. Their relaxation data obtained at high temperatures indicated the presence of a point of inflection in the curve for stress vs. the logarithm of time. In extending a concept of "endurance limit" from fatigue to relaxation studies, Stussi [1959] used an analytical expression resulting in an S-shaped curve for the stress vs. logarithm of time relationship. A similar approach, but with the extreme relaxation limit lowered to zero, was used in this study. The data were analyzed with the assumption that

$$f_s = \frac{f_{si}}{1 + 10^n} \qquad (1)$$

where f_s = the remaining stress at any time t after prestressing

f_{si} = the initial stress

n = a function of time and the initial stress ratio

The function n was found to be described satisfactorily by the expression

$$n = -1.3 + \frac{\log t}{3}(f_{si}/f_y - 0.55) \qquad (2)$$

where f_y = 0.1% offset stress

t = time in hours

The variations of stress with time as indicated by Eq. 1 and 2 are shown in Fig. 8 for different values of the initial stress ratio. After 100,000 hours (about 11 years) the stress is predicted to be 94 percent of the initial for an initial stress ratio of 0.6 and about 83 percent of the initial for an initial stress ratio of 0.9. The shape of the curves indicate the half-life (time at reaching of half the initial stress) to occur far in the future. According to Eq. 1 and 2, the half life would be reached in 10^6 years for a wire having an initial stress ratio of 0.9.

The curves in Fig 8 suggest that a linear approximation could be used to predict the stress satisfactorily up to a time of about 50 years at the practical levels of prestress. The following expression relating the logarithm of time to the ratio f_s/f_{si} linearly was derived from the data.

$$\frac{f_s}{f_{si}} = 1 - \frac{\log t}{10}\left[\frac{f_{si}}{f_y} - 0.55\right] \qquad (3)$$

$$\text{for } \frac{f_{si}}{f_y} \geqq 0.55$$

The stresses calculated on the basis of Eq. 1-2 and 3 are compared with results from tests with durations of greater than one year in Table 1. Although the test results refer to wires manufactured using different techniques, the comparison is favorable. For Eq. 1, the mean ratio of the measured to computed stress is 1.01, the standard deviation 0.05 and the range 0.92 to 1.16. For Eq. 3, the mean ratio is 1.02, the standard deviation 0.06, and the range 0.92 to 1.16. On the basis of these comparisons, it appears that Eq. 1-2 or Eq. 3 may be used to estimate the effect of relaxation on prestress. It is not strictly justifiable to project the conclusions from the test data to longer durations and to different conditions. However, the use of Eq. 1 or 3 should represent a better estimate than the use of a flat percentage.

With the assumption that Eq. 1 does predict the stress correctly, it is interesting to study the efficiency of the initial stress ratio. Figure 9 shows the ratio of the stress remaining after 50 years to the "yield" stress as a function of the initial stress ratio. It is seen that the efficiency, the ratio of the increase in remaining stress to the increase in initial stress, becomes about 50 percent at $f_{si}/f_y = 0.8$ and practically zero at $f_{si}/f_y = 0.9$. The curve is not extended beyond $f_{si}/f_y = 1$ because few tests of long duration were made above this value.

In the case of pretensioned specimens, the loss occurring before release should be subtracted from the total loss predicted for the effective stress at release. For example, if the stress is to be estimated at time t_n, the wire is tensioned at time zero, and released at time t_r, Eq. 3 may be modified as follows

$$\frac{f_s}{f_{si}} = 1 - \left[\frac{f_{si}}{f_y} - 0.55\right] \left[\frac{\log t_n - \log t_r}{10}\right] \qquad (3a)$$

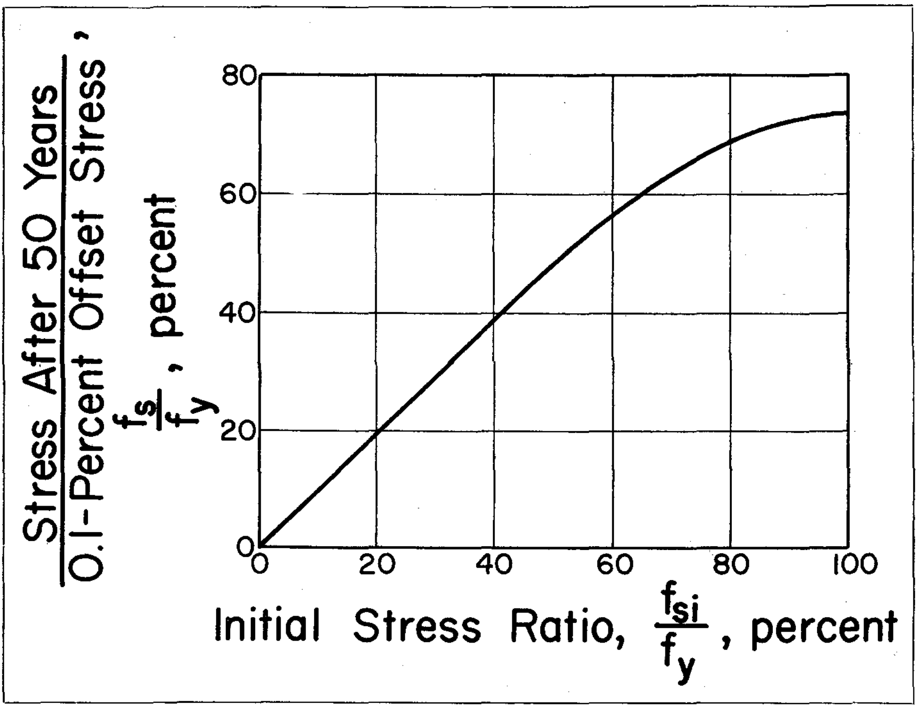

Fig. 9—Comparison of the Remaining Stress After 50 Years Based on Equation 1 with the Initial Stress.

The term f_{si} should be taken as the effective stress at release.

At present, experimental information on relaxation characteristics of seven-wire strand is rather limited. However, the available results (Table B.10 and B.17, Appendix B) do not indicate that strand should be treated differently; relaxation losses recorded are comparable to those of wire. Equation 3 was used to calculate the remaining stress in 10 specimens of seven-wire strand reported by Kingham [1961]. The average value for the ratios of measured to computed stress was 1.02 with a range of 1.01 to 1.03.

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TABLE I COMPARISON OF MEASURED AND COMPUTED STRESSES

Source	Mark	Initial Stress Ratio f_{si}/f_y %	Duration Hours	Final Stress Ratio $f_s/_{si}$ Measured %	Computed Eq. 1 %	Computed Eq. 3 %	Measured Stress / Computed Stress Eq. 1	Measured Stress / Computed Stress Eq. 3
Dawance [1948]	1	67	7,200	91	94	95	0.97	0.96
	2	67	7,200	90	94	95	0.96	0.95
	3	69	9,350	88	93	94	0.95	0.94
	4	69	9,350	87	93	94	0.94	0.93
	15	113	19,200	87	75	75	1.16	1.16
	16	113	19,200	87	75	75	1.16	1.16
	17	90	19,200	90	85	85	1.06	1.06
	18	90	19,200	91	85	85	1.06	1.07
Gifford [1953]	1	98	10,080	84	84	83	1.00	1.01
	20	97	10,080	84	84	83	1.00	1.01
	2	87	10,080	91	88	87	1.03	1.05
	19	87	10,080	89	88	87	1.01	1.02
	3	78	10,080	94	91	91	1.03	1.03
	18	75	10,080	93	92	92	1.01	1.01
	4	61	10,080	97	95	98	1.02	0.99
	17	61	10,080	97	95	98	1.02	0.99
	5	50	10,080	96	96	..	1.00	..
	16	50	10,080	97	96	..	1.01	..
Levi [1958]	1	72	75,000	88	91	92	0.97	0.96
	2	72	74,800	88	91	92	0.97	0.96
	3	80	72,000	82	89	88	0.92	0.93
	4	74	73,600	84	91	91	0.92	0.92
	5	77	73,600	83	89	89	0.93	0.93
	6	88	63,100	86	85	84	1.01	1.02
	7	100	17,700	89	82	81	1.08	1.10
	8	96	52,800	91	82	81	1.11	1.12
	9	74	53,000	90	91	90	0.99	1.00
	12	91	14,200	88	87	85	1.01	1.03
	13	99	47,300	90	80	80	1.12	1.12
	16	69	40,500	91	92	94	0.99	0.97
	19	77	39,100	92	90	90	1.02	1.02
	21	77	36,800	92	90	90	1.02	1.02
	22	88	36,800	93	86	85	1.08	1.09
	31	74	32,600	94	91	91	1.03	1.03
	32	64	32,600	96	94	96	1.02	1.00
Appendix A	OT101	69	41,139	90	92	94	0.98	0.96
	OT102	78	44,140	88	90	89	0.98	0.99
	OT103	83	44,140	85	88	87	0.97	0.98
	OT104	88	44,137	85	86	85	0.99	1.00
	OR210	85	81,720	87	87	85	1.00	1.02
	OR303-P	72	28,201	94	92	92	1.02	1.02
	OR304	72	28,201	95	92	92	1.03	1.03
	OR305	81	28,321	93	89	88	1.04	1.06
	OR306-P	81	28,321	93	89	88	1.04	1.06
	OR307-P	97	68,930	88	80	80	1.10	1.10
	OR308	95	68,560	85	82	81	1.04	1.05
	OR309-P	90	68,270	87	85	83	1.02	1.05
	OR310	90	68,270	87	85	83	1.02	1.05
	OR401-P	95	21,746	88	84	83	1.05	1.06
	OR402	94	21,745	88	85	83	1.03	1.06
	OR403-P	84	68,240	87	87	86	1.00	1.01
	OR404	85	21,743	85	88	87	0.97	0.98
	OR405	85	68,160	87	87	86	1.00	1.01
	NR101	58	44,303	93	95	99	0.98	0.94
	NR102	66	44,303	89	93	95	0.96	0.94
	NR103	77	44,304	86	90	90	0.96	0.96
	NR104	84	44,305	84	88	86	0.95	0.98
	NR105	88	44,309	83	86	85	0.97	0.98

APPENDIX A

TESTS AT THE UNIVERSITY OF ILLINOIS

Object

The object of the investigation at the Structural Research Laboratory of the University of Illinois Civil Engineering Department was to study the effects of time, level of initial stress, type of wire, and prestretching on the relaxation losses of prestressing wire.

Scope

A total of 57 specimens were tested, the longest reported test duration being 9 years. All tests were carried out on approximately 3-ft pieces of 0.2-in. prestressing wire.

The level of initial stress varied from 51 to 88.5 percent of the tensile strength of the specimen.

The prestressing wires tested were received from different manufacturers and had been given different treatments as described in a following section.

To study the effects of prestretching, pairs of specimens were tested, each pair at a given initial stress level. One of the wires of each pair was prestretched to a stress 10 percent greater than the desired stress and held there for 10 to 15 minutes before being anchored at the desired stress.

Outline of Tests and Designation of Test Specimens

The test specimens were cut from wire received from four different manufacturers and were subjected to six different types of treatment as shown at the bottom of this page.

The NR wire is distinguished from the OR wire in that the NR wire lies nearly straight when it is cut from the coil while the OR wire describes an arc with a radius of curvature of approximately six feet.

In the designation of the test specimens, three numerals follow the letters, e.g., SO101. The first numeral designates the coil from which the specimen was cut, the remaining two numerals distinguish that particular specimen from others cut from the same coil. The presence of a letter P after the numerals indicates that the specimen has been prestretched, e.g., OR202-P.

Description of Wire Properties

Specimens designated by the prefixes SO, SR, OR, and NR, with the exception of series OR400, were cut from wire manufactured by the American Steel and Wire Division of the United States Steel Corporation.

Designation	Manufacturer	Treatment	Number of Specimens
SO	AS&W[a]	Straightened, not stress-relieved	6
SR	AS&W	Straightened, stress relieved	8
OR	AS&W and UWR[b]	Stress relieved	32
NR	AS&W	Stress relieved	5
OT	Wickwire	Oil tempered	4
B	Somerset[c]	Special treatment to reduce relaxation loss	2

[a] American Steel and Wire Division of United States Steel Co.

[b] Union Wire Rope Corporation

[c] Somerset Wire Company Ltd., U.K.

The wire was drawn from high-carban open-hearth steel with the following ranges of chemical analysis: Carbon, 0.75-0.86 percent; Manganese, 0.50-0.90 percent; Silicon, 0.20 to 0.27 percent; Phosphorus, 0.045 percent maximum, and Sulphur, 0.050 percent maximum. The straight wire was straightened mechanically. Stress-relieving was accomplished for types SR and OR by immersion in hot lead at 800°F for a period of 5 to 15 sec.

The specimens of series OR400 were cut from wire manufactured by the Union Wire Rope Corporation of Kansas City, Missouri. This wire was drawn from a heat with the following chemical analysis: Carbon, 0.85 percent; Manganese, 0.84 percent; Phosphorus, 0.010 percent; Sulphur, 0.029 percent; and Silicon, 0.018 percent. The wire was stress-relieved and not straightened.

The specimens of series OT were cut from straight oil-tempered wire manufactured by the Wickwire Spencer Company.

The wire used in series B was manufactured specially to reduce relaxation losses by the Somerset Wire Company Ltd. of the U.K. The heat analysis was approximately in the following ranges: Carbon, 0.8 to 0.85 percent; Manganese, 0.6-0.8 percent; Sulphur, 0.05 percent maximum and Phosphorus, 0.05 percent maximum.

The stress-strain curves based on 8-in. gage lengths for all of the wires are shown in Fig. A.1. The tensile properties used in the study of the data are listed in Table A.1. The wire diameters for the different series are shown below.

Series	Measured Diameter
SO100	0.192
SR100	0.192
OT100	0.192
OR100	0.192
OR200	0.195
OR300	0.196
OR400	0.198
OR500	0.196
NR100	0.196
B100	0.200

Test Equipment

Because of the simplicity of the stressing frame and the small amount of laboratory space required, the vibration technique used by Dawance [1948] was adopted for the measurement of relaxation losses.

Wire specimens were mounted in steel frames which were fabricated from 3-ft. lengths of 8 by 8-in. wide-flange beam sections. Plates 1.5 in. thick were welded at the ends of the wide-flange section to provide abutments for the stressed wires. These end plates were drilled to accommodate four wires in each test frame.

In order to provide definite nodal points near the ends of the specimen when vibrated, quarter-inch screws were mounted in tapped holes in the beam flanges so that these screws could be adjusted to barely touch the wire.

Two types of anchorages were used to hold the stretched wires. For specimens with an initial stress up to about 70 percent of the tensile strength of the wires, threads were cut on the ends of the specimen and a hardened steel nut was run over the threads to bear against the end plates of the test frame. For specimens with an initial stress greater than about 70 percent of the tensile strength of the wire, the anchoring grip consisted of three hardened tapered wedges from a commercial 6 BWG-size Strandvise grip bearing on an internally tapered stud. Whenever this type of anchorage was used, 0.0001-in. dial

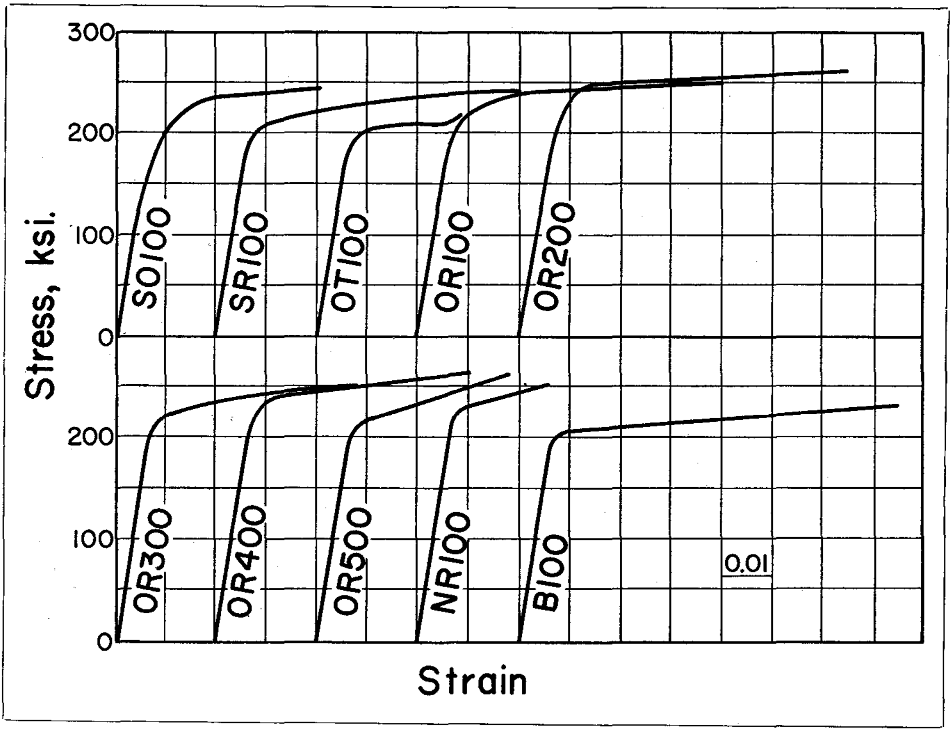

Fig. A.1—Stress-Strain Curves.

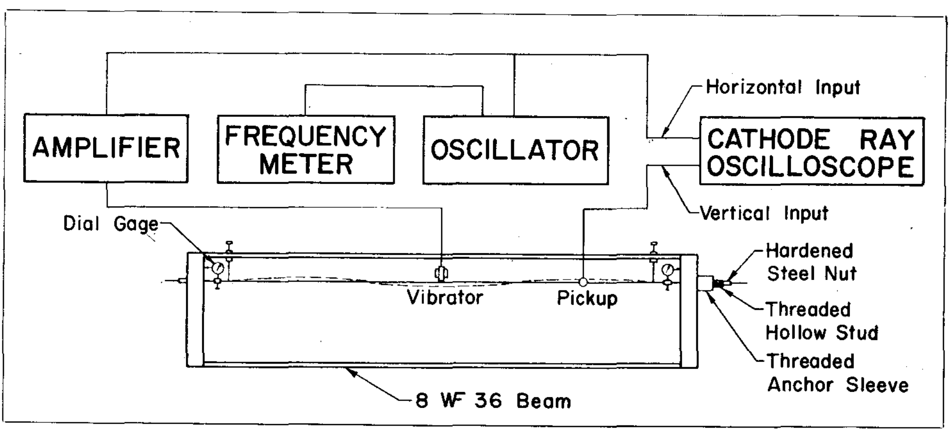

Fig. A.2—Schematic View of Test Setup.

gages were mounted on the ends of the specimen to measure slip at the anchorage, if any.

The wire was stressed by anchoring one end, and applying a force on the other end with a center-hole hydraulic jack; a pull-rod bearing on the ram was devised to grip the wire. When the wire was stressed to the desired level, anchorage was effected by turning the anchorage nut so that it made positive contact with the bearing plate or by turning the stud against the bearing plate so that the Strandvise grips locked the wire, depending upon the type of anchorage used.

The applied force was measured with a dynamometer incorporated in the pull-rod. This dynamometer, equipped with SR-4 strain gages, was calibrated at 10 lb per dial division on the strain indicator which could be read reliably to one-half dial division.

The electrical apparatus employed to vibrate the wire, to observe the resonant vibration of the wire and to measure the frequency of vibration, is shown schematically in Fig. A.2.

The main components of the electrical apparatus were:

(1) An oscillator, with variable frequency output.

(2) A frequency counter which counted the number of cycles in 10 seconds of the oscillator output, and hence gave the oscillator frequency correct to 0.1 cycles per second.

(3) An electromagnetic vibrator, fed by the oscillator through a variable-output amplifier. The vibrator was mounted about 1/32-in. from the wire,

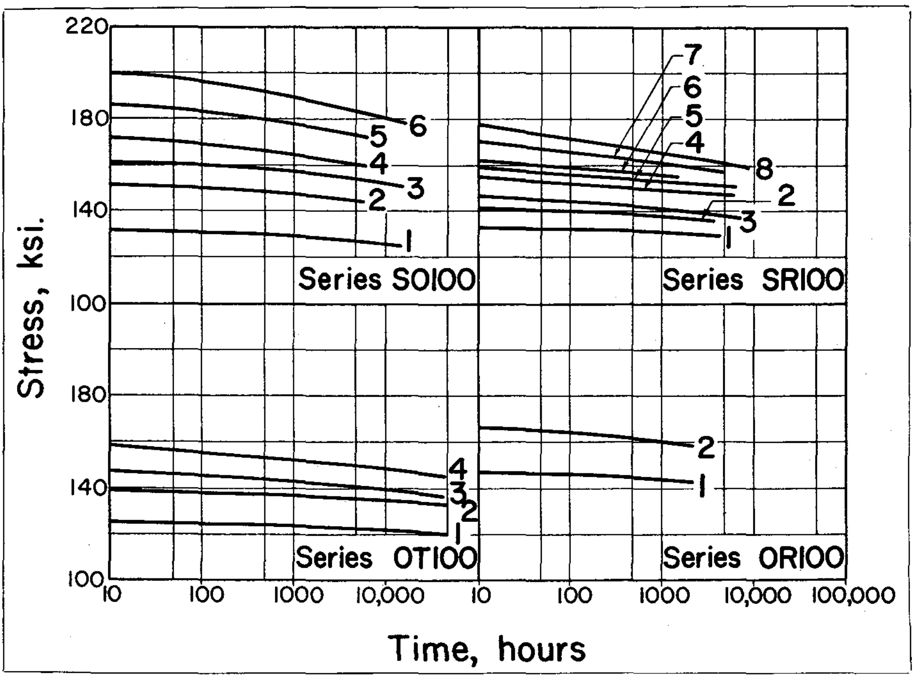

Fig. A.3—Measured Variation of Steel Stress with Time; Series SO100, SR100, OT100, and OR100.

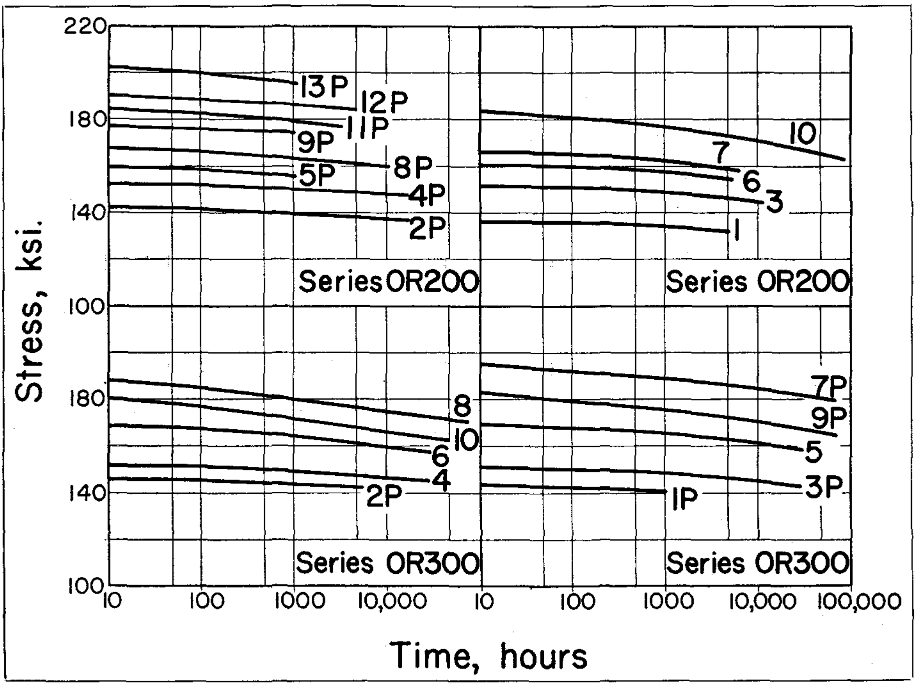

Fig. A.4—Measured Variation of Steel Stress with Time; Series OR200 and OR300.

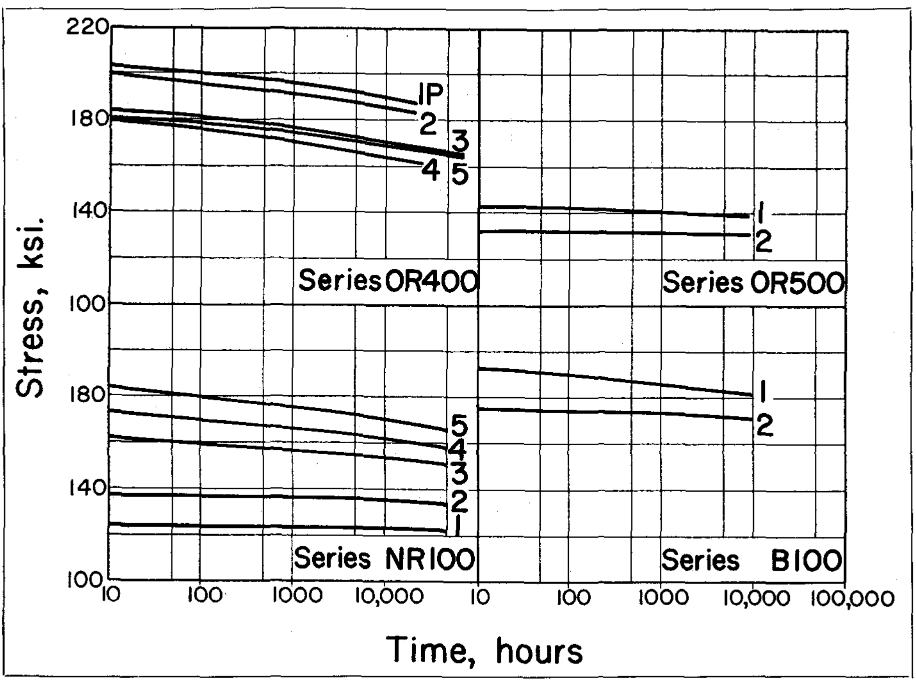

Fig. A.5—Measured Variation of Steel Stress with Time; Series OR400, NR100, and B100.

TABLE A.1

RESULTS OF TESTS AT THE UNIVERSITY OF ILLINOIS

Mark	Strength f'_s ksi	0.1% Offset Stress f_y ksi	Stress at 1% Strain f'_y ksi	Initial Stress f_{si} ksi	Initial / Offset f_{si}/f_y %	Initial / Stress at $\epsilon_s = 1\%$ f_{si}/f'_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
SO101	244.0	150.0	203.0	135.2	90.2	66.7	–	–	13,060	92.5
SO102	244.0	150.0	203.0	159.0	106.0	78.3	–	–	5,667	90.0
SO103	244.0	150.0	203.0	169.1	112.8	83.3	–	–	13,061	89.0
SO104	244.0	150.0	203.0	181.3	120.9	89.3	–	–	5,692	88.2
SO105	244.0	150.0	203.0	200.0	133.3	98.5	–	–	5,692	86.3
SO106	244.0	150.0	203.0	216.0	144.0	106.3	–	–	12,946	83.0
SR101	240.0	201.0	210.0	134.2	66.8	63.9	–	–	4,680	94.1
SR102	240.0	201.0	210.0	145.3	72.3	69.2	–	–	4,060	91.9
SR103	240.0	201.0	210.0	150.8	75.0	71.8	–	–	7,095	90.6
SR104	240.0	201.0	210.0	160.0	79.6	76.2	–	–	4,874	89.5
SR105	240.0	201.0	210.0	165.7	82.5	78.9	–	–	4,824	88.3
SR106	240.0	201.0	210.0	170.1	84.6	81.1	–	–	1,775	90.2
SR107	240.0	201.0	210.0	180.4	89.8	85.9	–	–	4,660	83.7
SR108	240.0	201.0	210.0	194.0	96.5	92.4	–	–	7,155	82.1
OT101	214.0	193.5	198.0	133.0	68.8	67.2	–	–	41,139	90.3
OT102	214.0	193.5	198.0	150.5	77.8	76.0	–	–	44,140	87.8
OT103	214.0	193.5	198.0	160.0	82.7	80.8	–	–	44,140	85.2
OT104	214.0	193.5	198.0	171.0	88.4	86.4	–	–	44,137	84.7
OR101	250.0	206.0	221.0	146.1	70.9	66.1	–	–	1,896	97.5
OR102	250.0	206.0	221.0	170.0	82.5	76.9	–	–	2,015	93.0
OR201	264.0	218.0	237.0	136.0	62.4	57.4	–	–	4,604	97.8
OR202-P	264.0	218.0	237.0	142.7	65.4	60.3	153.7	15	11,948	96.3
OR203	264.0	218.0	237.0	151.8	69.6	64.1	–	–	11,934	95.9
OR204-P	264.0	218.0	237.0	152.8	70.1	64.5	165.2	15	11,903	96.4
OR205-P	264.0	218.0	237.0	161.0	73.9	67.9	176.0	15	1,011	97.5

OR206	264.0	218.0	237.0	161.8	74.3	68.3	—	—	4,560	95.9
OR207	264.0	218.0	237.0	167.5	76.8	70.7	—	—	11,980	93.8
OR208-P	264.0	218.0	237.0	168.5	77.3	71.1	186.9	15	4,442	94.4
OR209-P	264.0	218.0	237.0	179.0	82.1	75.5	205.0	15	1,229	95.1
OR210	264.0	218.0	237.0	186.5	85.5	78.6	—	—	81,720	87.2
OR211-P	264.0	218.0	237.0	186.8	85.6	78.8	204.5	15	944	96.5
OR212-P	264.0	218.0	237.0	194.0	89.0	81.9	220.7	15	4,370	92.3
OR213-P	264.0	218.0	237.0	209.0	95.8	88.2	229.7	15	1,205	93.9
OR301-P	255.0	210.0	215.0	142.0	67.6	66.0	153.5	10	5,040	97.5
OR302-P	255.0	210.0	215.0	145.0	69.0	67.4	158.5	10	5,040	95.9
OR303-P	255.0	210.0	215.0	151.0	71.9	70.2	167.5	10	28,201	94.2
OR304	255.0	210.0	215.0	152.0	72.4	70.7	—	—	28,201	95.5
OR305	255.0	210.0	215.0	170.0	81.0	79.0	—	—	28,321	92.7
OR306-P	255.0	210.0	215.0	170.0	81.0	79.0	187.0	10	28,321	92.6
OR307-P	255.0	210.0	215.0	202.7	96.6	94.4	224.4	10	68,930	88.4
OR308	255.0	210.0	215.0	200.0	95.2	93.0	—	—	68,560	84.8
OR309-P	255.0	210.0	215.0	190.0	90.5	88.4	207.5	10	68,270	87.4
OR310	255.0	210.0	215.0	188.0	89.5	87.4	—	—	68,270	87.5
OR401-P	266	223	234	212.6	95.4	91.0	234.4	10	21,746	88.1
OR402	266	223	234	209.7	94.1	89.6	—	—	21,745	88.4
OR403-P	266	223	234	188.4	84.5	80.5	205.2	10	68,240	87.0
OR404	266	223	234	189.0	84.8	80.8	—	—	21,743	84.6
OR405	266	223	234	189.0	84.8	80.8	—	—	68,160	86.8
OR501	264	208	225	143.4	69.0	63.8	—	—	8,944	96.3
OR502	264	208	225	134.4	64.6	59.7	—	—	8,944	96.5
NR101	255	227	231	132.0	58.1	57.1	—	—	44,303	92.6
NR102	255	227	231	149.0	65.6	64.5	—	—	44,303	89.3
NR103	255	227	231	175.0	77.1	75.7	—	—	44,304	86.5
NR104	255	227	231	190.8	84.1	82.6	—	—	44,305	83.7
NR105	255	227	231	200.0	88.1	86.5	—	—	44,309	83.3
B101	234	201	204.5	203.0	101	99.2	—	—	9,703	89.1
B102	234	201	204.5	180.1	89.6	88.2	—	—	8,735	95.7

at its midpoint.

(4) An ear-phone, mounted close to the wire to pick up the forced vibration of the wire.

(5) A cathode-ray oscilloscope; the output of the oscillator was fed directly into the horizontal deflecting plates, and the current generated in the ear-phone by the vibrating wire was fed into the vertical deflecting plates.

When the oscillator frequency coincided with the natural frequency of the wire, a "figure eight" was obtained on the oscilloscope, since the wire made one complete oscillation for both the positive and negative half-cycles of the driving current.

The wire was vibrated in the third mode for two reasons: (1) It reduced the effects of uncertainties regarding the end conditions of the wires, and (2) it raised the frequency of the wire to a pitch at which it was audible, and hence the resonant frequency could be located approximately by ear. Thus, the resonant position was indicated by three means:

(1) sound,

(2) appearance of a "figure eight" on the oscilloscope, and

(3) reaching of the maximum vertical dimension of the figure on the oscilloscope.

The maximum vertical dimension of the figure eight increased greatly at resonance necessitating reduction in the amplification of the oscillator output.

Test Procedures and Results

The frequency of vibration of a stressed string is given by the expression

$$f = \frac{k}{2L}\sqrt{\frac{Tg}{w}} \qquad \text{(A.1)}$$

where f = frequency of lateral vibration

$k = 1, 2, 3, \ldots \infty$

L = length of string

T = force

w/g = mass per unit length

Equation A.1 was not directly applicable to the test conditions because the wires had a finite, though small, bending stiffness and the test frames were not absolutely rigid. However, a linear calibration could be obtained between the stress in the wire and the square of the frequency for a particular mode of vibration. Therefore, the stress in the wires was determined from individual calibrations. The calibration was obtained by making several frequency measurements as the wire was stressed to the desired level for series SO100, SR100, OR-100, OR200, and OR300. Since it was felt that this procedure might affect relaxation losses, the calibration was obtained for the remaining series from two calibration tests on identical wire samples prior to the stressing of the actual test specimen in a particular position in the test frame.

Thus, in some tests the desired level of stress was reached in five increments, with the frequency measured at each increment, while in others the desired stress was reached on one increment. As soon as this stress was reached the wire was anchored and the third-mode frequency was read immediately. This reading was taken to indicate the initial stress level in the wire. The dial gages, if any, were set as soon as the frequency reading was made.

The wire was subsequently vibrated at suitable intervals of time to obtain the stress in the wire and changes in the dial gage readings, if any, were noted. Several readings were taken in the first hour of test and later at greater intervals of time, in accordance with the decreasing rate of relaxation.

The test results for the 57 specimens are reported in detail in Fig. A.3, A.4, A.5 and Table A.1.

APPENDIX B
TESTS AT VARIOUS LABORATORIES

The following sections contain brief summaries of research on relaxation characteristics of prestressing reinforcement reported in the literature. The data from each investigation are tabulated at the end of this appendix.

Swiss Federal Testing Laboratory—1946

(a) *Object and Scope*

E.M.P.A. Report No. 155, a comprehensive report on prestressed concrete, included results of relaxation tests on 0.126-in. diameter, cold-drawn Swedish wire. Three wires with tensile strength of 279 ksi, were tested at initial stresses of 56, 66 and 76 percent of tensile strength for periods of 11, 16 and 56 days, respectively.

(b) *Results and Conclusions*

At initial stress of 56, 66 and 76 percent of tensile strength, losses were 2.7, 5.0, and 9.3 percent of the initial stress, respectively. It was observed that the relaxation loss increased with increase in initial stress. It was felt that the test periods were sufficiently long to observe the total relaxation loss.

Dawance—1948

(a) *Object and Scope*

The tests conducted by Dawance were carried out to determine the relaxation characteristics of 0.08-in., 0.1-in. and 0.2-in. diameter cold-drawn wires. The initial stress on the 0.1-in. diameter wire ranged from 67 to 113 percent of the 0.2 percent proof stress and the initial stress on the 0.2-in. diameter wire was varied between 0.62 and 1.17 of the 0.2 percent proof stress. The duration of test extended from about 6.5 days to over two years.

To measure the stress in the specimens, the vibration technique was developed as part of the research program.

(b) *Results and Conclusions*

The maximum losses recorded for the 0.1-in. diameter wire were about 13 percent of initial stress at time of about 2 years. For the same diameter wire, losses of about 10 percent were observed at 300 days. The greatest losses obtained for the 0.2-in. diameter wire were 9 percent of initial stress when the initial stress was 111 percent of the 0.2 percent proof stress.

The author noted that for wires whose stress versus logarithm of time plots exhibited a point of contraflexure, it would be possible to establish a limit of relaxation.

Magnel—1948

(a) *Object and Scope*

The purpose of the author's paper was to present results of creep tests on concrete and creep and relaxation tests on prestressing wire, and to draw conclusions from these results.

The relaxation losses were measured for a period of over 300 hours on two 82 ft. specimens of 0.2-in. cold-drawn wire. The initial stress of both specimens was 123,000 psi or 85 percent of the 0.1-percent offset stress.

For one specimen, an overstress of 137,000 psi was held for two minutes and then the stress was reduced to 123,000 psi. The initial stress for the second specimen was applied directly with no overstress.

(b) *Results and Conclusions*

For the specimen not subjected to prestretching, the loss was 12 percent of initial stress at the end of 12 days and was considered to be the complete stress reduction for the wire.

After two days, the loss for the prestretched specimen was 4 percent of the initial stress. The author felt this to be the limiting value of loss for the specimen.

Spare—1952, 1954

(a) *Object and Scope*

The object was to provide users of high strength wire with information on stability of stress over long periods of time.

The 1952 tests included two specimens of 0.192-in. diameter cold-drawn wire at initial stresses of 60 and 70 percent of tensile strength.

The relaxation tests conducted in 1954 consisted of nine cold-drawn and five stress-relieved specimens 0.2-in. in diameter. Initial stress varied from 54 to 93 percent of tensile strength.

For both series of tests, the facilities and procedures were the same. The specimens were 100-ft. long with wire stress measured by the aid of a load cell using the balancing technique (See Chapter 2). The test duration was 1000 hours for all specimens.

(b) *Results and Conclusions*

In comparing losses of cold-drawn and stress-relieved wire, the author concluded that, for initial stresses below 60 to 70 percent of tensile strength, stress-relieved wire had losses which are less than those for cold-drawn wire. For initial stresses above approximately 70 percent of tensile strength, cold-drawn wire had losses greater than those for stress-relieved wire.

It was noted that the rate of loss diminished rapidly and the results obtained at 1000 hours should be close to the final value for loss.

Bannister—1953

(a) *Object and Scope*

Tests were made primarily to study the effect of heat treatment on the relaxation characteristics of cold-drawn wire.

Four types of specimens were tested in the series for a duration of 250 hours. Specimens designated 1 and 2 were in the as-drawn condition, however, specimens 2 were produced by smaller reductions of area in the drawing process. To determine the effect of heat treatment on relaxation losses, two types of stress-relieved wires were tested. The stress-relieved specimens were designated 1-H and 1-H-T where T indicates that the wire was stress-relieved under tension. The wires were tested under initial stresses varying from 69 to 119 percent of the 0.1-percent proof stress to cover the range normally used in prestressed concrete construction.

As part of the test program, the tensile strength of wire 1 was measured after cooling from temperatures ranging from 212°F to 935° F.

(b) *Results and Conclusions*

The heat-treated specimens, 1-H, had lower losses than the as-drawn wires, 1, at the lower initial stresses, but had losses greater than those for wires 1 at the higher initial stresses. However, the wires heat treated under tension had lower losses than the as-drawn wire regardless of the initial stress and also had lower losses than the heat-treated specimens 1-H throughout the range of initial stress.

From the results of the tensile strength temperature tests a plot was made showing the tensile strength at the various temperatures. In the range 390°F to 750°F, the tensile strength is either unchanged or increased. Outside this range of temperatures the tensile strength was reduced.

In the conclusions of the paper the author states: "The characteristics of drawn wires are not a simple function of either diameter or maximum strength, but are dependent on the basic material and its treatment, and the extent and manner of subsequent cold reduction and aging. The relaxation of such wires is not related to elastic characteristics or the maximum strength or elongation at this stress."

Clark and Walley—1953

(a) *Object and Scope*

The object of this investigation was to determine the relaxation losses of cold-drawn wires obtained commercially.

The wires obtained were 0.104 in., 0.2 in. and 0.276 in. in diameter and had tensile strengths ranging from 225 ksi to 320 ksi. In testing the wires, a lever apparatus was arranged to accommodate specimens about 40 ft. in length. This length was chosen as an approximation of lengths commonly found in prestressed concrete beams. To determine whether a general relationship existed between relaxation loss and initial stress, the test series covered a wide range of initial stress, 29 to 117 percent of the 0.1-percent offset stress. A total of 23 specimens were tested for a duration of 1000 hours.

(b) *Results and Conclusions*

The authors felt that relaxation loss in a wire is a function of the initial stress and a property of the wire probably dependent on residual stresses and the crystalline structure. The characteristics of the wire would show up in the shape of the stress-strain curve and in the value of tensile strength and ultimate elongation. It was observed that losses were greater for wires wound on small diameter coils than for wires straightened and wound on large diameter coils. Relaxation loss increased at an increasing rate for initial stress levels greater than 40 percent of the 0.1-percent offset stress.

The authors felt that relaxation losses could be reduced by overstressing, especially in pretensioning operations since a large portion of the loss occurs after tensioning and before release.

Gifford—1953

(a) *Object and Scope*

Gifford tested 10 specimens of 0.2-in. diameter prestressing wire for a duration of over 400 days. Two specimens were tested at each of five levels of initial stress which ranged from 50 to 90 percent of tensile strength in approximately 10-percent increments. At each level of initial stress, one specimen was prestretched for two minutes to a load five percent of tensile strength above the intended initial stress. The stress was determined by measuring the lateral deflection of the 17.5 ft. specimen.

(b) *Results and Conclusions*

Gifford noted that for initial

stresses up to 60 percent of the tensile strength, the loss at 420 days was five percent or less of the initial stress and should reach a limiting value of about seven percent. Since losses caused by creep and shrinkage of concrete in prestressed concrete would reduce the initial stress, the value of five percent stress loss due to relaxation was sufficient allowance in design. For initial stresses greater than 60 percent of tensile strength, a higher allowance must be made.

Based on the test results, the author concluded that the effect of prestretch became significant only for wires with initial stress greater than 60 percent of tensile strength.

deStrycker—1953

(a) *Object and Scope*

One of the earlier investigators of relaxation characteristics of prestressing wire was deStrycker who reported some test results as early as 1948 and also in 1951. However, 1953 was the year when his most comprehensive report was published.

Tests were carried out by deStrycker to develop reliable and practical testing methods for the steel industry as well as to investigate the mechanism of the relaxation phenomenon and its relation to creep. Various types of wire were tested at an initial stress of approximately 60 percent of the tensile strength of the wire.

(b) *Results and Conclusions*

The 1953 reference by deStrycker contains the results of 291 relaxation tests in addition to creep tests on prestressing wire. However, the test duration for 241 of these tests was limited to 23 hours. The results of 50 tests with durations of 72 (32 tests) and 360 (18 tests) hours are listed in Table B.8.

For drawn wires under ordinary ranges of prestress, deStrycker concluded that creep and relaxation could be expressed approximately as functions of the logarithm of time and that short-duration tests limited to a few days or even a few hours could be used to predict long-time relaxation losses. However, for heat-treated or aged wires, it was not possible to predict the maximum relaxation loss on the basis of short-duration tests.

Prestretching was not found to have a significant effect on relaxation losses.

Burnheim—1954

(a) *Object and Scope*

The results of 1000-hour relaxation tests on nine 51-ft. specimens of 0.2-in. diameter wire and four specimens of 0.28-in. diameter were presented by Burnheim. The specimens, with tensile strengths ranging from 224 to 246 ksi, were subjected to various levels of initial stress varying between 70 and 190 ksi.

(b) *Results and Conclusions*

The losses measured at 1000 hours increased with increasing initial stress. At the lowest value of initial stress, 70 ksi, losses were one to four percent of initial stress while for the highest value of initial stress, 190 ksi, loss was nine percent of initial stress.

Schwier—1955

(a) *Object and Scope*

The loss of prestress for various types of steel was investigated by tests on 16 specimens. Four types of specimens were tested: stress-relieved and nonstress-relieved wires and strands. The strand was made up of seven wires each of

0.118 in. diameter with a tensile strength of either 258, 266 or 278 ksi. For the wires tested, the diameter varied between 0.158 and 0.407 inches and the tensile strength ranged from 238 to 270 ksi. To measure stress in the specimen, a lever arrangement was used. The specimens were tested for 1000 hours at levels of initial stress from about 48 to 92 percent of the tensile strength.

(b) *Results and Conclusions*

The results of the relaxation tests showed that up to an initial stress of about 70 percent of tensile strength nonstress-relieved specimens exhibited greater loss of stress than stress-relieved specimens. From this observation, the author concluded that stress-relieved steel is more favorable for use in prestressing.

C.U.R. [The Dutch Committee for Research]–1958

(a) *Object and Scope*

The tests were carried out to investigate the relaxation characteristics of cold-drawn and hot-rolled wire. A total of 21 specimens were tested for periods ranging from 300 to 3000 hours. Five types of wires were included: (1) cold-drawn, (2) cold-drawn and straightened, (3) cold-drawn and martempered, (4) cold-drawn and aged, and (5) hot-rolled, hardened and tempered.

The wires had a nominal diameter of 0.20 in. The initial stress varied from 62 to 118 percent of the 0.1 percent offset stress.

The lever system was used to measure the stress.

(b) *Results and Conclusions*

The results are shown in Table B.10. The major conclusion was that a test duration of 3000 hours is insufficient to make predictions about the maximum loss expected.

Dumas–1958

(a) *Object and Scope*

Results are presented to show the effect of prestretch on relaxation losses. Twenty-six specimens were tested at levels of initial stress ranging from about 60 to 90 percent of the tensile strength. No information was given on the type of wire and size of specimens. At each level of initial stress, one specimen was not overstressed; other specimens were prestretched for two minutes at various amounts of overstress. The duration of tests varied from 500 to 1500 hours.

(b) *Results and Conclusions*

It is concluded that prestretching is an effective technique to reduce relaxation loss. As overstress was increased for a particular level of initial stress, measured losses were reduced. It must be noted, however, that even for prestretched specimens, losses were substantial. This was particularly true for specimens tested at high initial stress. At 1000 hours, specimens with no overstress and an initial stress of 85 to 88 percent of tensile strength had losses amounting to 13 percent of initial stress while for specimens at the same level of initial stress and subjected to prestretching at the initial stress for two minutes, loss was measured to be from 14 to 15 percent of the initial stress.

Kajfasz–1958

(a) *Object and Scope*

A series of relaxation tests were conducted on 0.1-in. cold-drawn wire. The specimens tested were of two types: single wire and twin-twisted strand in which the pitch of twist was varied from 0.9 in. to infinity. Forty-six specimens of each type were tested for durations which varied from 10 to 130 days (Results are reported for only 80 tests). Initial stresses applied to the single strand specimens ranged from 77 to 108 percent of the 0.2-percent offset stress. Twelve of the single strand specimens were overstressed 10 percent above the initial stress for 10 minutes. All specimens were 79 in. long and were mounted in steel frames of rolled sections. To maintain constant length during the test period, a lever system was arranged such that weights were removed from an arm as wire stress decreased. From the statics of the system, wire stress was determined.

(b) *Results and Conclusions*

The author compared results obtained for the series of tests conducted with other published results. He concluded that the basis of comparison of relaxation tests should be the ratio of initial stress to the 0.2-percent offset stress.

The results of Kajfasz's tests on the single wire strand and results reported by Levi were used to study the relation between rate of relaxation and time. The following formula was developed to describe relaxation loss:

$$f_r = c(\log t - \log t_o)$$

where f_r = relaxation in kg/mm^2

c = a parameter depending on the ratio of initial stress to the 0.2-percent offset stress

$\log t$ = natural logarithm of time in minutes

$\log t_o$ = natural logarithm of time in minutes at which first reading was taken.

The parameter c was evaluated by assuming it was a linear function of the ratio of initial stress to offset stress. By including in the expression the loss occurring from zero time to the time at which the first reading was taken, the total loss at time, t, can be determined.

From extrapolation of the test results, Kajfasz noted that for an initial stress less than 0.55 of the 0.2-percent offset stress, losses are not of practical significance.

The parameter, c, was also evaluated for the twin-twisted strands. For values of initial stress less than the 0.2-percent offset stress, the value of c was nearly the same as that for single wire strand.

In evaluating the effect of prestretching on companion specimens at the same level of initial stress, Kajfasz noted that only in the verv early stages of the test was there a noticeable difference in losses between the prestretched and non-prestretched specimens. During the following period of testing, the losses were nearly identical for the companion specimens.

Levi—1958

(a) *Object and Scope*

At the Second and Third Congresses of the Federation Internationale de la Precontrainte, Levi presented results of an extensive series of tests on prestressing steel.

The diameter of the wires tested varied from 0.078 to 0.31 in. with tensile strengths of 182 ksi to 313 ksi. The initial stress applied to the specimens ranged from 52 to 90 percent of tensile strength.

Specimens were tested for durations of 120 hours to nearly nine years. From results of tests of long duration, it was felt that losses at 120 hours would indicate final values of loss, therefore, a considerable number of tests were terminated at that time.

(b) *Results and Conclusions*

Based on results of wires tested for long periods of time, the author concluded that the relaxation at 120 hours would be little more than half the final value. By carrying tests out to 120 hours, it would be possible to estimate the final value of relaxation loss.

In considering the results with respect to initial stress, the author stated that a stress of about 80 percent of the 0.2-percent proof stress can be maintained indefinitely.

Papsdorf and Schwier—1958

(a) *Object and Scope*

The authors studied the creep and relaxation of prestressing steel by conducting a survey of research literature and carrying out relaxation tests. The purpose was to examine behavior in an effort to arrive at a means of obtaining the loss of stress over a long period of time.

In the relaxation tests carried out, specimens were tested for 1000 hours at temperatures ranging from 72°F to 302°F. The specimens were made from a drawn and tempered wire 0.26 in. in diameter with a tensile strength of 254 ksi and the 0.2 percent proof stress of 224 ksi. To measure the loss of stress in the wire, a lever system was used which had a distance between anchorages of either 67 inches or 79 inches. The initial stress ranged from 43 to 96 percent of the tensile strength.

(b) *Results and Conclusions*

From their own tests and from others, the authors concluded that the strain versus logarithm of time curves in constant-stress tests and stress versus logarithm of time curves in relaxation tests exhibited a point of inflection which occurred after a length of time depending on the magnitude of the initial stress applied.

The results of relaxation tests at various temperatures showed that elevated temperatures produced higher relaxation losses at 1000 hours for initial stresses on the order of 55 to 60 percent of the tensile strength. With longer test periods the influence of temperature was noticed to be less. An increase in the initial stress had a similar effect in that the influence of temperature diminished for increasing loads.

The authors believe that tests at elevated temperatures will enable the relaxation curves to be determined fairly accurately without having to resort to excessively long test durations.

Jevtic—1959

(a) *Object and Scope*

Relaxation tests and tests of tensile strength at elevated temperatures were conducted by Jevtic as part of a program to determine the properties of cold-drawn wire manufactured in Jesenice, Yugoslavia.

The relaxation tests consisted of measuring losses on two series of specimens. One series of 0.1-in. diameter wire contained five specimens with f_{si}/f_y ranging from 0.91 to 1.19. In the second series, three wires of 0.2-in. diameter were subjected to f_{si}/f_y from 0.90 to 1.12. The test duration was 696 hours for the 0.1-in. diameter specimens. In the second series, the period of test was 720 hours for two specimens and 796 hours for the third specimen. Since the vibration method was used to measure wire stress, each specimen was mounted in a suitable steel frame. All wires tested had a free length of 80.7 in.

(b) *Results and Conclusions*

At the end of the test duration,

specimens of the first test series had losses ranging from 8.2 percent to 3.3 percent of the initial stress where the greater losses occurred in the wires with the higher initial stress. For the specimens of 0.2-in. diameter, losses at the final time ranged from 7.9 percent to 4.7 percent of the initial stress.

Kingham, Fisher and Viest—1961

(a) *Object and Scope*

As part of the bridge research at the AASHO Road Test, a study of the long-time behavior of prestressed concrete beams was carried out. In conjunction with the study, relaxation tests were conducted on stress-relieved prestressing steel used in the construction of bridge beams in the Road Tests.

The relaxation tests consisted of determining losses in two types of specimens: 0.192-in. diameter wire and seven-wire strand of 0.375-in. diameter with a mean cross-sectional area of 0.0806 square inches. Eight wire specimens and 10 specimens of seven-wire strand were tested for a minimum duration of 1000 hours with two specimens of each type observed for more than 7000 hours. To measure stress in the wires, the vibration technique was employed. For the seven-wire strand, a load cell was used to measure stress. Each specimen was mounted in a steel frame where the distance between anchorages was approximately 40 in. Initial stress for the specimens ranged from 60 to 78 percent of tensile strength.

(b) *Results and Conclusions*

From the results of the relaxation tests, the authors noted that substantial losses occurred beyond 1000 hours and although the rate of loss decreased with time, there was no indication that losses would approach a limiting value. At 1000 hours, losses for the wire specimens ranged from 4.2 to 9.0 percent of the initial stress while losses for the seven-wire strand varied between 2.0 and 6.1 percent of the initial stress.

In the analysis of test data, the authors developed a formula to be used in estimating relaxation losses in prestressed concrete beams. Using a modified form of similar formulas found in literature, the final expression was written as follows:

$$\Delta_r = f_i\left[\frac{f^i}{f'_s}\right]^c (1 - e^{-t/a})^b$$

where Δ_r = relaxation loss at time t

f_i = initial stress

f'_s = tensile strength

e = base of natural logarithm

t = time from application of initial stress in hours

a, b, c = empirical constants

Test data from 10 to 1000 hours was used to evaluate the empirical constants by multiple regression analyses. The authors concluded that the duration of their tests was not sufficient to provide information on the limiting value of the relaxation loss.

TABLE B.1
E.M.P.A. 1946

Mark*	Diameter in.	Strength f'_s ksi	Offset Stress** f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.126	279	240	156	65	—	—	288	97.3
2	0.126	279	240	185	77	—	—	388	95.0
3	0.126	279	240	213	89	—	—	1344	90.7

Length of Specimen: Not reported.
Type of Steel: Cold-Drawn single wire from Sweden.
Method of Stress Measurement: Not reported.
* Not indicated in original report.
** Based on 0.2 percent strain.

TABLE B.2
DAWANCE 1948

Mark*	Diameter in.	Strength f'_s ksi	Offset Stress** f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.10	284	226	152	67	—	—	7200	91
2	0.10	284	226	152	67	—	—	7200	90
3	0.10	284	226	152	69	—	—	9350	88
4	0.10	284	226	156	69	—	—	9350	87
5	0.20	224	183	114	62	—	—	156	96
6	0.20	224	183	114	62	—	—	156	95
7	0.20	224	183	152	83	—	—	228	97
8	0.20	224	183	152	83	—	—	228	97
9	0.20	224	183	204	111	—	—	156	91
10	0.20	224	183	204	111	—	—	156	91
11	0.20	224	183	182	99	—	—	408	94
12	0.20	224	183	182	99	—	—	408	93
13	0.20	224	183	214	117	—	—	288	92
14	0.20	224	183	214	117	—	—	288	92
15	0.10	284	226	256	113	—	—	19200	87
16	0.10	284	226	256	113	—	—	19200	87
17	0.10	284	226	204	90	—	—	19200	90
18	0.10	284	226	204	90	—	—	19200	91

Length of Specimen: 19.7 to 78.8 in.
Type of Steel: Cold-drawn single wire.
Method of Stress Measurement: Vibration.
* Not indicated in original report.
** Based on 0.2 percent strain.

TABLE B.3
MAGNEL 1948

Mark	Diameter in.	Strength f' ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
3	0.20	216	145	123	85	—	—	300	88
4	0.20	216	145	123	85	137	2	300	96.4

Length of Specimen: 82 ft.
Type of Steel: Cold-drawn single wire.
Method of Stress Measurement: Balancing.
* Based on 0.1 percent stress.

TABLE B.4
SPARE 1952 and 1954

Mark*	Diameter in.	Strength f'_s ksi	Offset Stress f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Stress / Initial Stress f_s/f_{si} %
1	0.20	223	–	145	–	–	–	1000	93
2	0.20	223	–	167	–	–	–	1000	93
3	0.20	253	–	222	–	–	–	1000	90
4	0.20	253	–	235	–	–	–	1000	88
5	0.20	260	–	141	–	–	–	1000	96
6	0.20	260	–	174	–	–	–	1000	93
7	0.20	260	–	208	–	–	–	1000	91
8	0.20	249	–	154	–	–	–	1000	95
9	0.20	249	–	172	–	–	–	1000	92
10	0.20	270	–	189	–	–	–	1000	93
11	0.20	249	–	179	–	–	–	1000	92
12	0.20	249	–	194	–	–	–	1000	87
13	0.20	240	–	168	–	–	–	1000	92
14	0.20	272	–	155	–	–	–	1000	97
15	0.192	250	–	155	–	–	–	1000	94
16	0.192	250	–	172	–	–	–	1000	92

Length of Specimen: 100 ft.
Type of Steel: Cold-Drawn (Specimens 11 through 15 were stress-relieved).
Method of Stress Measurement: Balancing.
* Not indicated in original report.

TABLE B.5
BANNISTER 1953

Mark	Diameter in.	Strength f'_s ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Stress / Initial Stress f_s/f_{si} %
1	0.20	226	150	134	89	–	–	250	96
1	0.20	226	150	157	105	–	–	250	96
1	0.20	226	150	179	119	–	–	250	94
2	0.20	241	195	134	69	–	–	250	97
2	0.20	241	195	157	80	–	–	250	96
2	0.20	241	195	179	92	–	–	250	95
1-H	0.20	235	150	134	89	–	–	250	97
1-H	0.20	235	150	157	105	–	–	250	95
1-H	0.20	235	150	179	119	–	–	250	92
1-H-T**	0.20	236	201	157	78	–	–	8	99
1-H-T**	0.20	236	201	179	89	–	–	8	99

Length of Specimen: 3 ft.
Type of Steel: Cold-drawn single wire (Specimens 1-H were heat-treated and specimens 1-H-T were heat-treated under tension).
Method of Stress Measurement: Lever.
* Based on 0.1 percent strain.
** Not included in over-all tally because of limited test duration.

TABLE B.6
CLARK AND WALLEY 1953

Mark	Diameter in.	Strength f'_s ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.104	260	177	52	29	—	—	1000	94
2	0.104	256	179	105	59	—	—	1000	92
3	0.104	260	177	157	89	—	—	1000	93
4	0.104	256	179	210	117	—	—	1000	90
5	0.104	308	224	70	31	—	—	1000	97
6	0.104	316	211	146	70	—	—	1000	95
7	0.104	311	211	175	83	—	—	1000	95
8	0.104	320	244	204	84	—	—	1000	94
9	0.104	320	244	232	95	—	—	1000	94
10	0.104	308	225	255	114	—	—	1000	90
11	0.20	225	125	70	44	—	—	1000	96
12	0.20	251	168	120	71	—	—	1000	95
13	0.20	248	161	130	81	—	—	1000	95
14	0.20	238	161	142	88	—	—	1000	92
15	0.20	238	161	152	95	—	—	1000	92
16	0.20	—	—	190	97	—	—	1000	92
17	0.20	251	212	70	33	—	—	1000	92
18	0.20	251	212	130	61	—	—	1000	98
19	0.20	251	212	170	80	—	—	1000	98
20	0.276	229	187	67	37	—	—	1000	95
21	0.276	229	187	101	55	—	—	1000	99
22	0.276	229	187	130	69	—	—	1000	98
23	0.276	225	187	168	90	—	—	1000	96

Length of Specimen: 40 ft.
Type of Steel: Cold-Drawn single wire.
Method of Stress Measurement: Lever.
* Based on 0.1 percent strain.

TABLE B.7
GIFFORD 1953

Mark	Diameter in.	Strength f'_s ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.20	241	210	207	98	219	2	10080	84
20	0.20	241	210	203	97	—	—	10080	84
2	0.20	241	210	182	87	194	2	10080	91
19	0.20	241	210	182	87	—	—	10080	89
3	0.20	241	210	164	78	176	2	10080	94
18	0.20	241	210	157	75	—	—	10080	93
4	0.20	241	210	129	61	141	2	10080	97
17	0.20	241	210	129	61	—	—	10080	97
5	0.20	241	210	104	50	116	2	10080	96
16	0.20	241	210	104	50	—	—	10080	97

Length of Specimen: 17 ft. 6 in.
Type of Steel: Single wire.
Method of Stress Measurement: Deflection.
* Based on 0.1 percent strain.

TABLE B.8
deSTRYCKER 1953

Mark	Diameter in.	Strength f'_s ksi	Offset Stress f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Stress / Initial Stress f_s/f_{si} %
B313	—*	—	—	121	—	—	—	72	95.7
B516	—*	—	—	121	—	—	—	72	95.4
B712	—*	—	—	121	—	—	—	72	95.8
SA03	0.274	223	—	123	—	—	—	360	95.7
SA13	0.274	223	—	123	—	—	—	72	96.5
SF03	0.274	229	—	124	—	—	—	360	95.7
SF13	0.274	229	—	124	—	—	—	360	96.2
SF23	0.274	229	—	124	—	—	—	72	96.8
SB03	0.238	239	—	121	—	—	—	72	96.7
SB13	0.238	239	—	121	—	—	—	360	95.8
SB23	0.238	239	—	121	—	—	—	72	96.7
SG04	0.236	236	—	121	—	—	—	360	96.2
SG14	0.236	236	—	121	—	—	—	72	97.0
SG24	0.236	236	—	121	—	—	—	360	97.0
SC06	0.198	236	—	120	—	—	—	72	95.9
SC16	0.198	236	—	120	—	—	—	360	95.1
SC23	0.198	236	—	120	—	—	—	72	96.0
SH03	0.198	236	—	121	—	—	—	72	97.3
SH13	0.198	236	—	121	—	—	—	360	96.3
SH23	0.198	236	—	121	—	—	—	72	97.1
SD05	0.157	245	—	119	—	—	—	72	95.7
SD13	0.157	245	—	119	—	—	—	72	95.7
SD23	0.157	245	—	119	—	—	—	360	94.7
SD34	0.157	245	—	119	—	—	—	72	96.1
SD43	0.157	245	—	119	—	—	—	72	95.8
SI03	0.157	256	—	124	—	—	—	360	95.6
SI13	0.157	256	—	124	—	—	—	72	96.6
SI23	0.157	256	—	124	—	—	—	72	96.7
PA02	0.277	222	—	135	—	—	—	360	97.7
PA12	0.277	222	—	135	—	—	—	72	98.2
PA22	0.277	222	—	135	—	—	—	72	98.2
PB02	0.199	252	—	150	—	—	—	72	98.4
PB12	0.199	252	—	150	—	—	—	72	99.1
PC02	0.159	234	—	141	—	—	—	360	97.2
PC12	0.159	234	—	141	—	—	—	72	98.3
PC22	0.159	234	—	141	—	—	—	72	98.3
PF04	0.198	239	—	152	—	—	—	360	98.5
PF14	0.198	239	—	152	—	—	—	360	98.4
PF23	0.198	239	—	152	—	—	—	72	99.0
PF33	0.198	239	—	152	—	—	—	72	98.9
PG03	0.278	220	—	136	—	—	—	360	97.6
PG14	0.278	220	—	136	—	—	—	72	98.0
PG23	0.278	220	—	136	—	—	—	72	98.2
PG33	0.278	220	—	136	—	—	—	72	98.3
BB03	0.276	228	—	136	—	—	—	360	97.8
BB14	0.276	228	—	136	—	—	—	360	97.1
BB23	0.276	228	—	136	—	—	—	72	98.5

TABLE B.8 (Cont.)

BC03	0.198	242	–	146	–	–	–	72	96.7
BC13	0.198	242	–	146	–	–	–	360	96.0
BC23	0.198	242	–	146		–	–	72	97.5

Length of Specimen: 10 to 22 in.
Type of Steel: Cold drawn single wire. Wires of Series P were aged. Wires of Series SA were straightened.
Method of Stress Measurement: Lever.
* Probably 0.2 in.

TABLE B.9
BURNHEIM 1954

Mark*	Diameter in.	Strength** f'_s ksi	Offset Stress f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.20	–	–	190	–	–	–	1000	91
2	0.20	–	–	150	–	–	–	1000	92
3	0.20	–	–	140	–	–	–	1000	92
4	0.20	–	–	130	–	–	–	1000	95
5	0.20	–	–	120	–	–	–	1000	95
6	0.20	–	–	70	–	–	–	1000	96
7	0.28	–	–	168	–	–	–	1000	96
8	0.28	–	–	130	–	–	–	1000	98
9	0.28	–	–	100	–	–	–	1000	99
10	0.28	–	–	67	–	–	–	1000	99
11	0.20	–	–	170	–	–	–	1000	95
12	0.20	–	–	130	–	–	–	1000	98
13	0.20	–	–	70	–	–	–	1000	98

Length of Specimen: 51 ft.
Type of Steel: Single wire.
Method of Stress Measurement: Lever.
* *Not indicated in original report.*
** reported to range from 224 to 246 ksi.

TABLE B.10
SCHWIER 1955

Mark*	Diameter in.	Strength f'_s ksi	Offset Stress** f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1a	0.158	270	210	149	71	–	–	1000	94.3
2a	0.158	270	210	176	84	–	–	1000	92.3
3a	0.158	270	210	203	96	–	–	1000	91.3
4a	0.158	270	210	229	108	–	–	1000	90.2
5a	0.158	270	210	248	118	–	–	1000	89.0
6b	0.407	246	229	123	54	–	–	1000	99.2
7b	0.389	238	214	135	64	–	–	1000	99.0
8b	0.368	249	228	149	66	–	–	1000	98.7
9c	7 × 0.118	266	192	133	70	–	–	1000	93.2
10c	7 × 0.118	258	192	156	82	–	–	1000	91.0
11c	7 × 0.118	258	192	181	95	–	–	1000	89.0
12d	7 × 0.118	278	260	132	51	–	–	1000	98.8
13d	7 × 0.118	278	260	162	62	–	–	1000	97.7

TABLE B.10 (Cont.)

14d	7 × 0.118	278	260	181	69	–	–	1000	96.2
15d	7 × 0.118	278	260	222	85	–	–	1000	91.5
16d	7 × 0.118	278	260	235	91	–	–	1000	88.2

Length of Specimen: 39.4 in.
Type of Steel: a–Cold-drawn wire; b–Stress-Relieved wire; c–Nonstress-Relieved 7 × 0.118″ strand; d–Stress-Relieved 7 × 0.118″ strand.
Method of Stress Measurement: Lever.
* Not indicated in original report.
** Based on 0.2 percent strain.

TABLE B.11
C.U.R. 1958

Mark	Diameter in.**	Strength f'_s ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
B-a	0.20	235	157	128	82	128	1	300	95
B-b	0.20	235	157	142	90	142	1	500	95
B-c	0.20	235	157	157	100	157	1	2000	92
B-d	0.20	235	157	171	109	171	1	300	94
C-a	0.20	232	145	128	88	128	1	300	95
C-b	0.20	232	145	142	98	142	1	300	94
C-c	0.20	232	145	158	109	158	1	3000	91
C-d	0.20	232	145	171	118	171	1	300	92
D-a	0.20	242	219	135	62	135	1	300	97
D-b	0.20	242	219	142	65	142	1	500	97
D-c	0.20	242	219	150	69	150	1	300	97
D-d	0.20	242	219	166	76	166	1	3000	92
F-a	0.20	228	208	128	62	128	1	300	99
F-b	0.20	228	208	142	68	142	1	500	97
F-c	0.20	228	208	159	76	159	1	3000	92
F-d	0.20	228	208	179	86	179	1	500	88
H-a	0.20[a]	226	212	142	67	142	1	300	99
H-e	0.20[a]	226	212	150	71	150	1	3000	98
H-b	0.20[a]	226	212	157	74	157	1	500	98
H-c	0.20[a]	226	212	166	78	166	1	300	96
H-d	0.20[a]	226	212	188	89	188	1	3000	89

Length of Specimen: (Not given in report).
Type of Steel: B–cold-drawn; C–cold-drawn, straightened; D–cold-drawn. aged; F–cold-drawn, martempered; H–hot-rolled, hardened, tempered.
Method of Stress Measurement: Lever.
* Based on 0.1 percent strain.
** Specimens with diameter marked with superscript *a* have an elliptical cross section.

TABLE B.12
DUMAS 1958

Mark	Diameter in.	Strength f'_s ksi	Offset Stress f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1Ad	–	242	–	142	–	142	2	500	93
2Ad	–	242	–	142	–	156	2	500	95
3Car	–	242	–	142	–	171	2	700	96
4Ad	–	242	–	142	–	192	2	1000	96
1Ab	–	242	–	142	–	213	2	1000	96
No. 2	–	242	–	142	–	206	2	1500	96
No. 3BG	–	242	–	142	–	–	–	1000	93

TABLE B.12 (Cont.)

2Ba	–	242	–	156	–	171	2	1000	95
3Ba	–	242	–	156	–	156	2	500	92
4Ba	–	242	–	156	–	192	2	1000	96
2Bb	–	242	–	156	–	213	2	1000	95
No. 5	–	242	–	156	–	206	2	1000	96
4DAR	–	242	–	156	–	–	–	1000	91
3Ca	–	242	–	171	–	171	2	1000	91
4Ca	–	242	–	171	–	191	2	1000	93
3Cb	–	242	–	171	–	213	2	1000	94
No. 9	–	242	–	171	–	206	2	1000	93
2Ab	–	242	–	171	–	–	–	1000	88
4Da	–	242	–	192	–	192	2	1000	89
4Ab	–	242	–	192	–	213	2	1000	92
No. 8	–	242	–	192	–	206	2	1000	90
No. 1	–	242	–	192	–	–	–	1000	86
No. 8	–	242	–	206	–	206	2	1000	87
4Bl	–	242	–	206	–	–	–	1000	86
4Db	–	242	–	213	–	213	2	1000	87
4Cb	–	242	–	213	–	–	–	1000	85

Length of Specimen: (Not given in report).
Type of Steel: Cold-drawn single wire.
Method of Stress Measurement: Lever.

TABLE B. 13a
KAJFASZ 1958

Mark	Diameter	Strength f'_s	Offset Stress* f_y	Initial Stress f_{si}	Initial / Offset f_{si}/f_y	Prestretch Stress	Prestretch Time	Final Measurement Time	Final Stress / Initial Stress f_s/f_{si}
	in.	ksi	ksi	ksi	%	ksi	min.	hours	%
3	0.10	320	278	214	77	–	–	360	98
3	0.10	320	278	214	77	–	–	360	98
13	0.10	320	278	214	77	–	–	960	97
13	0.10	320	278	214	77	–	–	960	97
22	0.10	320	278	214	77	–	–	3600	94
22	0.10	320	278	214	77	–	–	3600	96
4	0.10	320	278	214	77	235	10	360	98
4	0.10	320	278	214	77	235	10	360	98
14	0.10	320	278	214	77	235	10	120	99
14	0.10	320	278	214	77	235	10	120	99
5	0.10	320	278	242	87	–	–	120	97
5	0.10	320	278	242	87	–	–	120	97
23	0.10	320	278	242	87	–	–	2880	91
23	0.10	320	278	242	87	–	–	2880	92
6	0.10	320	278	242	87	266	10	720	98
6	0.10	320	278	242	87	266	10	720	98
15	0.10	320	278	242	87	266	10	120	99
15	0.10	320	278	242	87	266	10	120	98
9	0.10	320	278	242	87	–	–	2880	95
7	0.0985	320	278	270	97	–	–	960	95
7	0.0985	320	278	270	97	–	–	960	94
18	0.0985	320	278	270	97	–	–	96	97
18	0.0985	320	278	270	97	–	–	96	97
20	0.0985	320	278	270	97	–	–	72	95
20	0.0985	320	278	270	97	–	–	72	94

TABLE B.13a (Cont.)

8	0.0985	320	278	270	97	297	10	1440	96
8	0.0985	320	278	270	97	297	10	1440	96
16	0.0985	320	278	270	97	297	10	120	98
16	0.0985	320	278	270	97	297	10	120	98
9	0.0985	320	278	270	97	–	–	2880	93
19	0.0985	320	278	284	102	–	–	480	94
19	0.0985	320	278	299	108	–	–	480	95
21	0.0985	320	278	299	108	–	–	72	90
21	0.0985	320	278	299	108	–	–	72	91

Length of Specimen: 78.7 in.
Type of Steel: Cold-Drawn single wire.
Method of Stress Measurement: Lever.
* Based on 0.2 percent strain.

TABLE B. 13b
KAJFASZ 1958

Mark	Diameter	Strength	Offset Stress*	Initial Stress	Initial Offset	Prestretch Stress	Prestretch Time	Final Measurement Time	Final Measurement Final Stress / Initial Stress
		f'_s	f_y	f_{si}	f_{si}/f_y				f_s/f_{si}
	in.	ksi	ksi	ksi	%	ksi	min.	hours	%
1	0.10	316	292	214	73	–	–	96	97
1	0.10	316	292	214	73	–	–	96	97
9	0.10	316	292	214	73	–	–	96	98
9	0.10	316	292	214	73	–	–	120	98
10	0.10	316	292	214	73	–	–	120	95
10	0.10	316	292	214	73	–	–	120	96
18	0.10	316	292	214	73	–	–	120	97
18	0.10	316	292	214	73	–	–	120	98
19	0.10	316	292	214	73	–	–	120	97
19	0.10	316	292	214	73	–	–	120	97
8	0.10	299	263	214	81	–	–	120	96
8	0.10	299	263	214	81	–	–	120	96
17	0.10	299	263	214	81	–	–	96	96
17	0.10	299	263	214	81	–	–	96	96
26	0.10	299	263	214	81	–	–	120	96
26	0.10	299	263	214	81	–	–	120	95
7	0.10	299	246	214	87	–	–	120	96
7	0.10	299	246	214	87	–	–	120	96
16	0.10	299	246	214	87	–	–	120	96
16	0.10	299	246	214	87	–	–	120	95
25	0.10	299	246	214	87	–	–	120	94
25	0.10	299	246	214	87	–	–	120	93
6	0.10	299	232	214	92	–	–	120	94
6	0.10	299	232	214	92	–	–	120	94
15	0.10	299	232	214	92	–	–	120	93
15	0.10	299	232	214	92	–	–	120	93
24	0.10	299	232	214	92	–	–	120	94
24	0.10	299	232	214	92	–	–	120	94
4	0.10	290	206	214	104	–	–	120	92
4	0.10	290	206	214	104	–	–	120	93
13	0.10	290	206	214	104	–	–	120	92
13	0.10	290	206	214	104	–	–	120	93
22	0.10	290	206	214	104	–	–	120	92
22	0.10	290	206	214	104	–	–	120	93
3	0.10	279	178	214	120	–	–	96	90
3	0.10	279	178	214	120	–	–	96	88

TABLE B.13b (Cont.)

12	0.10	279	178	214	120	–	–	96	90
12	0.10	279	178	214	120	–	–	96	90
21	0.10	279	178	214	120	–	–	120	90
21	0.10	279	178	214	120	–	–	120	91
2	0.10	264	163	214	131	–	–	96	90
2	0.10	264	163	214	131	–	–	96	85
11	0.10	264	163	214	131	–	–	96	89
11	0.10	264	163	214	131	–	–	96	86
20	0.10	264	163	214	131	–	–	120	88
20	0.10	264	163	214	131	–	–	120	88

Length of Specimen: 78.7 in.
Type of Steel: Cold-Drawn two-wire strand (The pitch of the strand varied as follows. It was 0.9 in. for 2, 11, 20; 1.3 in. for 3, 12, 21; 1.7 in. for 4, 13, 22; 2.5 in. for 6, 15, 24; 3 in. for 7, 16, 25; 3.5 in. for 8, 17, 26, and infinite for 1, 9, 10, 18, 19).
Method of Stress Measurement: Lever.
* Based on 0.2 percent strain.

TABLE B. 14
LEVI 1958

Mark	Diameter in.	Strength f'_s ksi	Offset Stress* f_y ksi	Initial Stress f_{si} ksi	Initial Offset f_{si}/f_y %	Prestretch Stress ksi	Prestretch Time min.	Final Measurement Time hours	Final Measurement Final Stress / Initial Stress f_s/f_{si} %
1	0.078	302	228	165	72	–	–	75000	88
2	0.078	302	228	165	72	–	–	74800	88
3	0.078	313	284	228	80	–	–	72000	82
4	0.078	288	221	164	74	–	–	73600	84
5	0.078	288	221	170	77	–	–	73600	83
6	0.20	209	174	154	88	–	–	63100	86
7	0.20	213	171	172	100	–	–	17700	89
8	0.20	210	168	161	96	–	–	52800	91
9	0.20	270	242	178	74	–	–	53000	90
10	0.20	239	188	171	91	–	–	2130	89
11	0.20	239	188	156	83	–	–	5150	89
12	0.20	239	188	171	91	–	–	14200	88
13[a]	0.20	215	173	171	99	–	–	47300	90
14[a]	0.20	182	129	95	74	–	–	4150	97
15[a]	0.20	182	137	87	64	–	–	3940	96
16[a]	0.20	256	249	171	69	–	–	40500	91
17	0.08	258	–	199	–	–	–	39100	87
17bis	0.08	264	204	185	91	–	–	120	94
18	0.09	254	201	185	92	–	–	120	94
18bis	0.09	268	215	185	86	–	–	480	92
18bis	0.09	264	190	185	97	–	–	120	93
19	0.20	249	242	185	77	–	–	39100	92
20[a]	0.20	215	173	171	99	–	–	6310	89
21	0.20	261	241	185	77	–	–	36800	92
22[a]	0.20	204	194	171	88	–	–	36800	93
23[a]	0.20	204	194	171	88	–	–	4220	95
24	0.20	242	214	171	80	–	–	120	91
25[a]	0.20	227	208	171	82	–	–	4240	95
26[a]	0.20	230	230	171	74	–	–	120	97
27	0.20	242	234	171	73	–	–	4360	90
28	0.15	282	267	171	64	–	–	4240	96

29	0.20	224	210	171	82	–	–	120	96
30[a]	0.20	212	212	171	81	–	–	3260	94
31	0.20	212	211	156	74	–	–	32600	94
32	0.20	212	212	135	64	–	–	32600	96
33	0.20	230	216	168	78	–	–	120	97
33	0.20	230	220	171	78	–	–	120	97
34	0.31	205	187	171	91	–	–	120	95
34	0.31	208	192	171	89	–	–	120	95
35	0.28	209	172	163	95	–	–	120	95
36	0.16	293	226	171	76	–	–	120	96
36	0.16	289	222	171	77	–	–	120	96
37	0.20	269	196	171	87	–	–	120	94
37	0.20	274	202	171	85	–	–	120	94
38	0.20	243	224	171	76	–	–	120	95
39	0.20	241	199	171	86	–	–	120	95
40	0.20	245	237	171	72	–	–	120	98
41	0.20	262	228	135	59	–	–	1270	95
42	0.20	262	228	157	69	–	–	1300	97
43	0.20	262	228	171	75	–	–	1300	94
44	0.20	278	255	157	62	–	–	120	97
45	0.20	246	183	171	93	–	–	120	91
45	0.20	246	179	171	95	–	–	120	91
45	0.20	244	178	171	96	–	–	120	91
45	0.20	251	179	171	95	–	–	120	90
45	0.20	251	185	171	92	–	–	120	90
46	0.20	262	228	171	75	–	–	120	94
46	0.20	262	228	171	75	–	–	120	95
47	0.20	251	240	171	71	–	–	120	98
47	0.20	253	241	171	71	–	–	120	98
47bis	0.20	251	240	181	75	–	–	120	97
47bis	0.20	253	241	223	97	–	–	120	91
53	0.28	221	193	199	103	–	–	120	94
53	0.28	221	193	185	96	–	–	120	95
53	0.28	221	193	171	89	–	–	120	96
53	0.28	221	193	157	81	–	–	120	96
54	0.20	232	212	171	81	–	–	120	99
55	0.28	235	204	171	84	–	–	120	
56	0.20	240	196[b]	171	87	–	–	120	95
56	0.20	240	198[b]	171	87	–	–	120	95
58	0.20	250	202[b]	171	85	–	–	120	92
58	0.20	254	202[b]	142	70	–	–	120	94
58	0.20	254	202[b]	150	74	–	–	120	93
58	0.20	249	189[b]	171	90	–	–	120	90
59	0.28	222	193[b]	171	89	–	–	120	92
59	0.28	222	188[b]	157	84	–	–	120	92
59	0.28	222	193[b]	171	89	–	–	120	91
59	0.28	222	192[b]	157	82	–	–	120	92
61	0.20	255	186	149	80	–	–	120	93
61	0.20	274	196	171	87	–	–	120	91
61	0.20	268	190	171	90	–	–	120	92
61bis	0.20	259	189	149	79	–	–	120	94
62	0.20	251	168	178	106	–	–	120	91
62	0.20	257	168	178	106	–	–	120	90

TABLE B.14 (Cont.)

65	0.20	215	194	171	88	—	—	120	94
65	0.20	215	192	171	89	—	—	120	95
66	0.20	253	166	171	103	—	—	120	90
66	0.20	254	163	171	105	—	—	120	90
67	0.20	267	246	171	70	—	—	840	97
68	0.20	241	197	171	87	—	—	120	94
68	0.20	241	202	171	84	—	—	120	94
69	0.20	245	180	171	95	—	—	120	95
69	0.20	245	176	171	97	—	—	120	95
72	0.20	272	228[b]	171	75	—	—	120	96
72	0.20	271	228[b]	171	75	—	—	120	96
73	0.20	242	228[b]	135	59	—	—	120	98
73	0.20	242	228[b]	135	59	—	—	120	98
73	0.20	242	228[b]	135	59	—	—	120	98
74	0.20	242	228[b]	171	75	—	—	19300	91
75	0.20	242	228[b]	135	59	—	—	19300	97

Length of Specimen: 9 ft. 10 in.
Type of Steel: Cold-Drawn single wire. Some specimens, marked by the superscript *a* in the table, were cut from rolled wire.
Method of Stress Measurement: Lever.
* Based on 0.1 percent strain. Some values marked by the superscript *b* in the table, were based on 0.2 percent strain.

TABLE B. 15
PAPSDORF AND SCHWIER 1958

Mark*	Diameter	Strength	Offset Stress**	Initial Stress	Initial Offset	Prestretch Stress	Prestretch Time	Final Measurement Time	Final Stress*** / Initial Stress
		f_s'	f_y	f_{si}	f_{si}/f_y				f_s/f_{si}
	in.	ksi	ksi	ksi	%	ksi	min.	hours	%
1a	0.26	254	223	109	49	—	—	1000	99
1b	0.26	254	223	109	49	—	—	1000	98
1c	0.26	254	223	109	49	—	—	1000	97
1d	0.26	254	223	109	49	—	—	1000	92
1e	0.26	254	223	109	49	—	—	1000	90
2a	0.26	254	223	132	59	—	—	1000	99
2b	0.26	254	223	132	59	—	—	1000	97
2c	0.26	254	223	132	59	—	—	1000	95
2d	0.26	254	223	132	59	—	—	1000	91
2e	0.26	254	223	132	59	—	—	1000	91
3a	0.26	254	223	157	70	—	—	1000	96
3b	0.26	254	223	157	70	—	—	1000	93
3c	0.26	254	223	157	70	—	—	1000	90
3d	0.26	254	223	157	70	—	—	1000	88
3e	0.26	254	223	157	70	—	—	1000	87
4a	0.26	254	223	180	81	—	—	1000	92
4b	0.26	254	223	180	81	—	—	1000	88
4c	0.26	254	223	180	81	—	—	1000	85
4d	0.26	254	223	180	81	—	—	1000	83
5a	0.26	254	223	206	92	—	—	1000	86
5b	0.26	254	223	206	92	—	—	1000	82
5c	0.26	254	223	206	92	—	—	1000	79
5d	0.26	254	223	206	92	—	—	1000	78
6a	0.26	254	223	228	102	—	—	1000	81
6b	0.26	254	223	228	102	—	—	1000	79
6c	0.26	254	223	228	102	—	—	1000	78

TABLE B.15 (Cont.)

6d	0.26	254	223	228	102	–	–	1000	77
7a	0.26	254	223	244	109	–	–	1000	80
7b	0.26	254	223	244	109	–	–	1000	79
7c	0.26	254	223	244	109	–	–	1000	78
7d	0.26	254	223	244	109	–	–	1000	78

Length of Specimen: a, b, c–67 or 79 inches; d and e–79 inches.
Type of Steel: Drawn and Tempered.
Method of Stress Measurement: Lever.
* Not indicated in original report.
** Based on 0.2% proof stress.
*** The final stress represents an average obtained from 2 to 5 test specimens.
a–Test Temperature 72°F; b–Test Temperature 95°F; c–Test Temperature 122°F; d–Test Temperature 212°F; e–Test Temperature 302°F.

TABLE B. 16
JEVTIC 1959

Mark*	Diameter	Strength	Offset Stress**	Initial Stress	Initial Offset	Prestretch Stress	Prestretch Time	Final Measurement Time	Final Measurement Final Stress / Initial Stress
		f_s'	f_y	f_{si}	f_{si}/f_y				f_s/f_{si}
	in.	ksi	ksi	ksi	%	ksi	min.	hours	%
1	0.1	271	189	173	91.5	–	–	696	96.7
2	0.1	271	189	176	93.1	–	–	696	95.3
3	0.1	271	189	189	100.0	–	–	696	95.2
4	0.1	271	189	202	107	–	–	696	94.5
5	0.1	271	189	226	119	–	–	696	91.8
6	0.2	214	156	141	90.4	–	–	720	95.3
7	0.2	214	156	155	99.4	–	–	720	94.4
8	0.2	214	156	174	112.4	–	–	792	92.1

Length of Specimen: 80.7 in.
Type of Steel: Cold-drawn single wire.
Method of Stress Measurement: Vibration.
* Not indicated in original paper.
* Based on 0.1 percent strain.

TABLE B. 17
VIEST, KINGHAM, AND FISHER 1961

Mark	Diameter	Strength	Offset Stress	Initial Stress	Initial Offset	Prestretch Stress	Prestretch Time	Final Measurement Time	Final Measurement Final Stress / Initial Stress
		f_s'	f_y	f_{si}	f_{si}/f_y				f_s/f_{si}
	in.	ksi	ksi	ksi	%	ksi	min.	hours	%
509	0.192	257	215	199.1	92.6	219.1	1	1000	91.0
507	0.192	257	215	196.4	91.3	216.4	1	1000	92.8
506	0.192	257	215	187.5	87.2	207.5	1	1000	92.1
505	0.192	257	215	184.7	85.9	204.7	1	1000	94.1
502	0.192	257	215	180.8	84.1	200.8	1	1000	92.9
504	0.192	257	215	180.5	84.0	200.5	1	1000	95.7
503	0.192	257	215	175.0	81.4	195.0	1	1000	95.8
510	0.192	257	215	169.1	78.7	189.1	1	1000	95.1
604	0.375	265	240	187.5	78.1	a	0.3-0.5	1000	94.6
609	0.375	265	240	185.0	77.1	a	0.3-0.5	1000	93.6
610	0.375	265	240	165.4	69.0	a	0.3-0.5	1000	97.0
607	0.375	265	240	163.0	68.0	a	0.3-0.5	1000	97.4
602	0.375	265	240	158.0	65.9	a	0.3-0.5	1000	98.0

TABLE B.17 (Cont.)

606	0.375	275	240	195.5	81.5	a	0.3-0.5	1000	93.9
608	0.375	275	240	189.0	78.8	a	0.3-0.5	1000	95.7
603	0.375	275	240	185.8	77.5	a	0.3-0.5	1000	96.1
601	0.375	275	240	169.3	70.6	a	0.3-0.5	1000	96.9
605	0.375	275	240	168.3	70.1	a	0.3-0.5	1000	96.5

Length of Specimen: About 3 ft. 4 in.
Type of Steel: Cold-Drawn stress relieved wire in Series 500 and cold-drawn stress-relieved seven wire strand in Series 600.
Method of Stress Measurement: Vibration for the wires. The stress in the strand was measured directly.
a—An additional stress of 19 to 24 ksi.